NIST Technical Note 2096

Small Punch Testing to Estimate Mechanical Properties of Additively Manufactured Ti-6Al-4V

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Abstract

Small Punch (SP) testing is a methodology that uses small disk-shaped specimens, generally 8 mm in diameter and 0.5 mm thick, to estimate mechanical properties of metallic materials, such as tensile properties, fracture toughness, and ductile-to-brittle transition temperature. Empirical correlations are typically used to infer conventional mechanical properties from characteristic forces and displacements obtained from the test record. Most of the available literature relates to SP testing of steels, while relatively little information is available for other metallic materials. At NIST in Boulder, Colorado, SP tests were conducted on additively manufactured (AM) Ti-6Al-4V with different processing parameters and heat treatment conditions. The shape of force/punch displacement curves appeared different than typically reported for conventionally manufactured steels, and correlations with tensile parameters were generally weaker than those published for steel samples. We are led to conclude that the application of the SP technique, characterized by a biaxial loading mode, to materials with high anisotropy, such as current batches of AM Ti-6Al-4V, may be somewhat problematic and therefore of limited applicability. Finally, the use of actuator displacement instead of punch displacement in test analyses appeared to cause a generalized worsening of the correlations.

Key words

additive manufacturing, empirical correlations, fracture toughness, Small Punch, tensile properties, Ti-6Al-4V.

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Glossary

AM	Additive Manufacturing / Additively Manufactured
ASTM	American Society for Testing and Materials
CEN	European Committee for Standardization
EBM	Electron-Beam Melting, *aka* Electron-Beam Additive Manufacturing
EDM	Electro-Discharge Machining
D	In SP testing, specimen diameter (mm)
$\mathrm{d}v/\mathrm{d}t$	In SP testing, punch displacement rate (mm/s)
E_m	In SP testing, total energy calculated up to u_m (J)
E_PL	In SP testing, plastic energy calculated up to u_m (J)
E_SP	In SP testing, fracture energy calculated up to u_f (J)
ε_f	In SP testing, effective fracture strain
$\dot{\varepsilon}_{SP}^{max}$	In SP testing, estimated maximum strain rate (1/s)
ε_t	In tensile testing, total elongation (%)
ε_u	In tensile testing, uniform elongation (%)
F	Force (N)
F_e	In SP testing, elastic-plastic transition force (N)
$F_\mathrm{h0/10,off}$	In SP testing, force at the intersection between the test record and a line parallel to the slope of the initial linear region with an offset of $0.1 \cdot h_0$ (N)
F_infl	In SP testing, force at the inflection point of the curve ($\mathrm{d}^2F/\mathrm{d}u^2 = 0$) (N)
F_m	In SP testing, maximum force (N)
$F_\mathrm{0.1mm,off}$	In SP testing, force at the intersection between the test record and a line parallel to the slope of the initial linear region with an offset of 0.1 mm (N)
$F_\mathrm{0.1mm}$	In SP testing, force corresponding to a displacement value of 0.1 mm (N)
$F_\mathrm{0.48mm}$	In SP testing, force corresponding to a displacement value of 0.48 mm (N)
$F_\mathrm{0.5mm}$	In SP testing, force corresponding to a displacement value of 0.5 mm (N)
$F_\mathrm{0.645mm}$	In SP testing, force corresponding to a displacement value of 0.645 mm (N)
$F_\mathrm{0.65mm}$	In SP testing, force corresponding to a displacement value of 0.65 mm (N)
$F_\mathrm{0.9mm}$	In SP testing, force corresponding to a displacement value of 0.9 mm (N)
$f(v)$	In SP testing, bilinear function used to determine F_e [10,11].
h_0	In SP testing, initial specimen thickness (mm)
ISO	International Standardization Organization
K	In SP testing, curvature parameter according to [30]
KV	Charpy absorbed energy (J)
r	Pearson correlation coefficient
Ra	Surface roughness (μm)
R_m	In tensile testing, tensile strength (MPa)

R_{p02}	In tensile testing, yield strength (MPa)
$Slope_{ini}$	In SP testing, slope of the initial elastic region of the curve (N/mm)
SP	Small Punch
t_{calc}	Calculated value of the *t*-test statistic
$t_{critical}$	Critical value of the *t*-test statistic (if $t_{calc} > t_{critical}$, means are statistically different)
u	Specimen deflection (mm)
v	Punch displacement (mm)
v_f	In SP testing, punch displacement corresponding to a 20 % force drop with respect to maximum force (mm)
v_m	In SP testing, punch displacement at maximum force (mm)
v_{1p}	In SP testing, punch displacement at the occurrence of the first significant pop-in (mm).

1. Introduction

In the field of experimental techniques based on sub-size or miniaturized specimens, destructive testing of very small disk-shaped specimens allows characterizing the mechanical properties of service-exposed plant components or structures with a minimal amount of material extracted from the component [1]. Moreover, a considerable number of disk specimens can be extracted from machining leftovers or already tested conventional specimens.

The Small Punch (SP) test, also known as the Disk Bend test, was developed in the mid-1980s [2,3] through the use of tiny disks of 3 mm diameter and 0.25 mm thickness, centrally loaded by a spherical ball or hemispherical punch, and expanded into a larger lower die. The test system was a module that could be placed between the loading platens of a tensile machine and subsequently loaded in compression [3]. The outcome is a bulge in the disk rather than a shear cut, as in a similar methodology called the Shear Punch test [4]. Although disks of these dimensions are still used for SP testing, nowadays the most popular specimen geometry is a round disk with a diameter of 8 mm and a thickness of 0.5 mm, which is the geometry used in this study. The use of square specimens (10 mm × 10 mm) has also been reported [5] but is not as common.

A schematic representation of the SP test method is shown in Fig. 1.

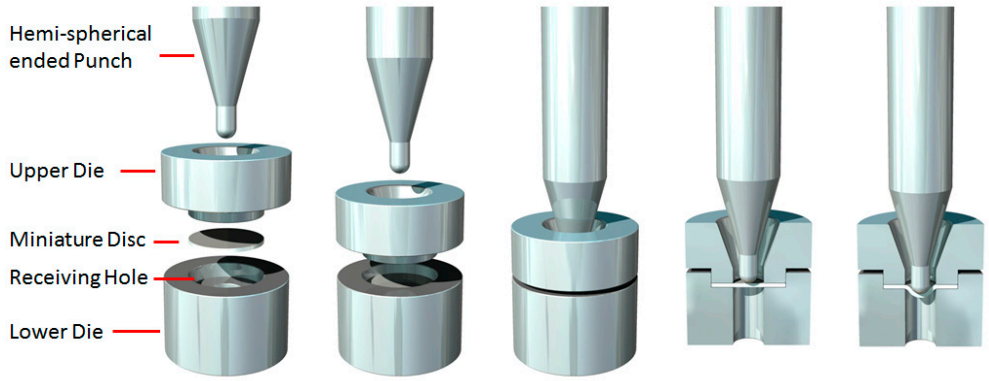

Figure 1 - Schematic representation of the SP test method.

The general form of a SP force/deflection test record for a steel specimen is shown in Fig. 2 [1]. Five distinct regions can be identified:

1. Elastic region,
2. Departure from linearity (elastic-plastic transition),
3. Local bending, transitioning to a membrane stress regime,
4. Membrane stress regime, and
5. Final failure region.

The general form of the test record suggests that yield stress may be associated with the change in slope between regions 1 and 2, while the ultimate tensile stress may be related to the maximum force, and ductility to maximum deflection. However, in the case of steels showing low ductility, the membrane stress regime and final failure region may be virtually absent or minimized.

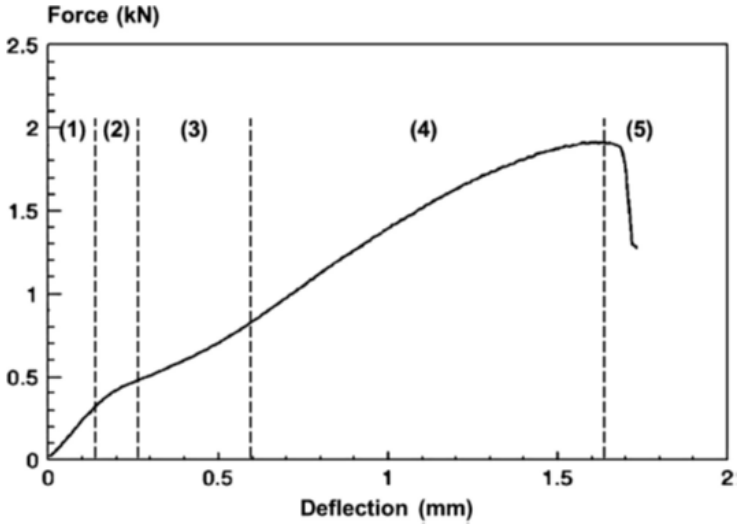

Figure 2 - Typical form of a SP force-deflection diagram for steel, showing five distinct regions [1].

Characteristic values of force, displacement, and energy (calculated by integrating force and displacement) are identified on the test record. These values are generally fed into empirical relationships to obtain estimates of specific mechanical parameters, such as tensile properties, ductile-to-brittle transition temperature, fracture toughness, for the material under investigation. Numerous empirical correlations are available in the literature, and have been developed by comparing characteristic parameters from SP tests with tensile properties, transition temperature data, and fracture toughness values measured by means of conventional tests.

In most cases, correlations appear to be strongly dependent on the material (or the class of material) under investigation, and cannot be expected to be applicable to other materials or material conditions [5].

However, alternative approaches of a more analytical nature have also been proposed. Several authors have matched force-displacement curves from SP tests, up to the point of observed crack initiation, to a database of curves corresponding to a range of stress-strain constitutive behaviors. The model used in this case is a Ramberg-Osgood model with a possible modification to accommodate the discontinuous yield observed in several low-alloy steels [6]. Other analytical methods have also been proposed, involving the use of Neural Networks and Finite Element simulations [7-9]. The approach used in this report for the analysis of SP test results, however, is strictly of a correlative nature.

Even though researchers all over the world have been performing SP tests since the 1980s, an official test standard issued by an internationally recognized standardization body (ASTM or ISO) has yet to be developed.

The currently available document that most closely resembles a test standard is a European CEN[1] Workshop Agreement, CWA 15627 (*Small Punch Test Method for Metallic Materials*), issued in 2007 [10]. At the time of writing, a Draft ASTM *Test Method for Small Punch Testing of Metallic Materials* [11], modeled after CWA 15627, is being developed inside the ASTM E10.02 Sub-Committee (*Behavior and Use of Nuclear Materials*), and is in the final balloting stages.

[1] CEN: *Comité Européen de Normalisation* (European Committee for Standardization).

The development of SP testing at NIST in Boulder, CO, and the validation of the relevant experimental and analytical procedures was covered in a recently published NIST Internal Report [12]. In this report, we present the results of SP testing conducted with the objective of deriving estimates of mechanical properties (tensile and fracture toughness) for additively manufactured (AM) Ti-6Al-4V in various conditions. Previously published investigations focused on the measurement of Charpy impact toughness [13] and room temperature elastic-plastic fracture toughness [14] of the same material under various manufacturing conditions.

Additive Manufacturing (AM), previously referred to as 3D printing, is a process in which material is joined or solidified under computer control to create a three-dimensional object, with material being fused (such as liquid molecules or powder grains being fused together), typically layer by layer. In the 1990s, 3D printing was considered only suitable to produce functional or aesthetical prototypes. Nowadays, the precision, repeatability, and material range have increased to the point that 3D printing, or AM, is considered an industrial production technology.

The objective of the NIST Additive Manufacturing Fatigue and Fracture Project is twofold:

- Develop appropriate measurement science for fatigue and fracture behavior of additively manufactured metals, to underpin a rapid qualification framework.
- Determine the effect of processing (including post-processing) and structure (e.g. internal defects, external defects, residual stress, crystallographic texture, grain size, and chemistry) on fatigue and fracture properties of additively manufactured metals.

Ti-6Al-4V (hereinafter referred to as Ti64) is the most widely used titanium alloy, featuring good machinability and excellent mechanical properties. It offers the best all-round performance for a variety of weight reduction applications in aerospace, automotive, and marine equipment. Its high strength, low weight, and outstanding corrosion resistance has led to a wide range of successful applications that demand high levels of reliable performance in surgery and medicine, aerospace, automotive, chemical plants, power generation, oil and gas extraction, sports, and other major industries.

2. Experimental setup for SP testing

The fixture developed at NIST for SP testing, following the recommendations in refs. [10,11], consists of an upper and a lower die, a rod (100 mm long, 2.5 mm diameter), and a ball (2.5 mm diameter). The combination of the rod and ball constitute the punch, which is driven through the specimen, held between the upper and lower dies. The fixture is shown in Fig. 3 in both disassembled (left) and assembled (right) form.

The fixture was mounted on a universal electro-mechanical test machine, equipped with a 5 kN capacity load cell and an extensometer[2]. The extensometer was attached to one of the columns of the machine in order to measure the relative displacement between the machine actuator and the machine frame, in close proximity to the punch. Fig. 4 shows the fixture mounted on the test machine and the positioning of the extensometer with respect to the

[2] Load cell, machine actuator, and extensometer are regularly calibrated in accordance with ASTM E4 and E83. Based on calibrations current at the time of testing, maximum errors were found to be less than 0.7 % for force values, less than 1.5 % for actuator displacements, and less than 2 % for extensometer displacement values.

machine actuator. Unlike the extensometer signal, actuator displacement includes the compliance of the whole test system.

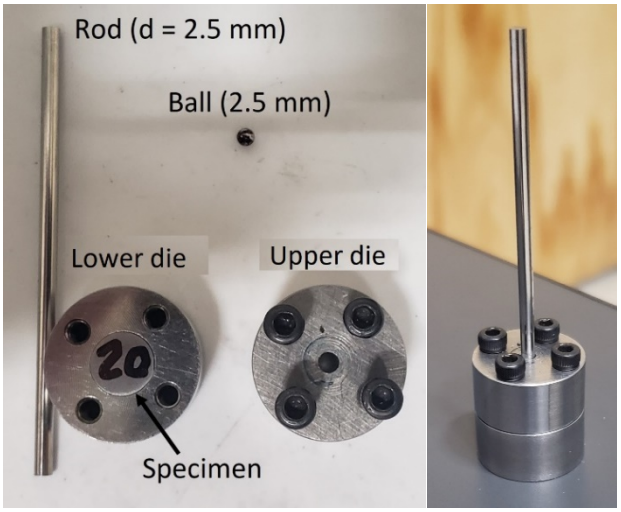

Figure 3 - SP testing fixture used at NIST, shown disassembled (left) and assembled (right).

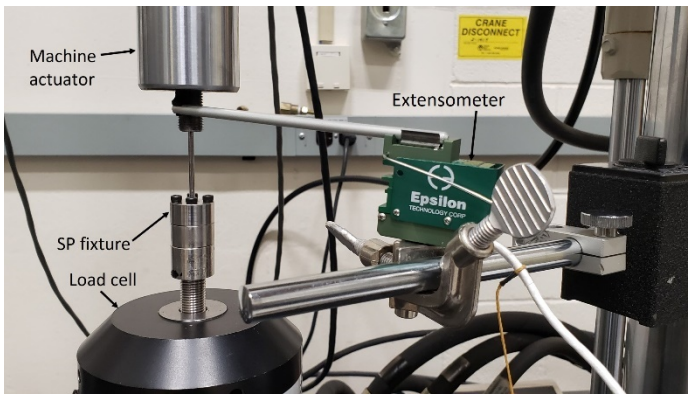

Figure 4 - SP testing fixture mounted on the test machine with the extensometer for punch displacement measurement.

All tests (except for a preliminary series described in Sec. 4.2) were performed at room temperature (21 °C ± 2 °C) in actuator displacement control, at rates between 0.001 mm/s and 0.003 mm/s. Force, actuator displacement, and punch displacement (extensometer) data were recorded at a sampling frequency of 1 Hz. To account for the compliance of the test system on punch displacement, actuator and extensometer displacements were recorded without a specimen in place, and then subtracted from displacements measured during the tests.[3]

[3] In a few SP tests, punch displacement is larger than actuator displacement, contrary to expectations. The reason for this is unclear, and the most likely explanation is related to the different positioning of the extensometer from one test to the other. The use of a clip-on-gage, always located in the same spot, instead of an extensometer should improve the consistency of the displacement signals in future tests.

3. Material and conditions investigated

The AM Ti64 parts used in this study were fabricated using an EBM powder bed fusion Arcam[4] A1 machine (software version 3.2.132,60 kV, 50 μm layer thickness) and standard Arcam Ti64 gas-atomized powder (70 μm average diameter).

The following conditions (AM processing parameters), for which conventional tensile and fracture toughness test results had been previously measured [14,15], were investigated:

a. As-built condition (*i.e.*, no heat treatment).
b. Non-standard Ti64 HIP (800 °C, 100 MPa, 2 h, Ar environment, standard heating and cooling rates[5]).
c. Standard Ti64 HIP (900 °C, 100 MPa, 2 h, Ar environment, standard heating and cooling rates[4]).
d. Non-standard Ti64 HIP (1050 °C, 100 MPa, 2 h, rapid cooling[6] in Ar) with an additional HIP (800 °C, 30 MPa, 2 h, slow cooling[4] in Ar – meant for martensite tempering).
e. Scan lengths[7] of:
   e1. 78 mm and
   e2. 26 mm.

In order to assess the applicability of SP testing to AM Ti64, a preliminary series of 10 tests was performed on supported[8] specimens, all in standard HIP condition (900 °C), corresponding to a different scan length (52 mm). An additional objective of these preliminary tests was to investigate the influence of different actuator displacement rates on the test results.

All SP disks were machined from AM Ti64 blocks by electrical discharge machining (EDM) in accordance with the drawing in Fig. 5.

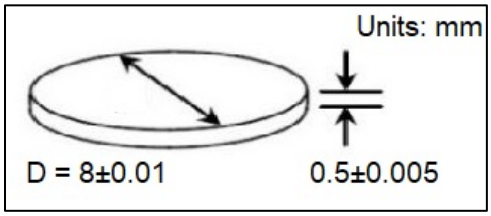

Figure 5 - Dimensions and tolerances of the SP specimens.

After machining, some of the specimens were polished to the surface finish required by the ASTM Draft [10], Ra ≤ 0.25 μm, by means of abrasive paper with an abrasive grit size designation P400 followed by fine grinding (P1200). As a result, polished disks had a thickness ranging from 0.43 mm to 0.48 mm. The rest of the specimens (rough disks) had surface roughness in the range Ra = 3 μm to 4 μm. This allowed us to investigate the influence of surface finish on SP test results.

[4] Certain commercial software, equipment, instruments or materials are identified in this paper to adequately specify the experimental procedure. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the equipment or materials identified are necessarily the best available for the purpose.
[5] 12 °C/minute.
[6] 1600 °C/minute.
[7] Scan length is a manufacturer-specific parameter that corresponds to the distance the electron beam travels on a single track before turning around to begin the next track. It has been shown to determine energy density and affect texture [16].
[8] Specimens directly attached to the build plate were identified as "non-supported", while "supported" specimens (such as the ones tested in the preliminary phase) were connected to the build plate by means of standard thin wafer supports.

The overall test matrix, excluding the preliminary study, is presented in Table 1. The total number of tests performed was 55 (36 on rough specimens and 19 on polished specimens). All specimens were extracted from non-supported parts, and were tested at room temperature (21 °C ± 2 °C).

Table 1 – Test matrix (for material condition codes, see bullet list in Section 3 above).

Material condition	Number of tests performed	
	Rough disks	Polished disks
a,e1	6	3
a,e2	6	3
b,e1	6	4
c,e1	6	2
c,e2	6	4
d,e1	6	3

The main tensile properties for the different conditions investigated, obtained from conventional tensile tests [15] and used for the correlations with SP test results, are listed in Table 2.

Table 2 – Tensile properties for the different material conditions.

Material condition	R_{p02} (MPa)	R_m (MPa)	ε_u (%)	ε_f (%)
a,e1	879	981	9.5	27.8
a,e2	875	972	9.1	25.5
b,e1	864	969	10.1	31.7
c,e1	838	951	10.0	31.0
c,e2	799	918	10.0	31.8
d,e1	885	985	7.9	18.8

4. Test results

4.1. General remarks

An example of force/punch displacement curve for condition {b,e1} is shown in Fig. 6. Depending on material condition, one or more force drops were observed before, at, and/or after maximum force.

The SP curves obtained in this study are qualitatively similar to those reported in the literature for other investigations on EBM AM Ti64 [17-20], and differ significantly from conventional SP test records for steel specimens, as in the example illustrated in Fig. 2. However, the five regions shown in Fig. 1 can still be reasonably identified, see Fig. 6, and the analysis of the test can be conducted in accordance with Refs. [10,11].

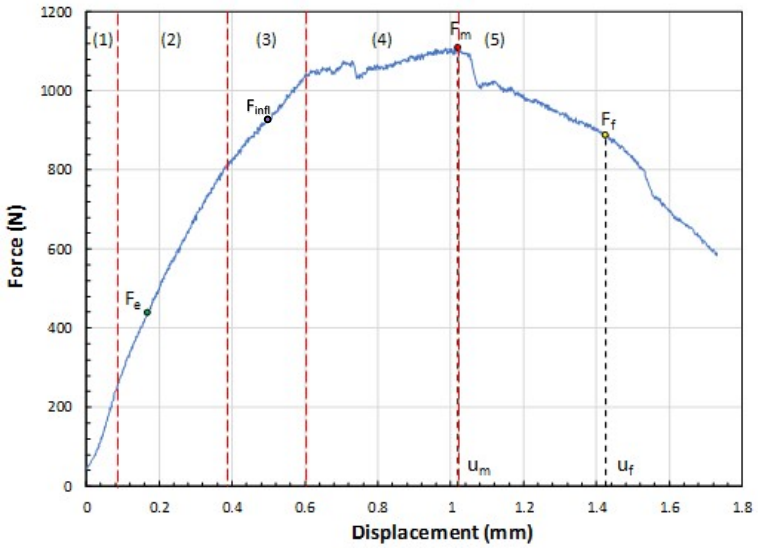

Figure 6 - Force-punch displacement curve for a SP test on AM Ti64 (as-built, scan length = 78 mm).

From the analysis of each individual force-punch displacement curve the following force values, to be used for correlation with tensile properties, were extracted:

- elastic-plastic transition force, F_e (Fig. 6)
- maximum force, F_m (Fig. 6)
- force at the intersection between the test record and a line parallel to the slope of the initial linear region with an offset of $0.1 \cdot h_0$, $F_{h0/10,off}$
- force at the inflection point of the curve ($d^2F/du^2 = 0$), F_{infl} (Fig. 6)
- force at the intersection between the test record and a line parallel to the slope of the initial linear region with an offset of 0.1 mm, $F_{0.1mm,off}$
- force corresponding to a displacement value of 0.XXX mm, $F_{0.XXXmm}$ (where 0.XXX = 0.48, 0.645, or 0.65).

Note that, in accordance with Refs. [10,11], the elastic-plastic transition force, F_e, is obtained as the projection on the test record of the intersection between two linear fits. However, one of the yield strength correlations that have been proposed in the literature directly uses the force corresponding to the intersection of the regression lines. Therefore, in this investigation, the two values are labelled respectively $F_{e,proj}$ and $F_{e,int}$ (see Fig. 7 for an illustration of the two values).

The following punch displacement values, corresponding to forces bearing the same subscript, will also recorded: u_e, u_m (Fig. 6), $u_{h0/10,off}$, u_{infl}, $u_{0.1mm,off}$, and $u_{e1.5}$.

Finally, three energy values were also calculated for each test:

- total energy calculated up to u_m, E_m;
- plastic energy calculated up to u_m, E_{SP};
- fracture energy calculated up to u_f, E_{SP}.

Additionally, the slope of the initial elastic part of the test record, $Slope_{ini}$, as well as forces and displacements corresponding to test end (F_f and u_f, Fig. 6), were also reported.

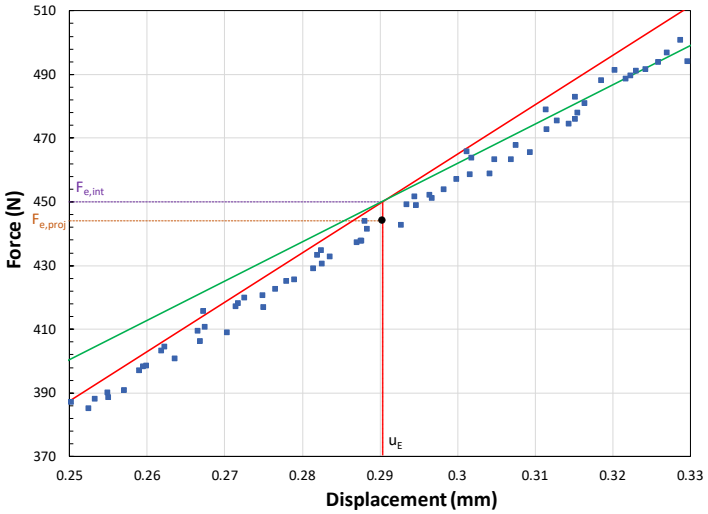

Figure 7 - Determination of two alternative values for the elastic-plastic transition force, $F_{\mathrm{e,proj}}$ and $F_{\mathrm{e,int}}$. The green and red lines are the two linear fits, while the blue squares are experimental force-displacement points.

All the analyses were performed by means of a macro-enabled spreadsheet, which has been described in [12]. This same report also provides specific details on the determination of the individual characteristic values of force, displacement, and energy.

4.2. Preliminary tests (standard HIP, scan length = 56 mm, supported)

Ten SP specimens (all rough) were tested in the preliminary series, with test speeds (actuator displacement rates) ranging between 0.0007 mm/s and 0.0084 mm/s. Note that the most commonly used test rate in the literature is 0.0015 mm/s. The applied displacement rates correspond to a range of maximum estimated strain rate $\dot{\varepsilon}_{max} = 7.35 \times 10^{-4}\mathrm{s}^{-1}$ to $8.38 \times 10^{-3}\mathrm{s}^{-1}$ [10,11], *i.e.*, more than an order of magnitude.

The results obtained are presented, with average values and standard deviations (absolute and relative[9]), in Table 3 (linear elastic slopes and characteristic forces) and Table 4 (characteristic displacements and energies). Data reported in the Tables show that forces and displacements corresponding to the elastic-plastic transition exhibit the largest standard deviations.

[9] The relative standard deviation, expressed in %, is obtained by dividing the absolute standard deviation by the average value. This is also called *coefficient of variation* (CV).

Table 3 - Test results for supported specimens with standard HIP and scan length = 56 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP1	0.0007	0.50	7.35E-04	1550.087	444.0	450.1	717.9	929.0	158.3	682.1	706.7	873.6	1132.5	1155.0	1039.1	924.0
SP2	0.0071	0.50	7.05E-03	2219.097	321.9	337.6	532.4	714.6	226.5	785.1	814.2	977.1	1053.2	1102.8	169.1	882.2
SP3	0.0030	0.50	3.00E-03	2129.119	412.0	429.3	607.7	768.0	221.2	782.8	808.5	960.7	1057.7	1107.5	1080.9	886.0
SP4	0.0007	0.51	7.23E-04	1767.222	319.7	329.3	557.7	760.7	174.1	697.7	722.3	904.2	1096.9	1128.8	1122.8	903.0
SP5	0.0070	0.49	7.01E-03	2008.641	346.0	351.1	613.3	785.1	208.1	775.4	793.7	958.5	1087.4	1091.8	1082.4	873.5
SP6	0.0010	0.49	1.01E-03	2045.639	371.8	390.6	590.3	743.8	209.9	767.7	788.2	964.4	1150.9	1169.2	693.0	935.3
SP7	0.0010	0.50	1.01E-03	1893.577	347.1	354.2	567.8	753.2	191.7	735.9	762.0	929.8	1092.3	1103.7	446.2	882.9
SP8	0.0010	0.50	1.02E-03	1797.352	354.0	366.1	560.1	782.2	182.3	704.7	735.4	928.1	1186.9	1186.9	790.2	949.5
SP9	0.0010	0.49	1.01E-03	2175.631	391.5	410.5	575.3	730.7	221.4	792.9	816.7	1006.7	1094.7	1154.0	1066.3	923.2
SP10	0.0084	0.49	8.38E-03	2050.102	423.4	441.0	661.4	821.2	201.1	790.3	815.8	959.7	1097.1	1157.3	720.7	925.8
			Mean	**1963.647**	**373.1**	**386.0**	**598.4**	**778.9**	**199.5**	**751.5**	**776.4**	**946.3**	**1105.0**	**1135.7**	**821.1**	**908.6**
			SD	**209.755**	**43.003**	**44.485**	**55.350**	**60.700**	**22.532**	**42.540**	**41.842**	**38.161**	**41.093**	**32.983**	**321.027**	**26.387**
				10.7%	**11.5%**	**11.5%**	**9.2%**	**7.8%**	**11.3%**	**5.7%**	**5.4%**	**4.0%**	**3.7%**	**2.9%**	**39.1%**	**2.9%**

Table 4 - Test results for supported specimens with standard HIP and scan length = 56 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP1	0.0007	0.50	7.35E-04	0.290	0.513	0.701	0.074	1.076	1.300	1.475	1.18	0.76	0.33
SP2	0.0071	0.50	7.05E-03	0.152	0.291	0.423	0.366	1.053	2.299	1.500	1.25	0.79	0.52
SP3	0.0030	0.50	3.00E-03	0.202	0.336	0.463	0.042	1.034	0.991	1.529	1.28	0.77	0.48
SP4	0.0007	0.51	7.23E-04	0.186	0.366	0.532	0.097	1.102	0.963			0.80	0.44
SP5	0.0070	0.49	7.01E-03	0.175	0.356	0.491	0.067	0.886	0.878			0.60	0.30
SP6	0.0010	0.49	1.01E-03	0.191	0.339	0.464	0.081	0.881	1.734	1.505	1.28	0.61	0.27
SP7	0.0010	0.50	1.01E-03	0.187	0.351	0.498	0.086	0.894	0.257	1.675	1.38	0.59	0.27
SP8	0.0010	0.50	1.02E-03	0.204	0.362	0.535	0.111	0.899	1.729	1.478	1.20	0.59	0.20
SP9	0.0010	0.49	1.01E-03	0.189	0.315	0.436	0.086	1.132	1.428	1.576	1.37	0.90	0.59
SP10	0.0084	0.49	8.38E-03	0.215	0.373	0.502	0.076	1.121	0.419	1.560	1.34	0.87	0.55
			Mean	**0.199**	**0.360**	**0.504**	**0.109**	**1.008**	**1.200**	**1.537**	**1.28**	**0.73**	**0.39**
			SD	**0.036**	**0.059**	**0.078**	**0.092**	**0.106**	**0.627**	**0.067**	**0.075**	**0.120**	**0.136**
				18.3%	**16.5%**	**15.5%**	**84.8%**	**10.5%**	**52.3%**	**4.3%**	**5.9%**	**16.5%**	**34.5%**

Test and analysis details for each of the tests performed on this group of specimens are provided in Annex 1.

The influence of estimated maximum strain rate on elastic-plastic transition forces ($F_{e,proj}$) and maximum forces (F_m) is illustrated in Fig. 8. For both force values, the slopes of the linear fits are statistically not different from zero based on ANOVA tests, indicating that the influence of displacement rate within the investigated range (0.0007 mm/s to 0.0084 mm/s) is negligible.

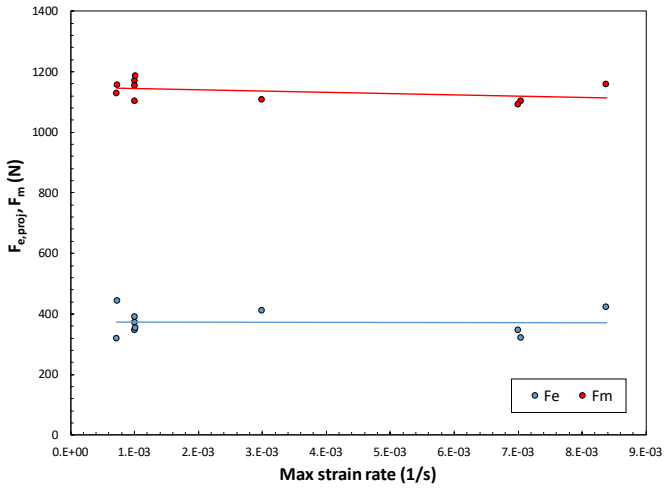

Figure 8 - Values of elastic-plastic transition forces and maximum forces as a function of estimated maximum strain rate.

4.3. As-built, scan length = 78 mm

Test results for the rough specimens is presented in Tables 5 and 6, which describe elastic slope/forces and displacements/energies, respectively. Likewise, Tables 7 and 8 describe the equivalent measurements for the polished specimens.

Table 5 – Test results for rough as-built specimens with scan length = 78 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{el}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP1	0.0009	0.51	9.34E-04	2098.05	352.6	361.0	621.7	808.2	216.0	807.1	831.2	995.7	1057.2	1070.8	645.2	856.7
SP2	0.0010	0.50	9.27E-04	2693.16	394.4	404.7	638.2	841.7	271.0	930.2	944.1	996.4	1047.2	1065.2	1038.6	852.2
SP4	0.0010	0.48	9.64E-04	3070.90	511.2	549.7	674.5	767.8	333.2	884.0	901.6	986.5	1103.1	1109.4	709.8	887.5
SP5	0.0010	0.49	9.64E-04	2960.92	396.4	424.7	571.1	732.9	299.7	879.4	899.0	973.8	1088.7	1098.1	635.9	878.4
SP6	0.0010	0.49	9.69E-04	2769.78	507.7	526.7	703.1	851.9	288.5	919.3	951.0	1009.7	1024.5	1050.7	740.5	840.6
SP7	0.0011	0.51	1.01E-03	2772.76	438.4	470.2	653.3	822.8	288.2	915.7	927.0	1059.5	1083.8	1109.3	703.4	887.4
			Mean	**2727.6**	**433.4**	**456.2**	**643.7**	**804.2**	**282.8**	**889.3**	**909.0**	**1003.6**	**1067.4**	**1083.9**	**745.6**	**867.1**
			SD	**338.711**	**64.851**	**72.952**	**45.500**	**45.717**	**38.718**	**45.085**	**43.665**	**29.862**	**29.503**	**24.972**	**149.028**	**19.978**
				12.4%	**15.0%**	**16.0%**	**7.1%**	**5.7%**	**13.7%**	**5.1%**	**4.8%**	**3.0%**	**2.8%**	**2.3%**	**20.0%**	**2.3%**

Table 6 – Test results for rough as-built specimens with scan length = 78 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP1	0.0009	0.51	9.34E-04	0.172	0.346	0.487	0.074	0.938	1.568	1.297	1.02	0.67	0.39
SP2	0.0010	0.50	9.27E-04	0.150	0.287	0.413	0.070	0.866	0.902	1.345	1.11	0.65	0.44
SP4	0.0010	0.48	9.64E-04	0.179	0.271	0.351	0.317	0.900	1.639	1.405	1.19	0.69	0.49
SP5	0.0010	0.49	9.64E-04	0.143	0.243	0.348	0.085	0.864	1.656	1.373	1.16	0.64	0.44
SP6	0.0010	0.49	9.69E-04	0.190	0.304	0.408	0.525	0.977	1.608	1.479	1.26	0.77	0.57
SP7	0.0011	0.51	1.01E-03	0.170	0.286	0.398	0.063	1.019	1.592	1.425	1.22	0.83	0.60
			Mean	**0.167**	**0.290**	**0.401**	**0.189**	**0.928**	**1.494**	**1.387**	**1.160**	**0.707**	**0.489**
			SD	**0.018**	**0.035**	**0.051**	**0.192**	**0.062**	**0.292**	**0.064**	**0.086**	**0.074**	**0.083**
				10.5%	**11.9%**	**12.7%**	**101.4%**	**6.7%**	**19.5%**	**4.6%**	**7.4%**	**10.5%**	**17.0%**

Table 7 – Test results for polished as-built specimens with scan length = 78 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP8	0.0014	0.45	1.44E-03	3519.91	387.3	421.6	521.6	694.8	336.9	903.1	921.2	911.2	972.6	975.4	505.2	780.3
SP9	0.0014	0.45	1.44E-03	3278.01	453.6	495.0	577.5	721.5	334.5	868.3	870.6	939.4	1006.8	1010.7	970.1	808.5
SP10	0.0014	0.45	1.43E-03	2907.81	390.0	419.9	532.1	698.4	298.2	845.6	852.7	865.9	937.9	955.3	487.2	764.3
			Mean	**3235.2**	**410.3**	**445.5**	**543.7**	**704.9**	**323.2**	**872.3**	**891.4**	**906.9**	**972.5**	**980.5**	**654.1**	**784.4**
			SD	**308.286**	**37.534**	**42.895**	**29.705**	**14.482**	**21.680**	**28.996**	**35.128**	**30.395**	**28.143**	**28.013**	**273.751**	**22.411**
				9.5%	**9.1%**	**9.6%**	**5.5%**	**2.1%**	**6.7%**	**3.3%**	**3.9%**	**3.4%**	**2.9%**	**2.9%**	**41.8%**	**2.9%**

Table 8 – Test results for polished as-built specimens with scan length = 78 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP8	0.0014	0.45	1.44E-03	0.120	0.194	0.298	0.328	0.861	1.624	1.250	0.98	0.63	0.49
SP9	0.0014	0.45	1.44E-03	0.151	0.221	0.321	0.311	0.893	1.010	1.271	1.01	0.66	0.50
SP10	0.0014	0.45	1.43E-03	0.144	0.228	0.340	0.399	0.976	1.611	1.351	1.03	0.70	0.54
			Mean	**0.138**	**0.214**	**0.320**	**0.346**	**0.910**	**1.415**	**1.291**	**1.006**	**0.661**	**0.512**
			SD	**0.016**	**0.018**	**0.021**	**0.047**	**0.059**	**0.351**	**0.053**	**0.026**	**0.036**	**0.027**
				11.9%	**8.5%**	**6.7%**	**13.5%**	**6.5%**	**24.8%**	**4.1%**	**2.6%**	**5.5%**	**5.3%**

Test and analysis details for each of the tests performed on this group of specimens are provided in Annex 2 (rough) and Annex 3 (polished).

4.4. As-built, scan length = 26 mm

Test results for the rough specimens is presented in Tables 9 and 10, which describe elastic slope/forces and displacements/energies, respectively. Likewise, Tables 11 and 12 describe the equivalent measurements for the polished specimens.

Table 9 – Test results for rough as-built specimens with scan length = 26 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{el}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP1	0.0009	0.51	1.03E-03	1876.53	398.1	408.4	643.2	787.6	188.5	745.2	770.4	920.4	1005.9	1093.5	1000.8	874.8
SP2	0.0010	0.50	1.04E-03	1860.63	449.1	457.0	673.4	831.5	186.6	758.0	777.1	939.1	1002.7	1158.1	630.8	926.5
SP4	0.0010	0.50	1.04E-03	1666.44	452.2	456.5	780.4	974.2	163.0	736.5	763.6	947.0	1060.2	1071.7	349.1	857.3
SP5	0.0010	0.49	1.04E-03	2016.45	383.2	393.2	612.4	785.9	198.4	774.2	799.9	921.8	1061.4	1107.0	740.2	885.6
SP6	0.0010	0.49	1.03E-03	1745.38	401.5	408.2	675.0	872.4	174.9	738.2	762.2	922.1	1003.1	1090.5	715.8	872.4
SP7	0.0011	0.49	1.04E-03	1752.85	364.6	370.9	637.4	832.6	172.4	725.1	742.0	915.6	1055.6	1088.0	634.4	870.4
			Mean	**1819.7**	**408.1**	**415.7**	**670.3**	**847.4**	**180.6**	**746.2**	**769.2**	**927.7**	**1031.5**	**1101.5**	**678.5**	**881.2**
			SD	**124.177**	**35.413**	**34.645**	**58.835**	**70.053**	**12.844**	**17.464**	**19.085**	**12.365**	**30.302**	**29.973**	**210.609**	**23.978**
				6.8%	**8.7%**	**8.3%**	**8.8%**	**8.3%**	**7.1%**	**2.3%**	**2.5%**	**1.3%**	**2.9%**	**2.7%**	**31.0%**	**2.7%**

Table 10 – Test results for rough as-built specimens with scan length = 26 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP1	0.0009	0.51	1.03E-03	0.218	0.393	0.520	0.100	1.142	0.774	1.585	1.28	0.84	0.52
SP2	0.0010	0.50	1.04E-03	0.246	0.412	0.547	0.084	1.150	1.799	1.463	1.21	0.88	0.51
SP4	0.0010	0.50	1.04E-03	0.274	0.519	0.685	0.105	0.987	1.765	1.395	1.09	0.68	0.33
SP5	0.0010	0.49	1.04E-03	0.195	0.355	0.490	0.083	1.152	0.452	1.481	1.20	0.88	0.57
SP6	0.0010	0.49	1.03E-03	0.234	0.437	0.601	0.079	1.058	1.752	1.558	1.25	0.75	0.41
SP7	0.0011	0.49	1.04E-03	0.212	0.414	0.576	0.093	1.101	1.794	1.524	1.21	0.79	0.45
			Mean	**0.230**	**0.422**	**0.570**	**0.091**	**1.098**	**1.389**	**1.501**	**1.208**	**0.801**	**0.467**
			SD	**0.028**	**0.055**	**0.069**	**0.010**	**0.066**	**0.610**	**0.069**	**0.066**	**0.079**	**0.088**
				12.2%	**13.0%**	**12.1%**	**11.6%**	**6.0%**	**43.9%**	**4.6%**	**5.5%**	**9.8%**	**18.7%**

Table 11 – Test results for polished as-built specimens with scan length = 26 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_{ept} (N)	$F_{e1.5}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP8	0.0014	0.45	1.44E-03	3010.25	418.2	454.3	558.7	705.8	310.4	853.6	875.2	956.3	934.8	81.4	760.3	968.0	515.4	774.4
SP9	0.0014	0.44	1.44E-03	2889.12	428.5	466.5	552.1	694.6	295.4	818.5	818.5	897.2	926.0	702.3	732.7	956.8	487.4	765.4
SP10	0.0014	0.45	1.45E-03	3283.40	363.6	404.3	522.6	688.9	317.7	880.6	898.1	949.1	962.4	430.5	658.3	981.3	76.1	785.1
			Mean	**3060.9**	**403.4**	**441.7**	**544.4**	**696.4**	**307.8**	**850.9**	**866.8**	**939.7**	**939.5**	**404.8**	**717.1**	**968.7**	**359.6**	**775.0**
			SD	**201.966**	**34.849**	**32.945**	**19.237**	**8.628**	**11.394**	**31.135**	**33.928**	**28.546**	**15.826**	**311.251**	**52.720**	**12.301**	**245.929**	**9.841**
				6.6%	**8.6%**	**7.5%**	**3.5%**	**1.2%**	**3.7%**	**3.7%**	**3.9%**	**3.0%**	**1.7%**	**76.9%**	**7.4%**	**1.3%**	**68.4%**	**1.3%**

Table 12 – Test results for polished as-built specimens with scan length = 26 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP8	0.0014	0.45	1.44E-03	0.151	0.231	0.335	0.379	0.680	1.661	1.245	0.95	0.44	0.28
SP9	0.0014	0.44	1.44E-03	0.161	0.236	0.341	0.372	0.844	1.631	1.232	0.91	0.57	0.42
SP10	0.0014	0.45	1.45E-03	0.123	0.205	0.310	0.294	0.818	0.018	1.219	0.94	0.58	0.43
			Mean	**0.145**	**0.224**	**0.329**	**0.348**	**0.780**	**1.103**	**1.232**	**0.934**	**0.531**	**0.377**
			SD	**0.020**	**0.017**	**0.016**	**0.047**	**0.088**	**0.940**	**0.013**	**0.021**	**0.080**	**0.082**
				13.6%	**7.5%**	**5.0%**	**13.6%**	**11.3%**	**85.2%**	**1.1%**	**2.2%**	**15.1%**	**21.8%**

Test and analysis details for each of the tests performed on this group of specimens are provided in Annex 4 (rough) and Annex 5 (polished).

4.5. Non-standard (800 °C) HIP, scan length = 78 mm

Test results for the rough specimens is presented in Tables 13 and 14, which describe elastic slope/forces and displacements/energies, respectively. Likewise, Tables 15 and 16 describe the equivalent measurements for the polished specimens.

Table 13 - Test results for rough specimens with non-standard HIP and scan length = 26 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{el}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP1	0.0009	0.49	1.00E-03	1958.20	443.2	455.3	691.4	868.9	202.7	790.4	815.5	959.6	1032.8	1082.5	468.1	866.0
SP2	0.0010	0.50	1.01E-03	2210.27	445.7	460.3	630.4	761.0	228.5	803.0	820.2	938.4	1020.1	1068.2	628.6	854.6
SP4	0.0010	0.49	1.01E-03	1801.57	487.1	492.4	663.9	828.7	179.3	737.4	765.0	915.6	1126.4	1157.1	590.9	925.7
SP5	0.0010	0.50	1.02E-03	1639.54	428.9	438.4	677.5	817.2	164.1	692.9	714.6	879.5	1054.7	1106.8	577.5	885.4
SP6	0.0010	0.51	1.04E-03	1754.55	436.8	447.0	658.3	845.0	173.6	722.7	747.9	927.5	1056.0	1070.9	565.7	856.7
SP7	0.0011	0.49	1.02E-03	1754.55	472.8	447.0	781.3	904.7	194.5	763.6	786.6	930.1	1093.5	1131.1	960.9	904.9
			Mean	**1853.1**	**452.4**	**456.7**	**683.8**	**837.6**	**190.5**	**751.7**	**774.9**	**925.1**	**1063.9**	**1102.8**	**632.0**	**882.2**
			SD	**203.128**	**22.560**	**19.048**	**51.957**	**48.816**	**23.321**	**41.878**	**40.725**	**26.722**	**39.555**	**35.741**	**169.768**	**28.593**
				11.0%	**5.0%**	**4.2%**	**7.6%**	**5.8%**	**12.2%**	**5.6%**	**5.3%**	**2.9%**	**3.7%**	**3.2%**	**26.9%**	**3.2%**

Table 14 - Test results for rough specimens with non-standard HIP and scan length = 26 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP1	0.0009	0.49	1.00E-03	0.232	0.404	0.544	-0.025	0.822	1.734	1.335	1.05	0.54	0.24
SP2	0.0010	0.50	1.01E-03	0.208	0.336	0.445	0.060	1.074	0.332	1.533	1.25	0.80	0.54
SP4	0.0010	0.49	1.01E-03	0.273	0.419	0.560	0.119	0.946	1.731	1.458	1.20	0.65	0.28
SP5	0.0010	0.50	1.02E-03	0.267	0.464	0.598	0.086	1.038	1.766	1.371	1.05	0.71	0.34
SP6	0.0010	0.51	1.04E-03	0.255	0.426	0.582	0.108	0.917	1.782	1.413	1.09	0.60	0.27
SP7	0.0011	0.49	1.02E-03	0.255	0.495	0.616	0.091	1.115	1.422	1.476	1.22	0.84	0.48
			Mean	**0.248**	**0.424**	**0.558**	**0.073**	**0.985**	**1.461**	**1.431**	**1.144**	**0.690**	**0.358**
			SD	**0.024**	**0.055**	**0.061**	**0.052**	**0.110**	**0.569**	**0.073**	**0.089**	**0.118**	**0.124**
				9.7%	**12.9%**	**10.9%**	**71.5%**	**11.2%**	**39.0%**	**5.1%**	**7.8%**	**17.1%**	**34.6%**

Table 15 - Test results for polished specimens with non-standard HIP and scan length = 26 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP7	0.0014	0.45	1.44E-03	3521.07	431.3	473.5	559.8	698.0	348.9	874.7	890.4	922.1	1005.9	1013.5	988.7	810.8
SP8	0.0014	0.44	1.44E-03	2983.80	381.2	413.1	513.8	661.1	298.0	832.4	850.4	961.4	918.9	963.9	592.8	771.1
SP9	0.0014	0.44	1.43E-03	3115.09	393.2	426.2	528.3	656.9	317.5	833.0	853.6	967.8	916.7	971.8	623.1	777.4
SP10	0.0014	0.44	1.43E-03	3258.38	348.2	381.0	484.1	630.0	314.7	854.8	874.9	917.2	989.1	996.4	686.5	797.1
			Mean	**3219.6**	**388.5**	**423.4**	**521.5**	**661.5**	**319.8**	**848.7**	**871.9**	**938.1**	**967.3**	**986.4**	**722.8**	**789.1**
			SD	**230.154**	**34.326**	**38.373**	**31.487**	**27.941**	**21.276**	**20.176**	**19.307**	**24.342**	**45.744**	**22.768**	**181.546**	**18.215**
				7.1%	**8.8%**	**9.1%**	**6.0%**	**4.2%**	**6.7%**	**2.4%**	**2.2%**	**2.6%**	**4.7%**	**2.3%**	**25.1%**	**2.3%**

Table 16 - Test results for polished specimens with non-standard HIP and scan length = 26 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP7	0.0014	0.45	1.44E-03	0.134	0.205	0.299	0.219	0.885	1.026	1.278	1.03	0.66	0.51
SP8	0.0014	0.44	1.44E-03	0.138	0.217	0.322	0.334	0.654	1.666	1.404	1.05	0.40	0.25
SP9	0.0014	0.44	1.43E-03	0.137	0.214	0.311	0.381	0.691	1.662	1.475	1.14	0.44	0.29
SP10	0.0014	0.44	1.43E-03	0.117	0.193	0.294	0.265	0.900	1.416	1.306	1.02	0.64	0.49
			Mean	**0.132**	**0.207**	**0.306**	**0.300**	**0.782**	**1.442**	**1.366**	**1.061**	**0.538**	**0.387**
			SD	**0.010**	**0.011**	**0.012**	**0.072**	**0.128**	**0.301**	**0.090**	**0.055**	**0.133**	**0.136**
				7.6%	**5.2%**	**4.1%**	**24.1%**	**16.4%**	**20.9%**	**6.6%**	**5.1%**	**24.8%**	**35.3%**

Test and analysis details for each of the tests performed on this group of specimens are provided in Annex 6 (rough) and Annex 7 (polished).

4.6. Standard (900 °C) HIP, scan length = 78 mm

Six rough specimens and four polished specimens were tested. Results are shown in Table 17 (elastic slopes and forces) and Table 18 (displacements and energies) for rough specimens, and Table 19 (elastic slopes and forces) and Table 20 (displacements and energies) for polished specimens.

Table 17 - Test results for rough specimens with standard HIP and scan length = 78 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{el}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP2	0.0009	0.51	1.02E-03	2099.36	401.3	417.4	583.9	720.0	207.5	762.7	784.5	918.6	1071.1	1123.6	650.9	898.9
SP3	0.0010	0.50	1.01E-03	1839.49	415.5	420.7	609.6	766.2	189.0	729.5	748.0	917.2	1037.6	1095.6	731.2	876.5
SP4	0.0010	0.55	1.00E-03	825.63	345.3	344.0	1011.2	1004.9	82.4	391.9	410.4	521.4	743.9	1022.4	5.0	817.9
SP5	0.0010	0.51	1.01E-03	1987.01	342.7	350.8	539.8	723.3	201.3	748.8	773.6	958.5	1047.8	1085.0	577.3	868.0
SP7	0.0010	0.51	1.02E-03	2057.23	447.6	457.9	662.2	792.1	211.6	791.3	810.9	946.7	1090.2	1112.3	515.1	889.9
SP8	0.0011	0.52	1.01E-03	2064.56	358.3	371.4	595.4	781.4	209.2	787.7	809.0	983.9	1042.8	1067.5	486.6	854.0
			Mean	**1812.2**	**385.1**	**393.7**	**667.0**	**798.0**	**183.5**	**702.0**	**722.7**	**874.4**	**1005.6**	**1084.4**	**494.3**	**867.5**
			SD	**492.099**	**42.872**	**45.216**	**173.226**	**105.646**	**50.196**	**153.698**	**154.800**	**174.744**	**129.710**	**36.274**	**255.897**	**29.019**
				27.2%	**11.1%**	**11.5%**	**26.0%**	**13.2%**	**27.4%**	**21.9%**	**21.4%**	**20.0%**	**12.9%**	**3.3%**	**51.8%**	**3.3%**

Table 18 - Test results for rough specimens with standard HIP and scan length = 78 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP2	0.0009	0.51	1.02E-03	0.199	0.328	0.444	0.064	1.091	1.748	1.450	1.18	0.81	0.51
SP3	0.0010	0.50	1.01E-03	0.229	0.383	0.517	0.082	1.094	0.483	1.567	1.28	0.79	0.47
SP4	0.0010	0.55	1.00E-03	0.417	1.276	1.320	0.176	1.267	-0.107	1.653	1.02	0.66	0.03
SP5	0.0010	0.51	1.01E-03	0.177	0.322	0.465	0.064	0.837	1.742	1.463	1.17	0.54	0.24
SP7	0.0010	0.51	1.02E-03	0.223	0.373	0.485	0.066	0.870	0.268	1.525	1.25	0.59	0.29
SP8	0.0011	0.52	1.01E-03	0.180	0.339	0.479	0.066	0.950	1.747	1.337	1.05	0.67	0.39
			Mean	**0.237**	**0.504**	**0.618**	**0.086**	**1.018**	**0.980**	**1.499**	**1.158**	**0.678**	**0.322**
			SD	**0.090**	**0.379**	**0.345**	**0.044**	**0.163**	**0.860**	**0.109**	**0.104**	**0.108**	**0.176**
				38.1%	**75.3%**	**55.7%**	**51.4%**	**16.0%**	**87.7%**	**7.2%**	**9.0%**	**16.0%**	**54.7%**

Table 19 - Test results for polished specimens with standard HIP and scan length = 78 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP9	0.0014	0.45	1.43E-03	2910.50	414.0	438.5	568.5	715.2	301.3	877.3	898.4	938.6	1015.8	1031.9	622.9	825.5
SP10	0.0014	0.46	1.44E-03	3178.87	357.8	385.1	496.9	656.5	311.3	869.2	881.3	971.0	1074.2	1081.8	573.1	865.4
			Mean	**3044.7**	**385.9**	**411.8**	**532.7**	**685.9**	**306.3**	**873.2**	**889.8**	**954.8**	**1045.0**	**1056.8**	**598.0**	**845.5**
			SD	**189.766**	**39.775**	**37.792**	**50.614**	**41.524**	**7.047**	**5.735**	**12.130**	**22.911**	**41.296**	**35.293**	**35.269**	**28.234**
				6.2%	**10.3%**	**9.2%**	**9.5%**	**6.1%**	**2.3%**	**0.7%**	**1.4%**	**2.4%**	**4.0%**	**3.3%**	**5.9%**	**3.3%**

Table 20 - Test results for polished specimens with standard HIP and scan length = 78 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP9	0.0014	0.45	1.43E-03	0.151	0.241	0.347	0.391	0.955	1.663	1.448	1.18	0.71	0.53
SP10	0.0014	0.46	1.44E-03	0.121	0.203	0.307	0.354	0.891	1.676	1.306	1.07	0.66	0.47
			Mean	**0.136**	**0.222**	**0.327**	**0.373**	**0.923**	**1.669**	**1.377**	**1.126**	**0.685**	**0.502**
			SD	**0.021**	**0.026**	**0.028**	**0.026**	**0.045**	**0.010**	**0.100**	**0.079**	**0.038**	**0.039**
				15.4%	**11.9%**	**8.7%**	**7.1%**	**4.9%**	**0.6%**	**7.3%**	**7.0%**	**5.6%**	**7.7%**

Test and analysis details for each of the tests performed on this group of specimens are provided in Annex 8 (rough) and Annex 9 (polished).

4.7. Standard (900 °C) HIP, scan length = 26 mm

Test results for the rough specimens is presented in Tables 21 and 22, which describe elastic slope/forces and displacements/energies, respectively. Likewise, Tables 23 and 24 describe the equivalent measurements for the polished specimens.

Table 21 - Test results for rough specimens with standard HIP and scan length = 26 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP1	0.0011	0.49	1.10E-03	1685.886	343.4	356.2	595.2	759.3	176.4	682.5	710.3	880.1	1035.2	1121.8	584.1	897.5
SP2	0.0012	0.49	1.17E-03	1482.609	412.2	420.5	668.2	920.9	146.5	641.9	668.0	844.5	1062.3	1085.3		868.2
SP3	0.0011	0.50	1.14E-03	1615.912	371.8	383.3	584.3	743.4	157.2	663.6	691.1	838.0	1046.7	1097.0	1083.1	877.6
SP4	0.0012	0.49	1.16E-03	1821.886	369.8	379.0	580.9	724.9	187.2	704.5	724.9	860.5	1049.7	1094.2	688.8	875.4
SP5	0.0012	0.48	1.17E-03	1641.543	381.6	390.5	573.8	715.8	162.4	662.9	679.5	828.5	1026.5	1071.5	46.1	857.2
SP6	0.0012	0.50	1.15E-03	1952.197	410.2	423.9	590.8	712.0	200.5	728.9	753.7	902.6	1027.1	1057.0	632.8	845.6
			Mean	**1700.006**	**381.5**	**392.2**	**598.9**	**762.7**	**171.7**	**680.7**	**704.6**	**859.0**	**1041.3**	**1087.8**	**607.0**	**870.2**
			SD	**165.170**	**26.249**	**25.916**	**34.762**	**79.509**	**20.112**	**31.655**	**31.632**	**28.027**	**14.132**	**22.394**	**370.515**	**17.915**
				9.7%	**6.9%**	**6.6%**	**5.8%**	**10.4%**	**11.7%**	**4.7%**	**4.5%**	**3.3%**	**1.4%**	**2.1%**	**61.0%**	**2.1%**

Table 22 - Test results for rough specimens with standard HIP and scan length = 26 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP1	0.0011	0.49	1.10E-03	0.211	0.403	0.552	0.042	1.201	0.389	1.491	1.18	0.89	0.51
SP2	0.0012	0.49	1.17E-03	0.284	0.501	0.721	0.057	0.924		1.799	1.44	0.56	0.16
SP3	0.0011	0.50	1.14E-03	0.237	0.412	0.561	0.082	1.213	1.131	1.726	1.39	0.88	0.50
SP4	0.0012	0.49	1.16E-03	0.208	0.369	0.498	0.114	1.238	2.005	1.800	1.49	0.92	0.60
SP5	0.0012	0.48	1.17E-03	0.238	0.400	0.536	0.078	1.146	0.014	1.733	1.38	0.80	0.45
SP6	0.0012	0.50	1.15E-03	0.217	0.353	0.465	0.559	0.948	1.994	1.708	1.38	0.63	0.34
			Mean	**0.233**	**0.406**	**0.555**	**0.155**	**1.112**	**1.107**	**1.709**	**1.38**	**0.78**	**0.43**
			SD	**0.028**	**0.052**	**0.089**	**0.199**	**0.140**	**0.909**	**0.114**	**0.105**	**0.150**	**0.154**
				12.1%	**12.7%**	**16.0%**	**128.1%**	**12.6%**	**82.1%**	**6.6%**	**7.6%**	**19.3%**	**36.0%**

Table 23 - Test results for polished specimens with standard HIP and scan length = 26 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP7	0.0014	0.45	1.44E-03	3201.67	373.5	397.2	522.2	653.3	309.9	870.1	882.4	965.2	918.4	992.2	593.6	793.7
SP8	0.0014	0.46	1.43E-03	3288.00	372.2	402.0	515.6	660.5	324.6	882.8	902.5	1026.6	1079.7	1091.8	559.0	873.4
SP9	0.0015	0.45	1.46E-03	2989.78	373.8	406.2	531.7	690.7	300.6	882.8	915.7	961.6	969.8	995.9	509.4	796.7
SP10	0.0014	0.45	1.44E-03	2849.28	434.7	467.2	595.3	748.0	293.0	872.8	878.4	921.6	1033.5	1040.8	967.1	832.7
			Mean	**2919.5**	**404.3**	**436.7**	**563.5**	**719.3**	**296.8**	**877.8**	**894.8**	**968.8**	**1000.3**	**1018.4**	**738.3**	**814.7**
			SD	**99.345**	**43.068**	**43.075**	**44.949**	**40.531**	**5.429**	**7.055**	**17.491**	**43.314**	**70.800**	**31.765**	**323.589**	**25.412**
				3.4%	**10.7%**	**9.9%**	**8.0%**	**5.6%**	**1.8%**	**0.8%**	**2.0%**	**4.5%**	**7.1%**	**3.1%**	**43.8%**	**3.1%**

Table 24 - Test results for polished specimens with standard HIP and scan length = 26 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP7	0.0014	0.45	1.44E-03	0.124	0.209	0.305	0.269	0.618	1.667	1.369	1.05	0.38	0.23
SP8	0.0014	0.46	1.43E-03	0.122	0.203	0.302	0.357	0.832	1.487	1.273	1.06	0.62	0.43
SP9	0.0015	0.45	1.46E-03	0.136	0.223	0.333	0.380	0.558	1.648	1.323	1.04	0.32	0.16
SP10	0.0014	0.45	1.44E-03	0.164	0.254	0.364	0.457	0.899	0.707	1.356	1.09	0.65	0.46
			Mean	**0.150**	**0.238**	**0.348**	**0.418**	**0.728**	**1.177**	**1.340**	**1.062**	**0.489**	**0.311**
			SD	**0.020**	**0.022**	**0.022**	**0.054**	**0.242**	**0.665**	**0.023**	**0.034**	**0.232**	**0.215**
				13.2%	**9.2%**	**6.3%**	**13.0%**	**33.2%**	**56.5%**	**1.7%**	**3.2%**	**47.4%**	**69.1%**

Test and analysis details for each of the tests performed on this group of specimens are provided in Annex 10 (rough) and Annex 11 (polished).

4.8. Non-standard (1050 °C) + additional (800 °C) HIP, scan length = 78 mm

Test results for the rough specimens is presented in Tables 25 and 26, which describe elastic slope/forces and displacements/energies, respectively. Likewise, Tables 27 and 28 describe the equivalent measurements for the polished specimens.

Table 25 - Test results for rough specimens with standard + additional HIP and scan length = 78 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP1	0.0010	0.47	1.04E-03	2139.702	407.3	420.1	576.8	703.8	218.3	768.0	791.8	932.3	1126.7	1192.9	702.3	954.3
SP2	0.0011	0.48	1.07E-03	2011.628	365.1	377.5	570.1	732.7	207.9	748.0	779.8	931.9	1138.0	1194.5	1189.5	955.6
SP4	0.0011	0.49	1.07E-03	1844.336	456.7	465.1	646.7	771.7	182.3	731.7	753.7	910.0	1138.2	1230.4	714.9	984.3
SP5	0.0011	0.49	1.08E-03	1930.462	475.7	485.1	644.0	765.3	196.2	748.9	772.8	928.4	1162.1	1225.3	61.4	980.2
SP6	0.0011	0.48	1.11E-03	1918.267	414.5	430.1	594.2	713.8	193.2	724.3	747.6	901.9	1106.7	1156.0	901.5	924.8
SP7	0.0011	0.47	1.04E-03	1874.916	380.2	393.6	604.0	742.3	191.4	732.4	752.2	912.0	1122.9	1196.6	678.8	957.2
			Mean	**1953.218**	**416.6**	**428.6**	**606.0**	**738.3**	**198.2**	**742.2**	**766.3**	**919.4**	**1132.4**	**1199.3**	**708.1**	**959.4**
			SD	**107.623**	**42.811**	**41.099**	**32.814**	**27.146**	**12.817**	**15.961**	**17.816**	**13.055**	**18.590**	**26.767**	**371.000**	**21.413**
				5.5%	**10.3%**	**9.6%**	**5.4%**	**3.7%**	**6.5%**	**2.2%**	**2.3%**	**1.4%**	**1.6%**	**2.2%**	**52.4%**	**2.2%**

Table 26 - Test results for rough specimens with standard + additional HIP and scan length = 78 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP1	0.0010	0.47	1.04E-03	0.196	0.320	0.430	0.104	1.066	1.760	1.498	1.29	0.81	0.48
SP2	0.0011	0.48	1.07E-03	0.188	0.335	0.465	0.072	1.071	1.077	1.458	1.23	0.80	0.45
SP4	0.0011	0.49	1.07E-03	0.252	0.401	0.519	0.096	1.065	1.831	1.560	1.34	0.79	0.38
SP5	0.0011	0.49	1.08E-03	0.251	0.385	0.496	0.066	1.005	0.027	1.524	1.32	0.74	0.35
SP6	0.0011	0.48	1.11E-03	0.224	0.360	0.472	0.075	1.002	0.649	1.628	1.36	0.71	0.36
SP7	0.0011	0.47	1.04E-03	0.210	0.372	0.496	0.082	1.023	1.843	1.412	1.14	0.73	0.35
			Mean	**0.220**	**0.362**	**0.480**	**0.083**	**1.039**	**1.198**	**1.513**	**1.28**	**0.76**	**0.39**
			SD	**0.027**	**0.031**	**0.031**	**0.015**	**0.032**	**0.751**	**0.076**	**0.083**	**0.043**	**0.055**
				12.4%	**8.5%**	**6.5%**	**17.7%**	**3.1%**	**62.7%**	**5.0%**	**6.5%**	**5.7%**	**14.1%**

Table 27 - Test results for polished specimens with standard + additional HIP and scan length = 78 mm (linear elastic slopes and forces).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
SP8	0.0014	0.43	1.43E-03	2957.72	367.2	392.6	490.5	657.8	295.8	833.8	859.5	975.0	999.1	1023.0	849.4	818.4
SP9	0.0015	0.46	1.47E-03	3214.86	418.1	453.3	576.1	713.0	321.2	908.7	920.9	1039.7	1045.0	1064.1	545.6	851.3
SP10	0.0015	0.44	1.46E-03	3294.63	403.9	436.2	549.7	691.2	325.1	904.6	926.6	1069.5	1024.2	1096.7	895.1	877.4
			Mean	**3254.7**	**411.0**	**444.7**	**562.9**	**702.1**	**323.1**	**906.7**	**902.3**	**1028.1**	**1022.8**	**1080.4**	**720.4**	**864.3**
			SD	**56.403**	**10.033**	**12.074**	**18.685**	**15.372**	**2.758**	**2.886**	**37.219**	**48.302**	**22.945**	**23.017**	**247.087**	**18.413**
				1.7%	**2.4%**	**2.7%**	**3.3%**	**2.2%**	**0.9%**	**0.3%**	**4.1%**	**4.7%**	**2.2%**	**2.1%**	**34.3%**	**2.1%**

Table 28 - Test results for polished specimens with standard + additional HIP and scan length = 78 mm (displacements and energies).

Specimen id	Displacement rate (mm/s)	h_0 (mm)	$\dot{\varepsilon}_{SP}^{max}$ (s^{-1})	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
SP8	0.0014	0.43	1.43E-03	0.133	0.209	0.323	0.386	0.761	1.174	1.260	0.97	0.51	0.33
SP9	0.0015	0.46	1.47E-03	0.141	0.226	0.322	0.342	0.719	1.614	1.242	1.02	0.51	0.33
SP10	0.0015	0.44	1.46E-03	0.132	0.211	0.311	0.282	0.693	0.470	1.109	0.89	0.48	0.30
			Mean	**0.137**	**0.219**	**0.316**	**0.312**	**0.706**	**1.042**	**1.176**	**0.958**	**0.494**	**0.315**
			SD	**0.006**	**0.011**	**0.008**	**0.043**	**0.019**	**0.809**	**0.094**	**0.089**	**0.019**	**0.023**
				4.4%	**4.9%**	**2.5%**	**13.8%**	**2.6%**	**77.6%**	**8.0%**	**9.3%**	**3.8%**	**7.4%**

Test and analysis details for each of the tests performed on this group of specimens are provided in Annex 12 (rough) and Annex 13 (polished).

4.9. Comparison between different conditions (non-supported specimens)

4.9.1. rough specimens

Average values and standard deviations (absolute and relative) for the various characteristic parameters of the different conditions examined (excluding the preliminary tests) are compared in Table 29 (elastic slopes and forces) and Table 30 (displacements and energies).

Table 29 – Average values and standard deviations for rough specimens in the different conditions (elastic slopes and forces).

Material condition	Scan length (mm)	Displacement rate (mm/s)	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
As-Built	78	0.001	**2727.595**	**433.4**	**456.2**	**643.7**	**804.2**	**282.8**	**889.3**	**909.0**	**1003.6**	**1067.4**	**1083.9**	**745.6**	**867.1**
			338.711	*64.9*	*73.0*	*45.5*	*45.7*	*38.7*	*45.1*	*43.7*	*29.9*	*29.5*	*25.0*	*149.0*	*20.0*
			12.4%	*15.0%*	*16.0%*	*7.1%*	*5.7%*	*13.7%*	*5.1%*	*4.8%*	*3.0%*	*2.8%*	*2.3%*	*20.0%*	*2.3%*
	26	0.001	**1819.712**	**408.1**	**415.7**	**670.3**	**847.4**	**180.6**	**746.2**	**769.2**	**927.7**	**1031.5**	**1101.5**	**678.5**	**881.2**
			124.177	*35.4*	*34.6*	*58.8*	*70.1*	*12.8*	*17.5*	*19.1*	*12.4*	*30.3*	*30.0*	*210.6*	*24.0*
			6.8%	*8.7%*	*8.3%*	*8.8%*	*8.3%*	*7.1%*	*2.3%*	*2.5%*	*1.3%*	*2.9%*	*2.7%*	*31.0%*	*2.7%*
HIP 800 °C	78	0.001	**1853.112**	**452.4**	**456.7**	**683.8**	**837.6**	**190.5**	**751.7**	**774.9**	**925.1**	**1063.9**	**1102.8**	**632.0**	**882.2**
			203.128	*22.6*	*19.0*	*52.0*	*48.8*	*23.3*	*41.9*	*40.7*	*26.7*	*39.6*	*35.7*	*169.8*	*28.6*
			11.0%	*5.0%*	*4.2%*	*7.6%*	*5.8%*	*12.2%*	*5.6%*	*5.3%*	*2.9%*	*3.7%*	*3.2%*	*26.9%*	*3.2%*
HIP 900 °C	78	0.001	**1812.213**	**385.1**	**393.7**	**667.0**	**798.0**	**183.5**	**702.0**	**722.7**	**874.4**	**1005.6**	**1084.4**	**494.3**	**867.5**
			492.099	*42.9*	*45.2*	*173.2*	*105.6*	*50.2*	*153.7*	*154.8*	*174.7*	*129.7*	*36.3*	*255.9*	*29.0*
			27.2%	*11.1%*	*11.5%*	*26.0%*	*13.2%*	*27.4%*	*21.9%*	*21.4%*	*20.0%*	*12.9%*	*3.3%*	*51.8%*	*3.3%*
	26	0.001	**1700.006**	**381.5**	**392.2**	**598.9**	**762.7**	**171.7**	**680.7**	**704.6**	**859.0**	**1041.3**	**1087.8**	**607.0**	**870.2**
			165.170	*26.2*	*25.9*	*34.8*	*79.5*	*20.1*	*31.7*	*31.6*	*28.0*	*14.1*	*22.4*	*370.5*	*17.9*
			9.7%	*6.9%*	*6.6%*	*5.8%*	*10.4%*	*11.7%*	*4.7%*	*4.5%*	*3.3%*	*1.4%*	*2.1%*	*61.0%*	*2.1%*
HIP 1050 °C + 800 °C	78	0.001	**1953.218**	**416.6**	**428.6**	**606.0**	**738.3**	**198.2**	**742.2**	**766.3**	**919.4**	**1132.4**	**1199.3**	**708.1**	**959.4**
			107.623	*42.8*	*41.1*	*32.8*	*27.1*	*12.8*	*16.0*	*17.8*	*13.1*	*18.6*	*26.8*	*371.0*	*21.4*
			5.5%	*10.3%*	*9.6%*	*5.4%*	*3.7%*	*6.5%*	*2.2%*	*2.3%*	*1.4%*	*1.6%*	*2.2%*	*52.4%*	*2.2%*

Table 30 – Average values and standard deviations for rough specimens in the different conditions (displacements and energies).

Material condition	Scan length (mm)	Displacement rate (mm/s)	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
As-Built	78	0.001	**0.167**	**0.290**	**0.401**	**0.189**	**0.928**	**1.494**	**1.387**	**1.16**	**0.71**	**0.49**
			0.018	*0.035*	*0.051*	*0.192*	*0.062*	*0.292*	*0.064*	*0.09*	*0.07*	*0.08*
			1.8%	*3.5%*	*5.1%*	*19.2%*	*6.7%*	*29.2%*	*4.6%*	*7.4%*	*10.5%*	*17.0%*
	26	0.001	**0.230**	**0.422**	**0.570**	**0.091**	**1.098**	**1.389**	**1.501**	**1.21**	**0.80**	**0.47**
			0.028	*0.055*	*0.069*	*0.010*	*0.066*	*0.610*	*0.069*	*0.07*	*0.08*	*0.09*
			12.2%	*13.0%*	*12.1%*	*11.6%*	*6.0%*	*43.9%*	*4.6%*	*5.5%*	*9.8%*	*18.7%*
HIP 800 °C	78	0.001	**0.248**	**0.424**	**0.558**	**0.073**	**0.985**	**1.461**	**1.431**	**1.14**	**0.69**	**0.36**
			0.024	*0.055*	*0.061*	*0.052*	*0.110*	*0.569*	*0.073*	*0.09*	*0.12*	*0.12*
			9.7%	*12.9%*	*10.9%*	*71.5%*	*11.2%*	*39.0%*	*5.1%*	*7.8%*	*17.1%*	*34.6%*
HIP 900 °C	78	0.001	**0.237**	**0.504**	**0.618**	**0.086**	**1.018**	**0.980**	**1.499**	**1.16**	**0.68**	**0.32**
			0.090	*0.379*	*0.345*	*0.044*	*0.163*	*0.860*	*0.109*	*0.10*	*0.11*	*0.18*
			38.1%	*75.3%*	*55.7%*	*51.4%*	*16.0%*	*87.7%*	*7.2%*	*9.0%*	*16.0%*	*54.7%*
	26	0.001	**0.233**	**0.406**	**0.555**	**0.155**	**1.112**	**1.107**	**1.709**	**1.38**	**0.78**	**0.43**
			0.028	*0.052*	*0.089*	*0.199*	*0.140*	*0.909*	*0.114*	*0.10*	*0.15*	*0.15*
			12.1%	*12.7%*	*16.0%*	*128.1%*	*12.6%*	*82.1%*	*6.6%*	*7.6%*	*19.3%*	*36.0%*
HIP 1050 °C + 800 °C	78	0.001	**0.220**	**0.362**	**0.480**	**0.083**	**1.039**	**1.198**	**1.513**	**1.28**	**0.76**	**0.39**
			0.027	*0.031*	*0.031*	*0.015*	*0.032*	*0.751*	*0.076*	*0.08*	*0.04*	*0.06*
			12.4%	*8.5%*	*6.5%*	*17.7%*	*3.1%*	*62.7%*	*5.0%*	*6.5%*	*5.7%*	*14.1%*

Comparisons in terms of $F_{e,proj}$ and F_m are illustrated in Fig. 9 and Fig. 10, respectively. Considering that $F_{e,proj}$ is directly proportional to the yield strength and F_m is directly proportional to the ultimate tensile strength, the condition which exhibited the best combination of tensile properties, in terms of high values and low standard deviations, corresponds to the non-standard HIP treatment (800 °C) with scan length = 78 mm.

A decrease in scan length (from 78 mm to 26 mm) appears to have a minor influence on both lower yield strength and ultimate tensile strength, as can be observed for the as-built and standard HIP conditions.

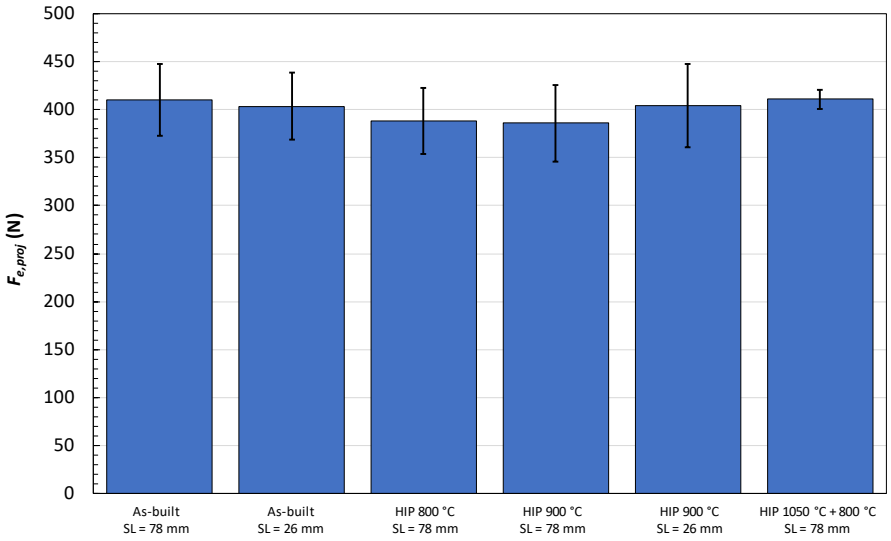

Figure 9 - Average values and standard deviations for $F_{e,proj}$.

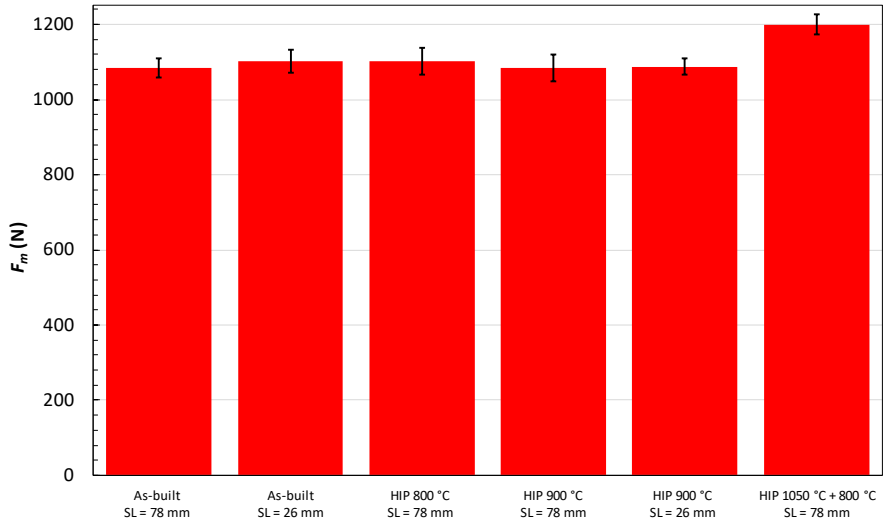

Figure 10 - Average values and standard deviations for F_m.

4.9.2. Polished specimens

Average values and standard deviations (absolute and relative) for the various characteristic parameters of the different conditions examined (excluding the preliminary tests) are compared in Table 31 (elastic slopes and forces) and Table 32 (displacements and energies).

Table 31 – Average values and standard deviations for polished specimens in the different conditions (elastic slopes and forces).

Material condition	Scan length	Supported (Y/N)	Displacement rate (mm/s)	$Slope_{ini}$ (N/mm)	$F_{e,proj}$ (N)	$F_{e,int}$ (N)	$F_{h0/10,off}$ (N)	$F_{0.1mm,off}$ (N)	$F_{0.1mm}$ (N)	$F_{0.48mm}$ (N)	$F_{0.5mm}$ (N)	$F_{0.65mm}$ (N)	$F_{0.9mm}$ (N)	F_m (N)	F_{infl} (N)	F_f (N)
As-Built	78	N	0.0014	**3235.245**	**410.3**	**445.5**	**543.7**	**704.9**	**323.2**	**872.3**	**891.4**	**906.9**	**972.5**	**980.5**	**654.1**	**784.4**
				308.286	*37.534*	*42.895*	*29.705*	*14.482*	*21.680*	*28.996*	*35.128*	*30.395*	*28.143*	*28.013*	*273.751*	*22.411*
				9.5%	*9.1%*	*9.6%*	*5.5%*	*2.1%*	*6.7%*	*3.3%*	*3.9%*	*3.4%*	*2.9%*	*2.9%*	*41.8%*	*2.9%*
	26	N	0.0014	**3060.926**	**403.4**	**441.7**	**544.4**	**696.4**	**307.8**	**850.9**	**866.8**	**939.7**	**939.5**	**968.7**	**359.6**	**775.0**
				201.966	*34.849*	*32.945*	*19.237*	*8.628*	*11.394*	*31.135*	*33.928*	*28.546*	*15.826*	*12.301*	*245.929*	*9.841*
				6.6%	*8.6%*	*7.5%*	*3.5%*	*1.2%*	*3.7%*	*3.7%*	*3.9%*	*3.0%*	*1.7%*	*1.3%*	*68.4%*	*1.3%*
HIP 800 °C	78	N	0.0014	**3219.586**	**388.5**	**423.4**	**521.5**	**661.5**	**319.8**	**848.7**	**871.9**	**938.1**	**967.3**	**986.4**	**722.8**	**789.1**
				230.154	*34.326*	*38.373*	*31.487*	*27.941*	*21.276*	*20.176*	*19.307*	*24.342*	*45.744*	*22.768*	*181.546*	*18.215*
				7.1%	*8.8%*	*9.1%*	*6.0%*	*4.2%*	*6.7%*	*2.4%*	*2.2%*	*2.6%*	*4.7%*	*2.3%*	*25.1%*	*2.3%*
HIP 900 °C	78	N	0.0014	**3044.687**	**385.9**	**411.8**	**532.7**	**685.9**	**306.3**	**873.2**	**889.8**	**954.8**	**1045.0**	**1056.8**	**598.0**	**845.5**
				189.766	*39.775*	*37.792*	*50.614*	*41.524*	*7.047*	*5.735*	*12.130*	*22.911*	*41.296*	*35.293*	*35.269*	*28.234*
				6.2%	*10.3%*	*9.2%*	*9.5%*	*6.1%*	*2.3%*	*0.7%*	*1.4%*	*2.4%*	*4.0%*	*3.3%*	*5.9%*	*3.3%*
	26	N	0.0014	**2919.529**	**404.3**	**436.7**	**563.5**	**719.3**	**296.8**	**877.8**	**894.8**	**968.8**	**1000.3**	**1018.4**	**738.3**	**814.7**
				99.345	*43.068*	*43.075*	*44.949*	*40.531*	*5.429*	*7.055*	*17.491*	*43.314*	*70.800*	*31.765*	*323.589*	*25.412*
				3.4%	*10.7%*	*9.9%*	*8.0%*	*5.6%*	*1.8%*	*0.8%*	*2.0%*	*4.5%*	*7.1%*	*3.1%*	*43.8%*	*3.1%*
HIP 1050 °C + 900 °C	78	N	0.0015	**3254.743**	**411.0**	**444.7**	**562.9**	**702.1**	**323.1**	**906.7**	**902.3**	**1028.1**	**1022.8**	**1080.4**	**720.4**	**864.3**
				56.403	*10.033*	*12.074*	*18.685*	*15.372*	*2.758*	*2.886*	*37.219*	*48.302*	*22.945*	*23.017*	*247.087*	*18.413*
				1.7%	*2.4%*	*2.7%*	*3.3%*	*2.2%*	*0.9%*	*0.3%*	*4.1%*	*4.7%*	*2.2%*	*2.1%*	*34.3%*	*2.1%*

Table 32 – Average values and standard deviations for polished specimens in the different conditions (displacements and energies).

Material condition	Scan length	Supported (Y/N)	Displacement rate (mm/s)	u_e (mm)	$u_{h0/10,off}$ (mm)	$u_{0.1mm,off}$ (mm)	$u_{e1.5}$ (mm)	u_m (mm)	u_{infl} (mm)	u_f (mm)	E_{SP} (J)	E_m (J)	E_{PL} (J)
As-Built	78	N	0.0014	**0.138**	**0.214**	**0.320**	**0.346**	**0.910**	**1.415**	**1.291**	**1.01**	**0.66**	**0.51**
				0.016	*0.018*	*0.021*	*0.047*	*0.059*	*0.351*	*0.053*	*0.026*	*0.036*	*0.027*
				11.9%	*8.5%*	*6.7%*	*13.5%*	*6.5%*	*24.8%*	*4.1%*	*2.6%*	*5.5%*	*5.3%*
	26	N	0.0014	**0.145**	**0.224**	**0.329**	**0.348**	**0.780**	**1.103**	**1.232**	**0.93**	**0.53**	**0.38**
				0.020	*0.017*	*0.016*	*0.047*	*0.088*	*0.940*	*0.013*	*0.021*	*0.080*	*0.082*
				13.6%	*7.5%*	*5.0%*	*13.6%*	*11.3%*	*85.2%*	*1.1%*	*2.2%*	*15.1%*	*21.8%*
HIP 800 °C	78	N	0.0014	**0.132**	**0.207**	**0.306**	**0.300**	**0.782**	**1.442**	**1.366**	**1.06**	**0.54**	**0.39**
				0.010	*0.011*	*0.012*	*0.072*	*0.128*	*0.301*	*0.090*	*0.055*	*0.133*	*0.136*
				7.6%	*5.2%*	*4.1%*	*24.1%*	*16.4%*	*20.9%*	*6.6%*	*5.1%*	*24.8%*	*35.3%*
HIP 900 °C	78	N	0.0014	**0.136**	**0.222**	**0.327**	**0.373**	**0.923**	**1.669**	**1.377**	**1.13**	**0.69**	**0.50**
				0.021	*0.026*	*0.028*	*0.026*	*0.045*	*0.010*	*0.100*	*0.079*	*0.038*	*0.039*
				15.4%	*11.9%*	*8.7%*	*7.1%*	*4.9%*	*0.6%*	*7.3%*	*7.0%*	*5.6%*	*7.7%*
	26	N	0.0014	**0.150**	**0.238**	**0.348**	**0.418**	**0.728**	**1.177**	**1.340**	**1.06**	**0.49**	**0.31**
				0.020	*0.022*	*0.022*	*0.054*	*0.242*	*0.665*	*0.023*	*0.034*	*0.232*	*0.215*
				13.2%	*9.2%*	*6.3%*	*13.0%*	*33.2%*	*56.5%*	*1.7%*	*3.2%*	*47.4%*	*69.1%*
HIP 1050 °C + 900 °C	78	N	0.0015	**0.137**	**0.219**	**0.316**	**0.312**	**0.706**	**1.042**	**1.176**	**0.96**	**0.49**	**0.31**
				0.006	*0.011*	*0.008*	*0.043*	*0.019*	*0.809*	*0.094*	*0.089*	*0.019*	*0.023*
				4.4%	*4.9%*	*2.5%*	*13.8%*	*2.6%*	*77.6%*	*8.0%*	*9.3%*	*3.8%*	*7.4%*

Comparisons for $F_{e,proj}$ and F_m are illustrated in Fig. 11 and Fig. 12, respectively. Unlike rough specimens, for polished specimen the condition which exhibited the best combination of tensile properties, in terms of high values and low standard deviations, corresponds to the non-standard multiple HIP treatment (1050 °C + 800 °C) with scan length = 78 mm.

A univocal effect of scan length cannot be detected for polished specimens, as can be observed from the as-built and standard HIP conditions.

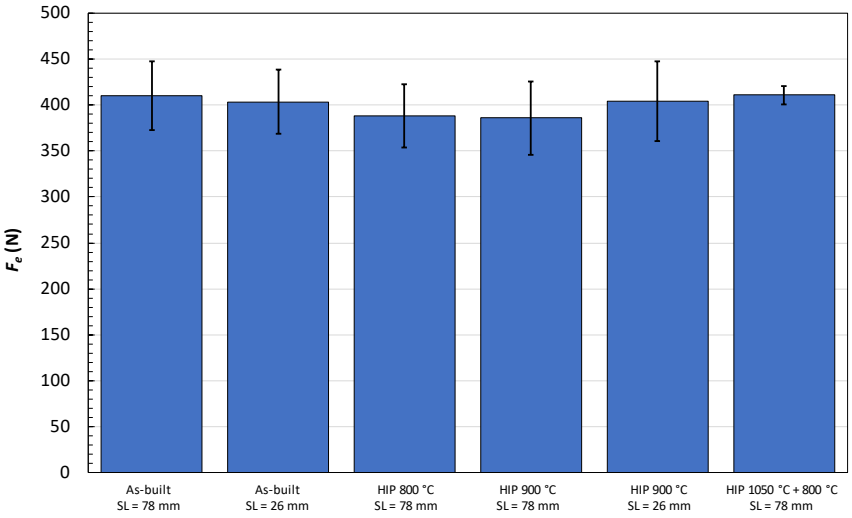

Figure 11 - Average values and standard deviations for $F_{e,proj}$.

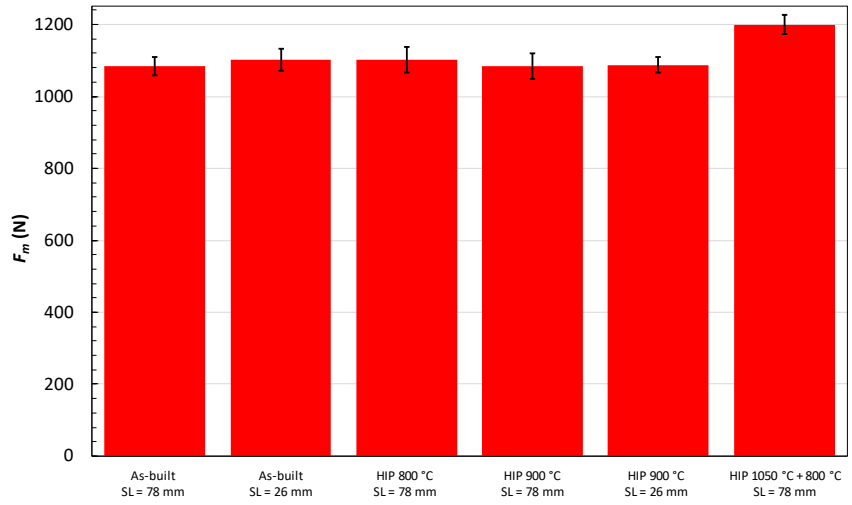

Figure 12 - Average values and standard deviations for F_m.

4.9.3. General considerations

It must be stressed that average values in Tables 29 to 31 should not be compared directly between rough and polished specimens, as these latter had a lower thickness (0.43 mm - 0.47 mm) than the former (0.5 mm). However, standard deviations can be legitimately compared.

The SP parameter that exhibits the least variability (1.3 % – 3.3 %) is the maximum force F_m, whereas elastic-plastic transition forces $F_{e,proj}$ and $F_{e,int}$, which are calculated from the intersection of two linear fits, yielded relative standard deviations in the range 2.4 % – 15.0 %. Interestingly, displacements at maximum force, u_m, generally showed larger scatter than displacements corresponding to a 20 % force drop from the maximum, u_f. In terms of calculated energies, the most consistent parameter is the fracture energy, E_{SP}.

No obvious effect of surface finish (rough vs. polished) could be detected on the variability of SP parameters.

5. Correlations with tensile properties

Many empirical correlations between normalized SP parameters and conventional tensile properties have been proposed in the literature, almost exclusively for steels. For most of these correlations, the accuracy of the predicted strength values (yield and ultimate) was reported to be in the order of ± 25 MPa. Specifically:

- Yield strength has been mostly correlated with F_e/h_0^2 [21-27]. Alternative correlations for R_{p02} have been proposed with:
  - $F_{h0/10,off}$, normalized by h_0^2 [23];
  - $F_{0.1mm,off}$, normalized by h_0^2 [22,24];
  - $Slope_{ini}$, normalized by h_0 [28].
- Tensile strength has been mostly correlated with F_m, normalized either by h_0^2 [23,25,27] or $h_0 \cdot u_m$ [21-27,29]. Other force values that have been correlated with R_m are:
  - F_{infl}, normalized by $h_0 \cdot u_m$ [27];
  - $F_{0.48mm}$ [27], $F_{0.645mm}$ [25], and $F_{0.65mm}$ [28], all normalized by h_0^2.
- Total elongation has been correlated with u_m [23,31], u_m/h_0 [23,32], and $\frac{u_f - h_0}{h_0}$ [33].

Almost every correlation was proposed in the generic linear form:

$$Y = \alpha_1 X + \alpha_2 \quad , \tag{1}$$

where Y is the tensile property of interest, X is the normalized SP parameter, and α_1, α_2 are slope and intercept, respectively, of a least-squares linear regression between X and Y.

As far as energy values are concerned, in the literature they are only used to construct a transition curve by performing tests at different temperatures. The flexural point of the energy/temperature curve is then empirically correlated to the ductile-to-brittle transition temperature established from Charpy tests [34,35].

In previous work by the authors [12], correlations for three investigated steels (A533B cl. 1, 4340 low-energy, and 4340 high-energy) were derived and compared with those proposed by other authors. A similar approach was taken for this investigation.

The strength of the established correlations is hereinafter defined on the basis of the Pearson correlation coefficient, r:

- strong ($r > 0.70$) – color: green,
- moderate ($0.70 \leq r < 0.50$) – color: yellow,
- weak ($0.50 \leq r < 0.30$) – color: pink, or
- absent/no correlation ($r \leq 0.30$) – color: red.

5.1. Yield strength correlations

A summary of the yield strength correlations obtained for rough specimens is provided in Table 33, while the same information is shown in Table 34 for polished specimens. The Tables present the values of the linear coefficients (slope and intercept), as well as the values of the correlation coefficient r. The yield properties to be correlated with SP parameters were measured in [15].

Table 33 - Summary of yield strength correlations obtained for rough specimens of AM Ti64.

		Slope	0.1462	0.1190	0.0264	0.1853	0.0987	0.0737	0.0227
		Intercept	610.82	657.04	754.16	372.04	536.89	786.89	766.22
		r	0.6661	0.5574	0.5597	0.6946	0.5079	0.5553	0.5338
Material condition	Scan length (mm)	Tensile property	SP parameter	SP parameter	SP parameter	SP parameter	SP parameter	SP parameter	SP parameter
		0.2% YS	$F_{e,proj}/h_0^2$	$F_{e,int}/h_0^2$	$F_{e,proj}/(u_e h_0)$	$F_{h0/10,off}/h_0^2$	$F_{0.1mm,off}/h_0^2$	$R_{p0.2,Hähner}$	$Slope_{ini}/h_0$
As-Built	78	879	1767.1	1860.5	5229.1	2614.9	3261.8	1329.3	5504.99
	26	875	1653.8	1684.5	3596.0	2717.5	3437.7	1097.1	3664.67
HIP 800 °C	78	864	1837.0	1853.6	3694.5	2777.0	3400.1	986.2	3732.27
HIP 900 °C	78	838	1451.6	1484.6	3446.2	2474.9	2978.5	881.4	3532.78
	26	799	1578.6	1565.1	3361.1	2478.7	3157.5	668.5	3456.76
HIP 1050+800 °C	78	885	1805.4	1622.8	3955.3	2629.1	3204.4	720.6	4072.12

Table 34 - Summary of yield strength correlations obtained for polished specimens of AM Ti64.

		Slope	0.4042	0.2934	0.0860	0.3697	0.3204	0.3374	0.0842
		Intercept	60.79	231.42	301.34	-131.46	-239.58	322.70	268.19
		r	0.8545	0.8167	0.5143	0.6709	0.7681	0.3967	0.6079
Material condition	Scan length (mm)	Tensile property	SP parameter	SP parameter	SP parameter	SP parameter	SP parameter	SP parameter	SP parameter
		0.2% YS	$F_{e,proj}/h_0^2$	$F_{e,int}/h_0^2$	$F_{e,proj}/(u_e h_0)$	$F_{h0/10,off}/h_0^2$	$F_{0.1mm,off}/h_0^2$	$R_{p0.2,Hähner}$	$Slope_{ini}/h_0$
As-Built	78	878.9	2026.2	2200.1	6620.8	2685.1	3481.0	1567.1	7189.43
	26	875.5	2024.6	2216.5	6250.2	2730.4	3491.7	1558.2	6850.70
HIP 800 °C	78	863.7	1982.0	2160.3	6671.0	2661.8	3377.1	1594.6	7272.78
HIP 900 °C	78	837.8	1867.6	1992.8	6262.8	2578.0	3317.2	1548.3	6689.19
	26	799.3	1899.1	2043.5	6328.9	2645.1	3363.1	1573.4	6809.58
HIP 1050+800 °C	78	885.1	2016.0	2172.8	6604.2	2738.3	3499.0	1654.4	7118.34

All the correlations established for rough specimens were moderate ($0.70 \leq r < 0.50$), while for polished specimens three of the correlations were found to be strong ($r > 0.70$) and one weak ($0.50 \leq r < 0.30$). The three strong correlations obtained are depicted in Figs. 13 to 15, which also include data and linear fits for rough specimens.

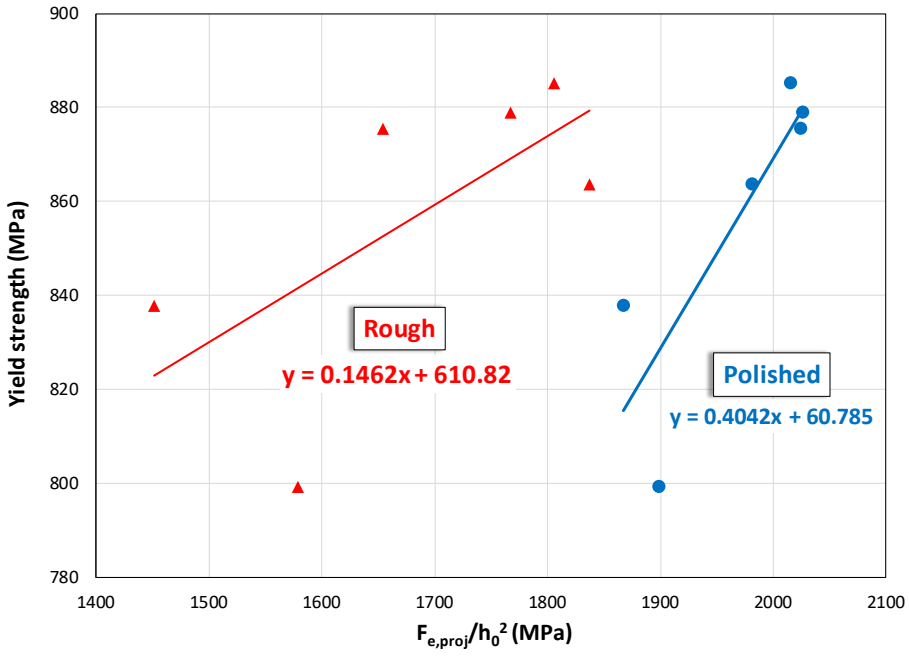

Figure 13 - Correlations between $F_{e,proj}/h_0^2$ and yield strength for rough and polished specimens of AM Ti64.

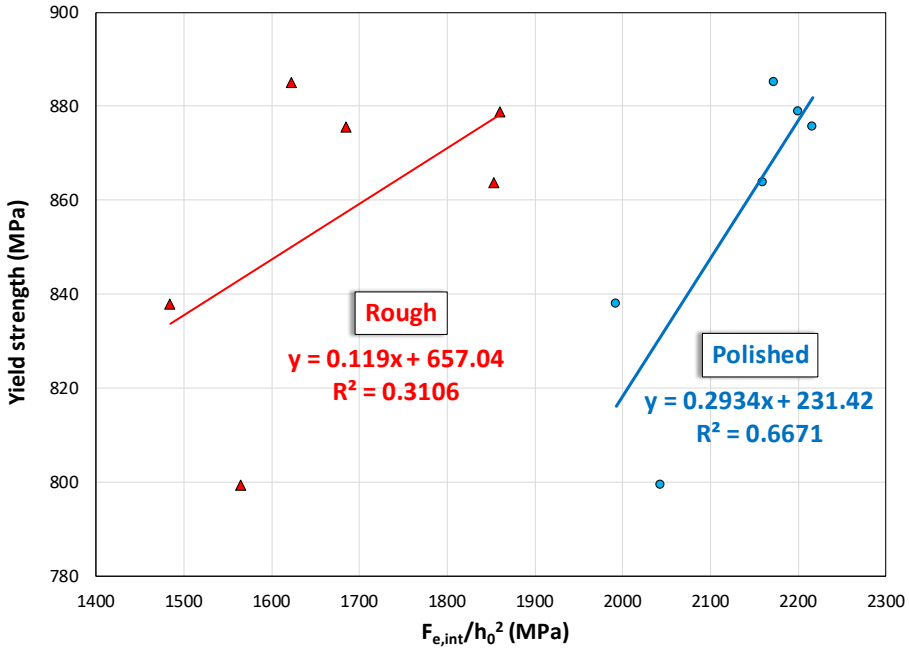

Figure 14 - Correlations between $F_{e,int}/h_0^2$ and yield strength for rough and polished specimens of AM Ti64.

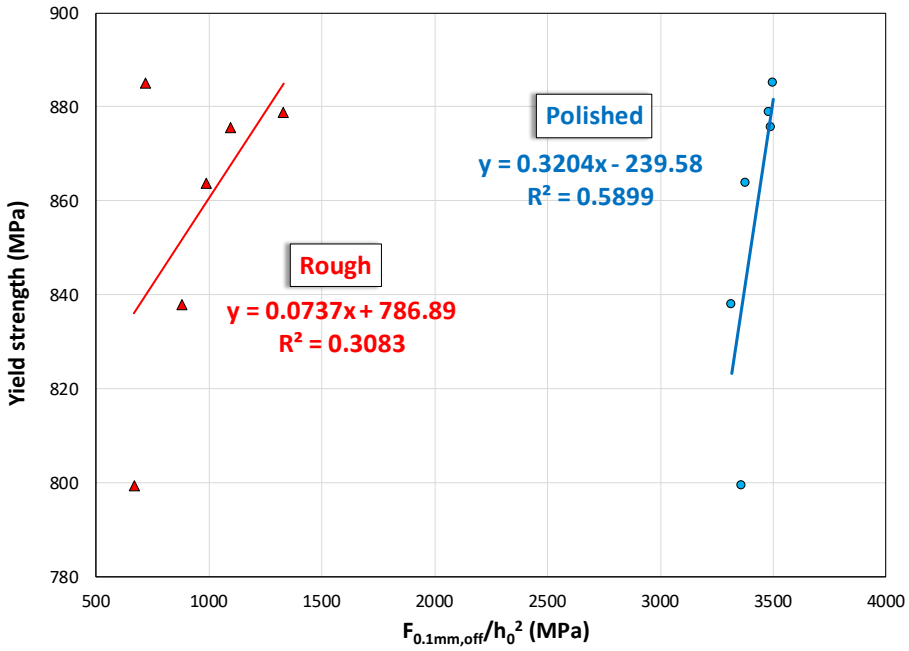

Figure 15 - Correlations between $F_{0.1mm,off}/h_0^2$ and yield strength for rough and polished specimens of AM Ti64.

All the yield strength correlations, obtained for both rough and polished specimens, are documented in Annex 14.

5.2. Ultimate tensile strength correlations

A summary of the ultimate tensile strength correlations obtained for rough specimens is provided in Table 35, while the same information is shown in Table 36 for polished specimens. The Tables present the values of the linear coefficients (slope and intercept), as well as the values of the correlation coefficient *r*. The ultimate tensile values to be correlated with SP parameters were measured in [15].

Table 35 - Summary of ultimate tensile strength correlations obtained for rough specimens of AM Ti64.

		Slope	0.0273	0.1074	0.0817	0.0530	0.0654
		Intercept	839.28	726.27	861.04	800.01	717.99
		r	0.4040	0.7386	0.8852	0.7036	0.7312
Material condition	Scan length (mm)	Tensile property	SP parameter	SP parameter	SP parameter	SP parameter	SP parameter
		UTS	F_m/h_0^2	$F_m/(h_0u_m)$	$F_{infl}/(h_0u_m)$	$F_{0.48mm}/h_0^2$	$F_{0.65mm}/h_0^2$
As-Built	78	981	4401.2	2364.3	1631.7	3612.1	4071.6
	26	972	4467.9	2024.4	1232.0	3027.0	3762.7
HIP 800 °C	78	969	4476.0	2277.9	1281.6	3050.9	3753.5
HIP 900 °C	78	951	4079.7	2116.3	1001.8	2663.4	3314.6
	26	918	4502.7	2015.7	889.0	2816.2	3554.2
HIP 1050+800 °C	78	985	5207.7	2407.2	1416.1	3224.8	3994.1

Table 36 - Summary of ultimate tensile strength correlations obtained for polished specimens of AM Ti64.

		Slope	0.0129	-0.0167	0.0004	0.1362	0.0242
		Intercept	897.43	1010.27	961.83	374.43	847.22
		r	0.1066	-0.2458	0.0081	0.5135	0.2539
Material condition	Scan length (mm)	Tensile property	SP parameter	SP parameter	SP parameter	SP parameter	SP parameter
		UTS	F_m/h_0^2	$F_m/(h_0u_m)$	$F_{infl}/(h_0u_m)$	$F_{0.48mm}/h_0^2$	$F_{0.65mm}/h_0^2$
As-Built	78	980.9	4841.8	2402.0	1608.7	4307.8	4471.7
	26	971.7	4856.1	2802.6	1068.0	4263.9	4681.2
HIP 800 °C	78	969.1	5037.5	2902.2	2081.8	4334.3	4814.0
HIP 900 °C	78	950.6	5104.0	2520.4	1424.0	4219.9	4612.1
	26	917.8	5029.3	3240.3	2003.7	4284.6	4729.5
HIP 1050+800 °C	78	985.3	5408.8	3313.0	2393.5	4492.1	5237.1

Interestingly, the results point in a different direction with respect to what we obtained for the yield strength. Correlations are generally much stronger for rough specimens (four strong and one weak) than for polished specimens (four non-existent and one moderate).

The empirical relationships established between R_m and F_m/h_0^2, $F_m/(h_0u_m)$, $F_{infl}/(h_0u_m)$, and $F_{0.65mm}/h_0^2$ are shown in Figs. 16-19 for both groups of specimens.

All the ultimate tensile strength correlations, obtained for both rough and polished specimens, are documented in Annex 15.

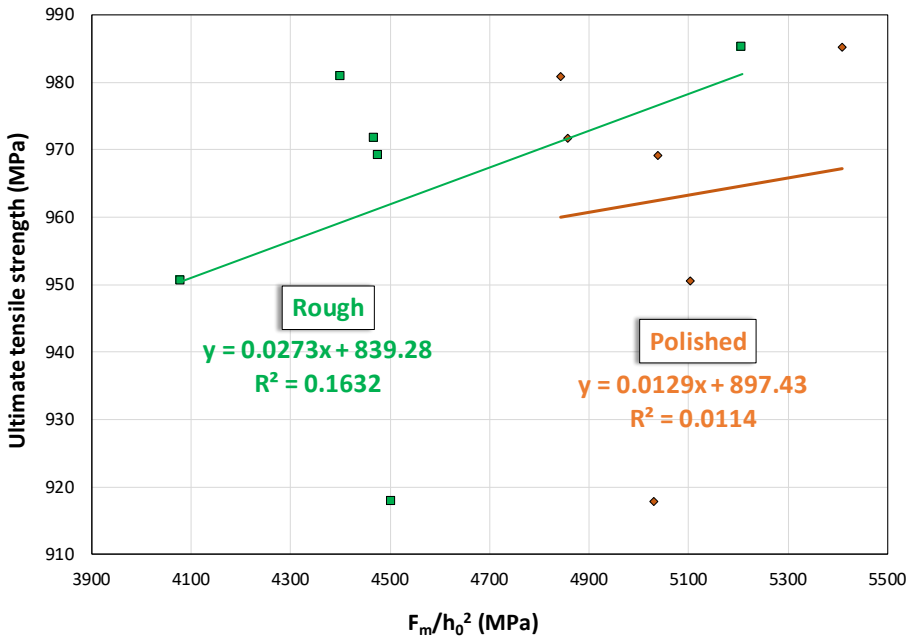

Figure 16 - Correlations between F_m/h_0^2 and ultimate tensile strength for rough and polished specimens of AM Ti64.

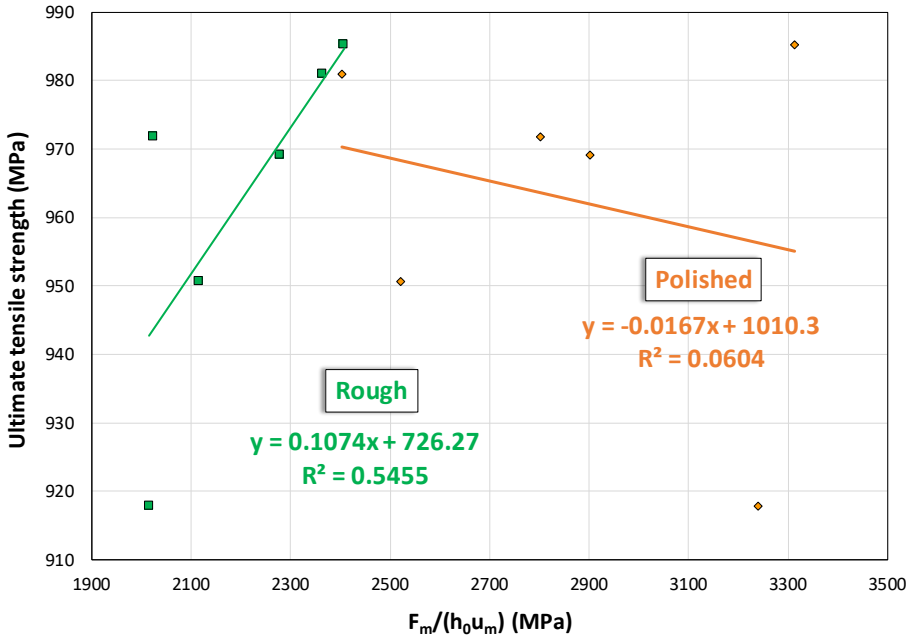

Figure 17 - Correlations between $F_m/(h_0u_m)$ and ultimate tensile strength for rough and polished specimens of AM Ti64.

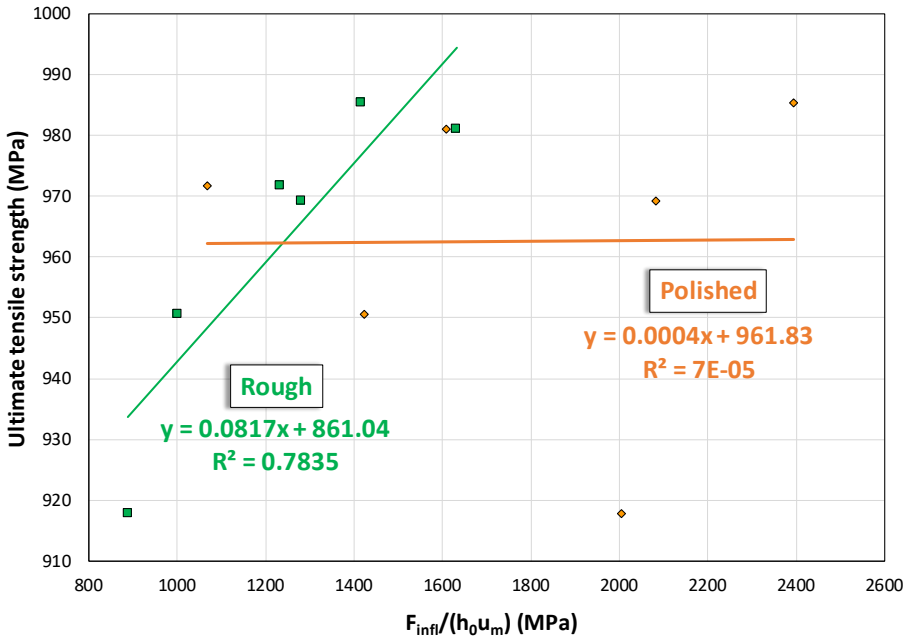

Figure 18 - Correlations between $F_{\mathrm{infl}}/(h_0 u_{\mathrm{m}})$ and ultimate tensile strength for rough and polished specimens of AM Ti64.

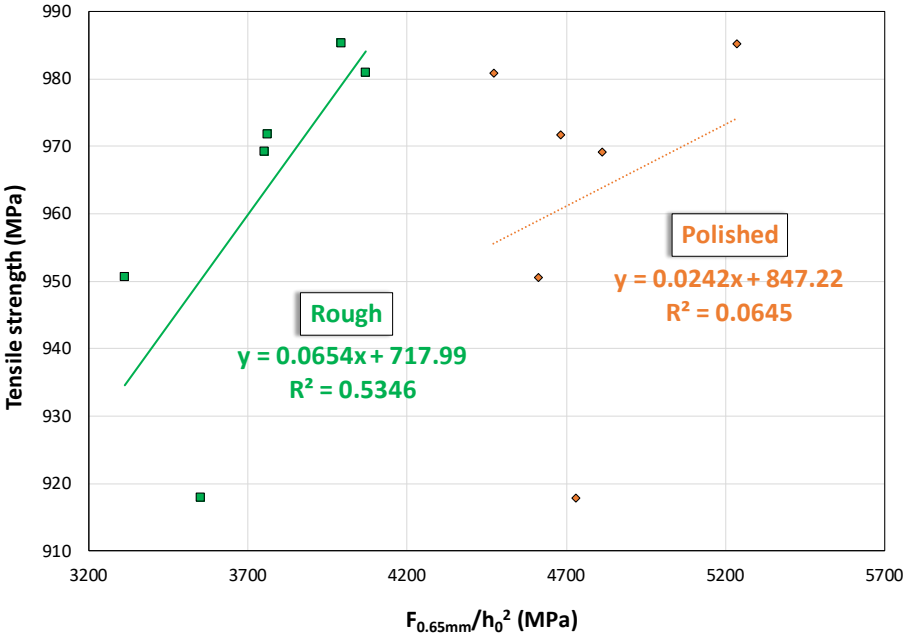

Figure 19 - Correlations between $F_{0.65\mathrm{mm}}/h_0^2$ and ultimate tensile strength for rough and polished specimens of AM Ti64.

5.3. Elongation correlations

A summary of the correlations with total elongation from tensile tests obtained for rough specimens is provided in Table 37, while the same information is shown in Table 38 for

polished specimens. The Tables present the values of the linear coefficients (slope and intercept), as well as the values of the correlation coefficient *r*. The total elongation values to be correlated with SP parameters were measured in [15].

Table 37 - Summary of total elongation correlations obtained for rough specimens of AM Ti64.

		Slope	-0.0861	-0.0089
		Intercept	0.46	0.30
		r	-0.2681	-0.0436
Material condition	Scan length (mm)	Tensile property	SP parameter	SP parameter
		TE	u_m/h_0	$(u_f-h_0)/h_0$
As-Built	78	27.8%	1.867	1.796
	26	25.5%	2.211	2.023
HIP 800 °C	78	31.7%	1.984	1.882
HIP 900 °C	78	31.0%	1.968	1.902
	26	31.8%	2.262	2.477
HIP 1050+800 °C	78	18.8%	2.165	2.152

Table 38 - Summary of total elongation correlations obtained for polished specimens of AM Ti64.

		Slope	**0.0832**	**0.3047**
		Intercept	**0.13**	**-0.30**
		r	**0.3036**	**0.8838**
Material condition	Scan length (mm)	**Tensile property**	**SP parameter**	**SP parameter**
		TE	u_m/h_0	$(u_f-h_0)/h_0$
As-Built	78	27.8%	2.023	1.868
	26	25.5%	1.749	1.759
HIP 800 °C	78	31.7%	1.767	2.088
HIP 900 °C	78	31.0%	2.029	2.029
	26	31.8%	1.605	1.941
HIP 1050+800 °C	78	18.8%	1.636	1.717

For rough specimens, negative (and therefore non-physical) correlations were found between ε_t and both u_m/h_0 and $\frac{u_f-h_0}{h_0}$ (Fig. 20). In the case of polished specimens, however, both correlations were positive, and the correlation with $\frac{u_f-h_0}{h_0}$ (Fig. 20) was quite strong.

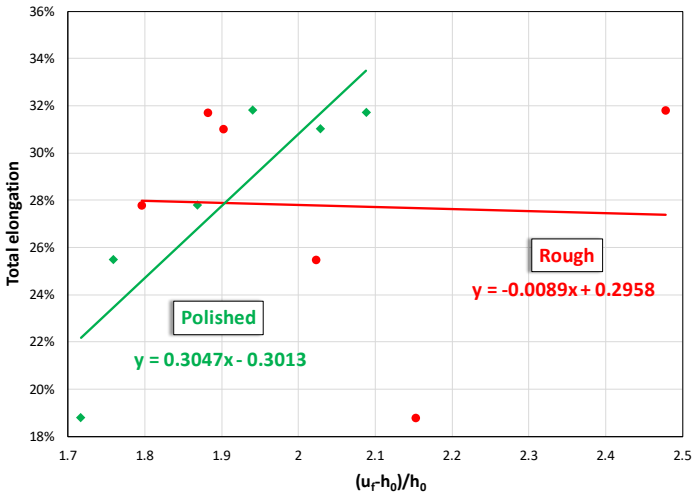

Figure 20 - Correlations between ($u_f - h_0$) and total elongation for rough and polished specimens of AM Ti64.

We also attempted to correlate uniform elongation, ε_u, to the normalized punch displacement at maximum force, u_m/h_0 (Tables 39-40 and Fig. 21). Once again, a non-physical negative relationship was found for rough specimens, whereas a weak (r = 0.39) positive correlation was obtained for polished specimens.

Table 39 - Uniform elongation correlation obtained for rough specimens of AM Ti64.

		Slope	-0.0179
		Intercept	0.13
		r	-0.3420
Material condition	Scan length (mm)	Tensile property UE	SP parameter u_m/h_0
As-Built	78	9.5%	1.867
	26	9.1%	2.211
HIP 800 °C	78	10.1%	1.984
HIP 900 °C	78	10.0%	1.968
	26	10.0%	2.262
HIP 1050+800 °C	78	7.9%	2.165

Table 40 - Uniform elongation correlation obtained for polished specimens of AM Ti64.

		Slope	0.0173
		Intercept	0.06
		r	0.3870
Material condition	Scan length (mm)	Tensile property UE	SP parameter u_m/h_0
As-Built	78	9.5%	2.023
	26	9.1%	1.749
HIP 800 °C	78	10.1%	1.767
HIP 900 °C	78	10.0%	2.029
	26	10.0%	1.605
HIP 1050+800 °C	78	7.9%	1.636

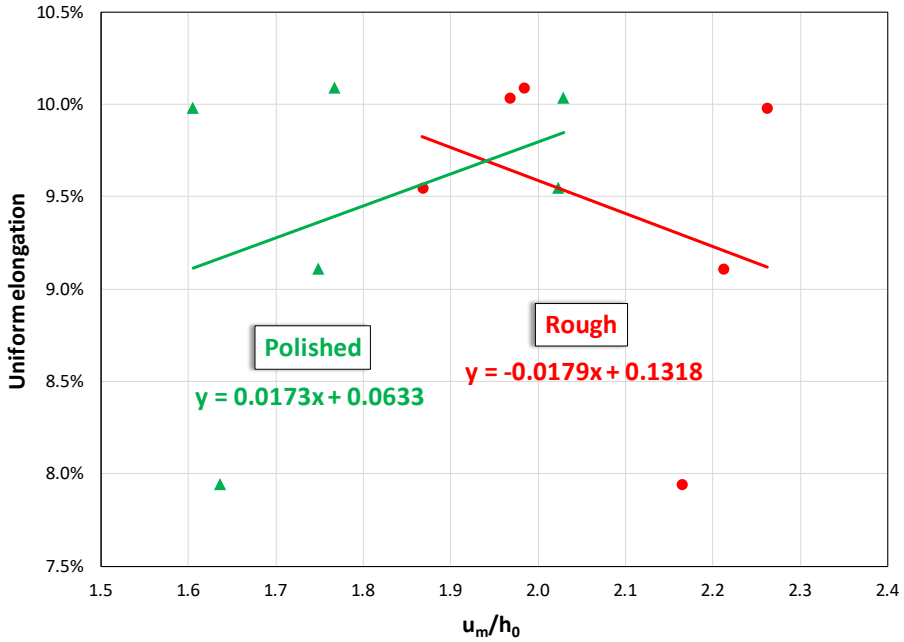

Figure 21 - Correlations between u_m/h_0 and uniform elongation for rough and polished specimens of AM Ti64.

All the total and uniform elongation correlations, obtained for both rough and polished specimens, are documented in Annex 16.

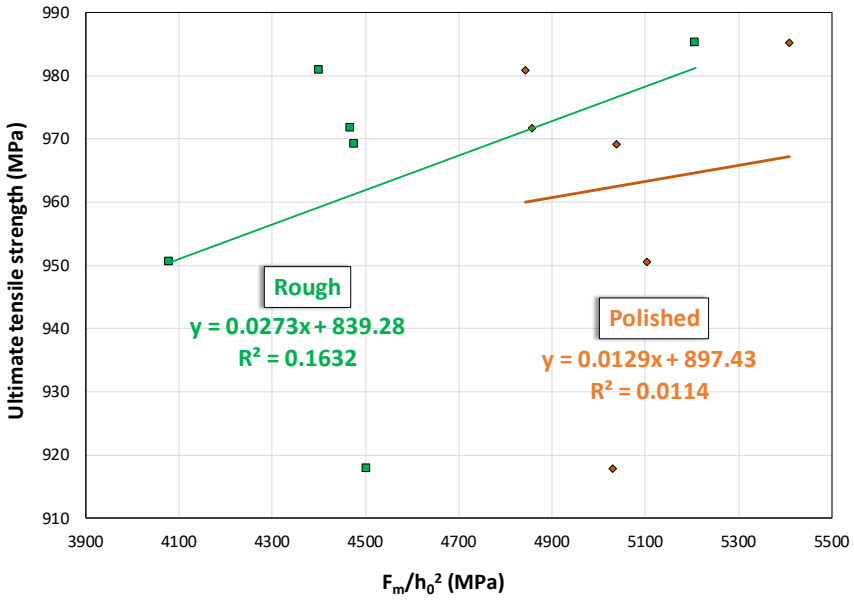

Figure 22 - Correlations between F_m/h_0^2 and ultimate tensile strength for rough and polished specimens of AM Ti64.

6. Correlations with fracture toughness

In the literature, fracture toughness has been generally estimated from SP test results by means of analytical approaches involving finite element calculations [37,38]. Most of the few published empirical correlations were established between critical *J*-integral (J_{Ic}, J_Q) and effective (or biaxial) fracture strain [10,23,38,39], calculated as:

$$\varepsilon_f = ln\left(\frac{h_0}{h_f}\right) \quad . \tag{2}$$

However, at the time of writing, h_f values were not available for the specimens tested.

The room temperature elastic-plastic fracture toughness of four of the AM Ti64 investigated conditions (as-built and non-standard 900 °C HIP, two scan lengths) was measured on fatigue precracked Charpy-type specimens in a previous investigation [14], by means of the Elastic Compliance single-specimen methodology, in terms of size-sensitive critical value of *J*-integral, J_Q (Table 41).

Table 41 - Elastic-plastic fracture toughness measured on four AM Ti64 conditions [14].

Material condition	J_Q (kN/m²)
a,e1	121.14
a,e2	93.23
c,e1	157.67
c,e2	151.61

In this study, we attempted novel correlations between J_Q and the following normalized SP energy values: $\frac{E_{SP}}{h_0 u_f}$, $\frac{E_m}{h_0 u_m}$, and $\frac{E_{PL}}{h_0 u_{m,pl}}$. In each case, SP energy was normalized by the product of the initial thickness by the corresponding displacement value. For E_{PL}, the plastic component of u_m was calculated as:

$$u_{m,pl} = u_m - \frac{F_m}{Slope_{ini}} \quad . \tag{3}$$

For both rough and polished specimens, moderately strong correlations were found between J_Q and the normalized fracture energy $\frac{E_{SP}}{h_0 u_f}$ ($r = 0.60$ and 0.62, respectively, Fig. 17). The remaining correlations obtained were negative and therefore unacceptable for rough specimens, while in the case of polished specimens a weak correlation was obtained for the plastic energy, $\frac{E_{PL}}{h_0 u_{m,pl}}$ ($r = 0.43$), and no correlation was observed with the normalized total energy, $\frac{E_m}{h_0 u_m}$ ($r = 0.18$).

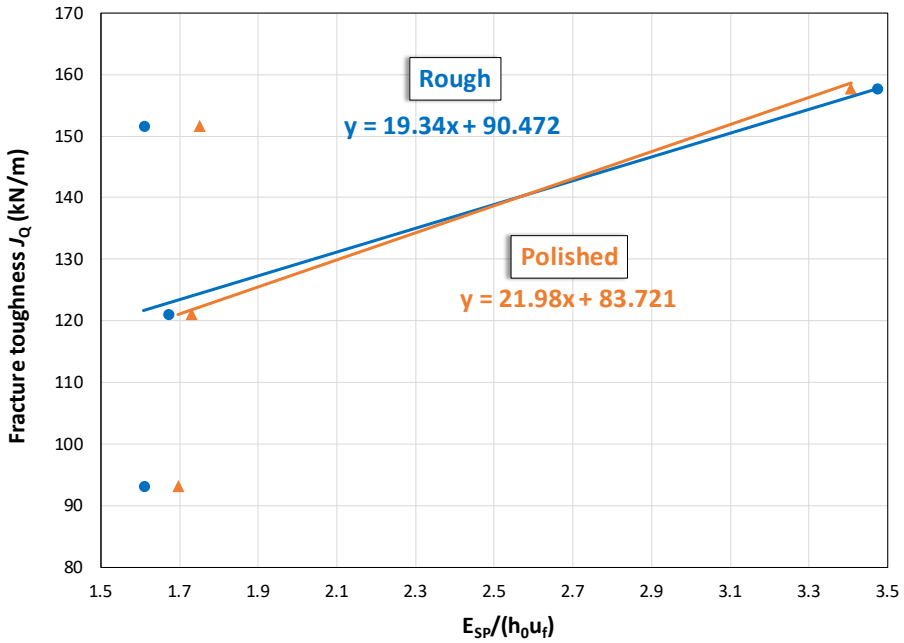

Figure 23 - Empirical correlations between J_Q and $E_{SP}/(h_0 u_f)$ for rough and polished SP specimens of AM Ti64.

7. Use of actuator displacement in the analyses

Two displacement signals were recorded during SP testing: the signal of the extensometer, which corresponds to punch displacement, and the displacement of the machine actuator. Several authors have also reported the use of another displacement (specimen deflection), measured by a transducer (LVDT) positioned below the specimen being tested.

All the analyses of the tests performed on rough specimens were repeated using actuator displacement as a surrogate of punch displacement. Comparisons between average values and standard deviations for selected characteristic force, displacement, and energy

values obtained using extensometer and actuator displacements are illustrated in Fig. 24 ($F_{e,proj}$ and $F_{0.1mm,off}$), Fig. 25 (u_e, $u_{0.1mm,off}$, u_m, and u_f), and Fig. 26 (E_{SP}, E_m, and E_{PL}).

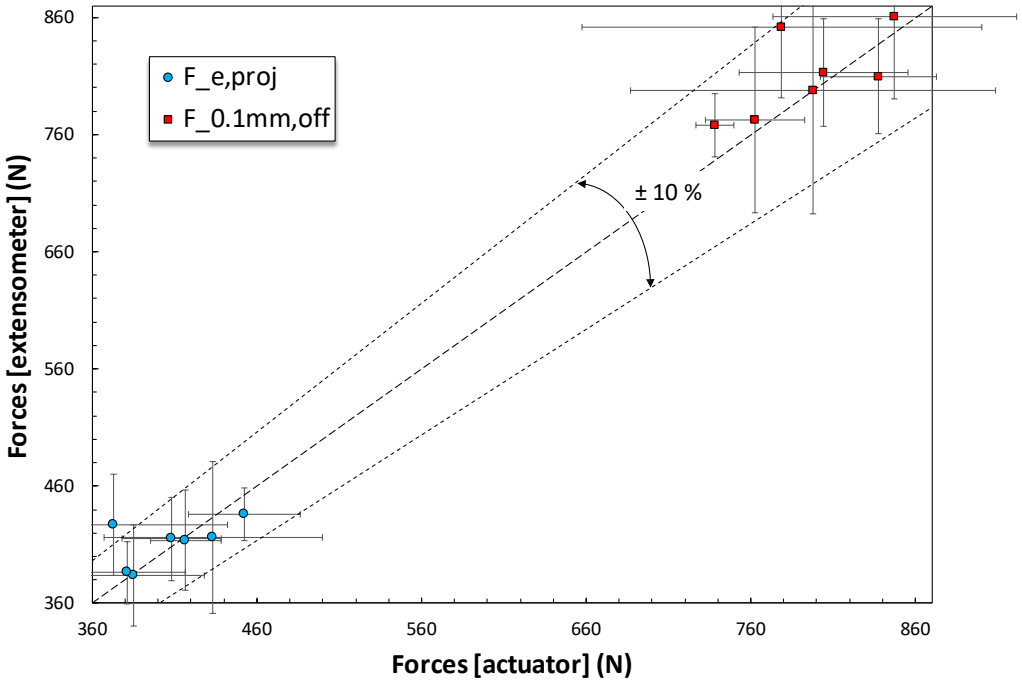

Figure 24 – Mean characteristic force values obtained for rough specimens using extensometer and actuator displacements, with ± 1σ error bands.

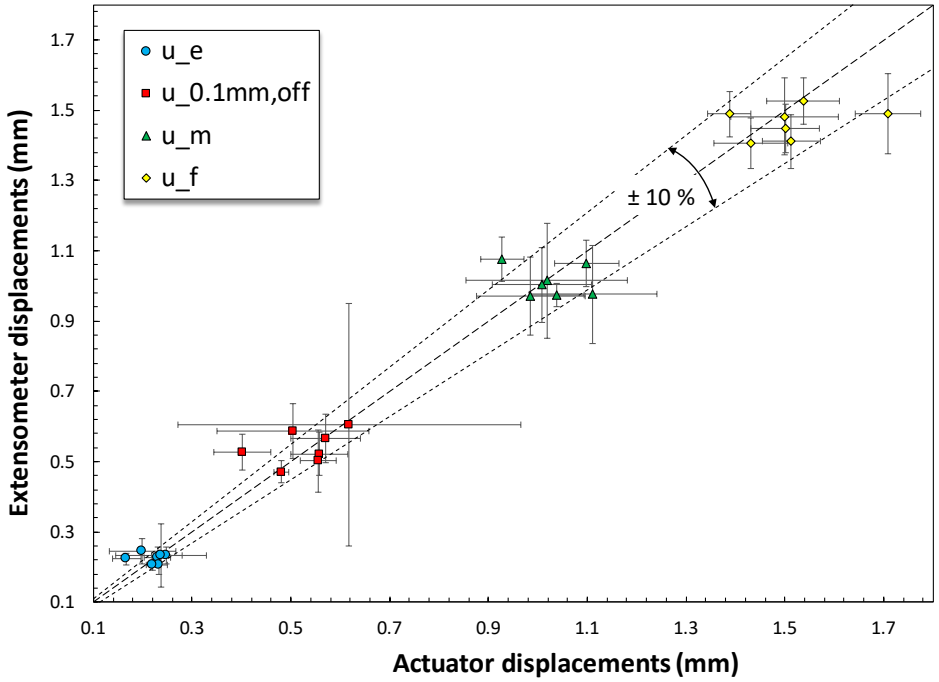

Figure 25 – Mean characteristic displacement values obtained for rough specimens using extensometer and actuator displacements, with ± 1σ error bands.

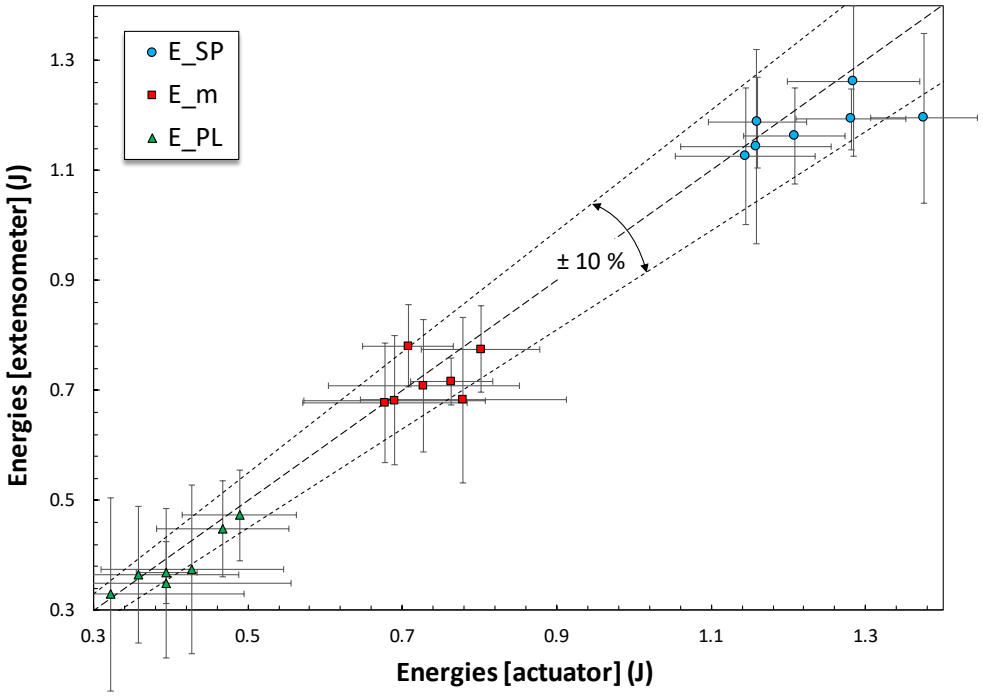

Figure 26 – Mean characteristic energy values obtained for rough specimens using extensometer and actuator displacements, with ± 1σ error bands.

The data shown in Figs. 24-26 show a relatively modest influence of the choice of displacement signal on the characteristic parameters obtained from SP tests, also considering the relatively large standard deviations. Two qualitative remarks can nonetheless be formulated:

- Most of the average values are within ± 10 % of each other.
- In case of force values (Fig. 24), a specific trend is not clearly visible. For displacements (Fig. 25) and energies (Fig. 26), it can be observed that actuator-based values tend to be generally higher than extensometer-based values.

The most practical information, however, is the effect of using actuator displacements to derive correlations with tensile properties, in a hypothetical situation where no external displacement transducer is available. Such an effect is illustrated in Table 42, which compares values of Pearson's correlation coefficient, *r*, from selected empirical correlations established by using SP extensometer-based and actuator-based parameters for rough specimens.

Note that we will not report details on specific actuator-based empirical correlations here, as the reference procedure this document uses is based on measuring punch displacement by means of an extensometer.

Table 42 - Correlation coefficients for extensometer-based and actuator-based correlations for rough specimens. In the last column, red arrows indicate a decrease in *r* going from extensometer to actuator (two red arrows = substantial decrease), green arrows an increase, and black horizontal arrows a minor variation.

		Correlation coefficients, *r*		
Y-variable	**X-variable**	**Extensometer**	**Actuator**	**Change**
Yield strength	$F_{e,proj}/h_0^2$	0.6661	0.5619	⇓
	$F_{e,proj}/(u_e h_0)$	0.5597	0.4458	⇓
	$F_{0.1mm,off}/h_0^2$	0.1262	0.4257	⇑
	$Slope_{el}/h_0$	0.5338	0.3972	⇓
Ultimate tensile strength	F_m/h_0^2	0.4040		
	$F_m/(u_m h_0)$	0.7386	0.0608	⇓⇓
UE	u_m/h_0	-0.3420	-0.3580	⇔
TE	u_f/h_0	-0.2681	-0.1304	⇔
	$(u_f-h_0)/h_0$	-0.0436	0.1975	⇑

As can be seen in Table 42, the use of actuator displacement generally tends to weaken the strength of the strongest correlations that were established on the basis of extensometer displacement. Relative improvements are only observed for relationships that were already rather shaky, or even non-physical (negative values of *r*).

8. Discussion

Across the board, the quality of empirical correlations between tensile properties and SP parameters for AM Ti64 was found to be poorer than that reported for steels in the open literature. This is hardly surprising, considering that the Small Punch methodology was developed for application to high-quality materials in the power industry [1], and was found to be inaccurate for highly anisotropic materials, such as oxide dispersion strengthened (ODS) steels [40]. As an example, the force-displacement curve for a SP test on ODS 14YWT steel [40] shown in Figure 24, exhibits several force drops ("pop-in" type events), associated with the steel's susceptibility to secondary cracking, and has a different form than the classical SP curve for homogeneous steels (Figure 1).

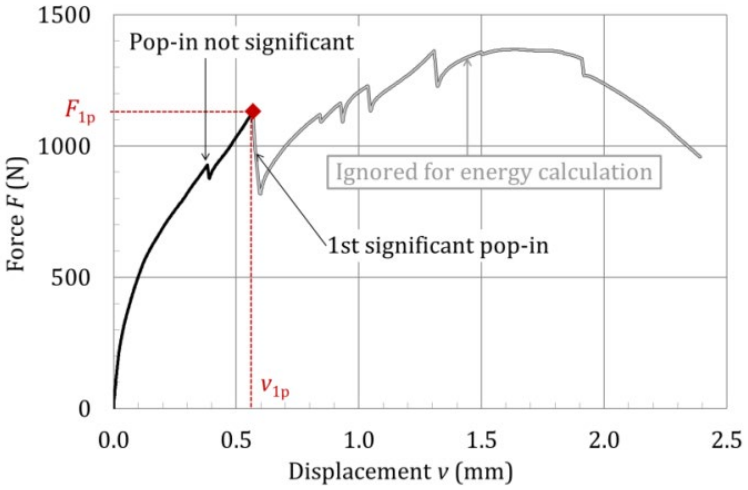

Figure 27 – Force-displacement curve for a SP test on ODS 14YWT steel [40].

It should also be noted that the range of tensile properties for the AM Ti64 investigated conditions, with respect to the property average value was relatively limited, particularly in the case of R_{p02} and R_m (10.1 % and 7 %, respectively). This makes it even more difficult to obtain strong correlations, particularly in the presence of significant experimental variability.

As far as the influence of specimen surface finish is concerned, we can generally state that polished specimens correlate slightly better with AM Ti64 tensile properties than rough specimens, which supports the inclusion of the Ra < 0.25 µm requirement in both the ASTM draft [11] and the CEN Workshop Agreement CWA15627:2007 [10]. Moreover, we observe that normalized force values are systematically larger for polished specimens.

Follow-up microstructural investigations are planned to provide a more complete interpretation of the SP results obtained in the different conditions, including measurements of final specimen thickness values, h_f, on the fracture surface to be correlated with fracture toughness.

9. Conclusions

The overall quality of the empirical correlations that we obtained between tensile properties and SP test parameters for six conditions of AM Ti64 is not satisfactory. Most correlations were found to be non-existent or weak at best. This is not an unexpected conclusion, since the Small Punch methodology has been shown to have limited applicability for highly anisotropic materials, such as those currently produced via Additive Manufacturing. However, it's important to note that the AM community is actively working on decreasing the anisotropy of AM materials, and therefore these correlations could be revisited once significant progress has been made in this direction.

The available literature on the application of various SP testing techniques, including fatigue and creep, to various types of Ti64 (forged, cast, and EBM) [17-20, 41] demonstrates a significant level of interest in the material testing community. Published force-displacement curves of AM specimens [17-20] are similar to those we obtained in this study. Several references also show significantly lower tensile properties for AM Ti64 with respect to forged

and cast material, as inferred from SP tests performed both at ambient and elevated temperatures [17,19,20].

In our study, the strongest correlations (correlation coefficient $r > 0.70$[10]) for polished specimens were found between:

- Yield strength (R_{p02}) and normalized SP elastic-plastic transition force (F_e/h_0^2), Eqs. (2) and (3).
- Yield strength (R_{p02}) and normalized SP force at $h_0/10$ offset ($F_{h0,off}/h_0^2$) for rough specimens (Ra > 3 µm), Eq. (4).
- Yield strength (R_{p02}) and normalized SP force at 0.1 mm offset ($F_{0.1mm,off}/h_0^2$) for polished specimens (Ra < 0.25 µm), Eq. (5).
- Total elongation (ε_t) and normalized SP displacement at fracture ($\frac{u_f - h_0}{h_0}$) for polished specimens, Eq. (8).

Correlations between fracture toughness and normalized SP energies were also attempted, but were not particularly successful, with a highest degree of correlation around $r = 0.60$ obtained between J_Q and normalized fracture energy.

The influence of surface roughness on SP characteristic parameters was found to be significant on specimen yielding and fracture, in that these phenomena tend to occur earlier in the test in the case of rougher specimens. Across the board, polished specimens (Ra < 0.25 µm, in accordance with current normative or pre-normative documents) appear to yield better correlations.

Finally, the use of actuator displacement in the place of punch displacement (measured by an extensometer) in the analysis of SP tests did not have a particularly significant influence on characteristic parameters, but caused a generalized weakening of the empirical correlations with tensile properties.

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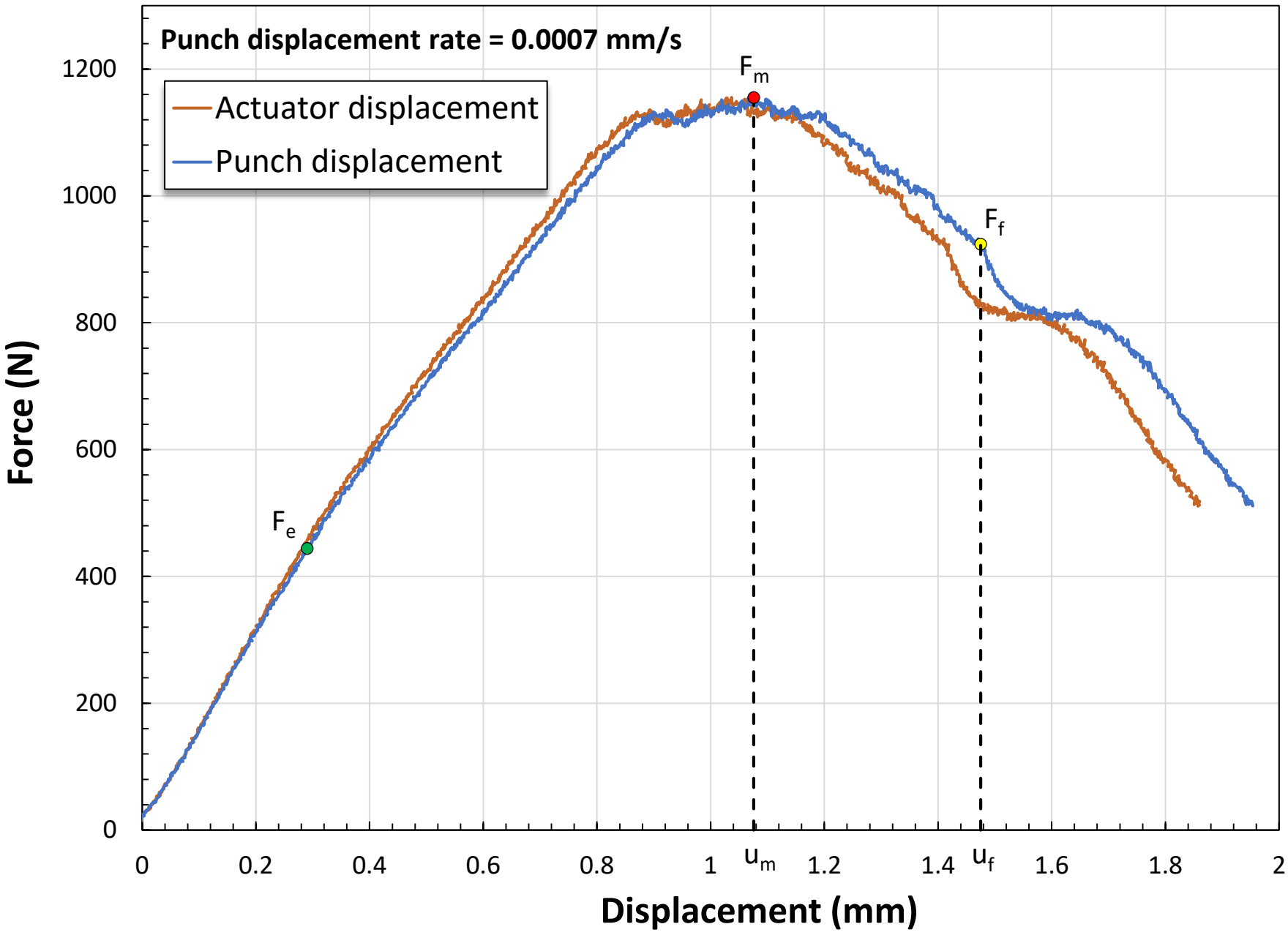
ANNEX 1

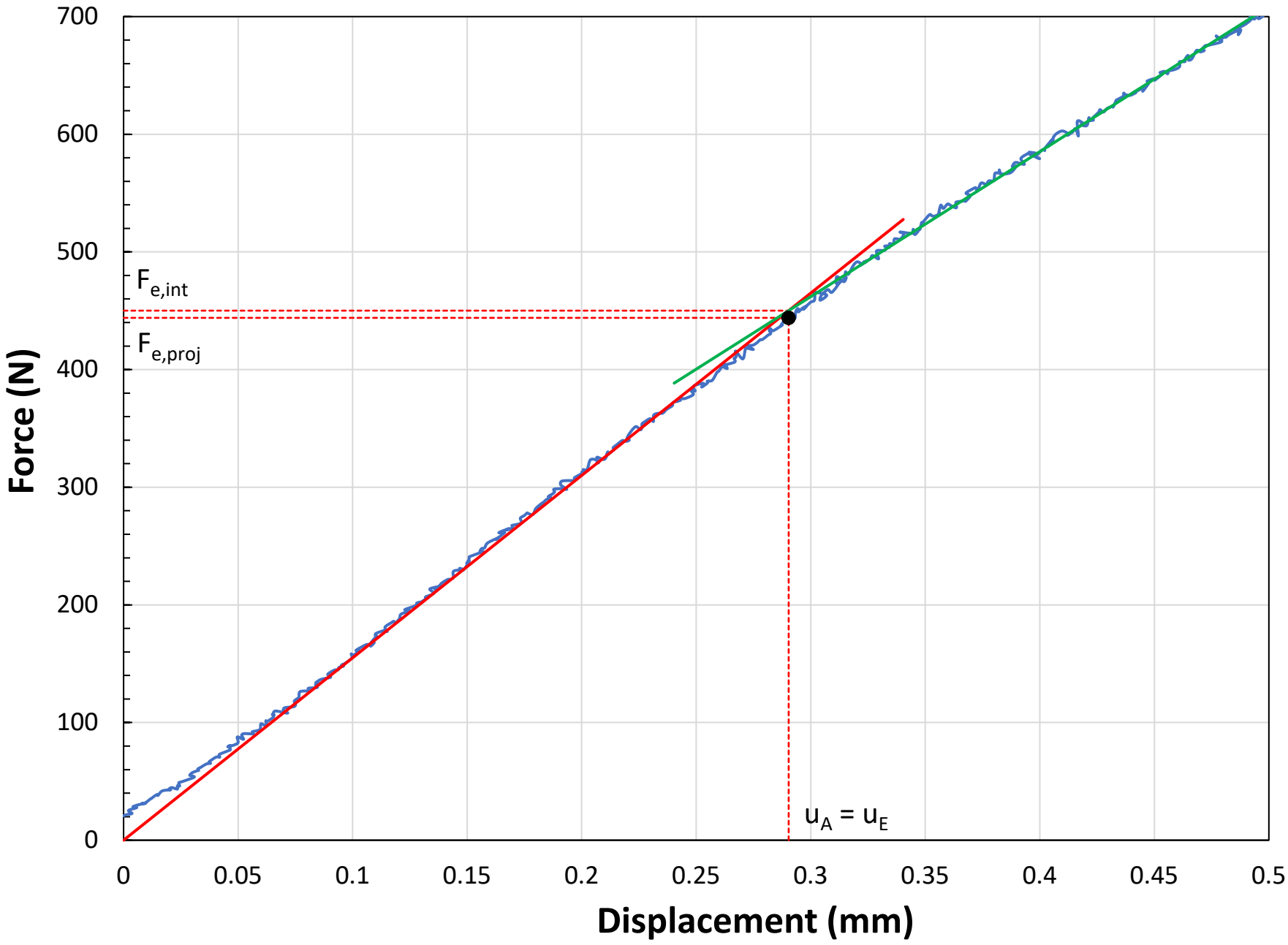
SP Test Results for
900 °C HIP, scan length = 52 mm, supported
(“rough” specimens)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP1
Material: AM Ti-64
Test speed: 0.000735 mm/s
Max strain rate: 7.35E-04 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	444.0	N
$F_{e,int}$ =	450.1	N
$F_{h0/10,off}$ =	717.9	N
$F_{0.1mm,off}$ =	929.0	N
$F_{0.1mm}$ =	158.3	N
$F_{0.48mm}$ =	682.1	N
$F_{0.5mm}$ =	706.7	N
$F_{0.65mm}$ =	873.6	N
$F_{0.9mm}$ =	1132.5	N
F_{ept} =	320.9	N
$F_{e1.5}$ =	113.5	N
F_m =	1155.0	N
F_{infl} =	1039.1	N
F_f =	924.0	N
Displacement values		
u_e =	0.290	mm
$u_{h0/10,off}$ =	0.513	mm
$u_{0.1mm,off}$ =	0.701	mm
$u_{e1.5}$ =	0.074	mm
u_m =	1.076	mm
u_{infl} =	1.300	mm
u_f =	1.475	mm
Initial linear slope		
$Slope_{ini}$ =	1550.09	N/mm
Energy values		
E_{SP} =	1.18	J
E_m =	0.76	J
E_{PL} =	0.33	J

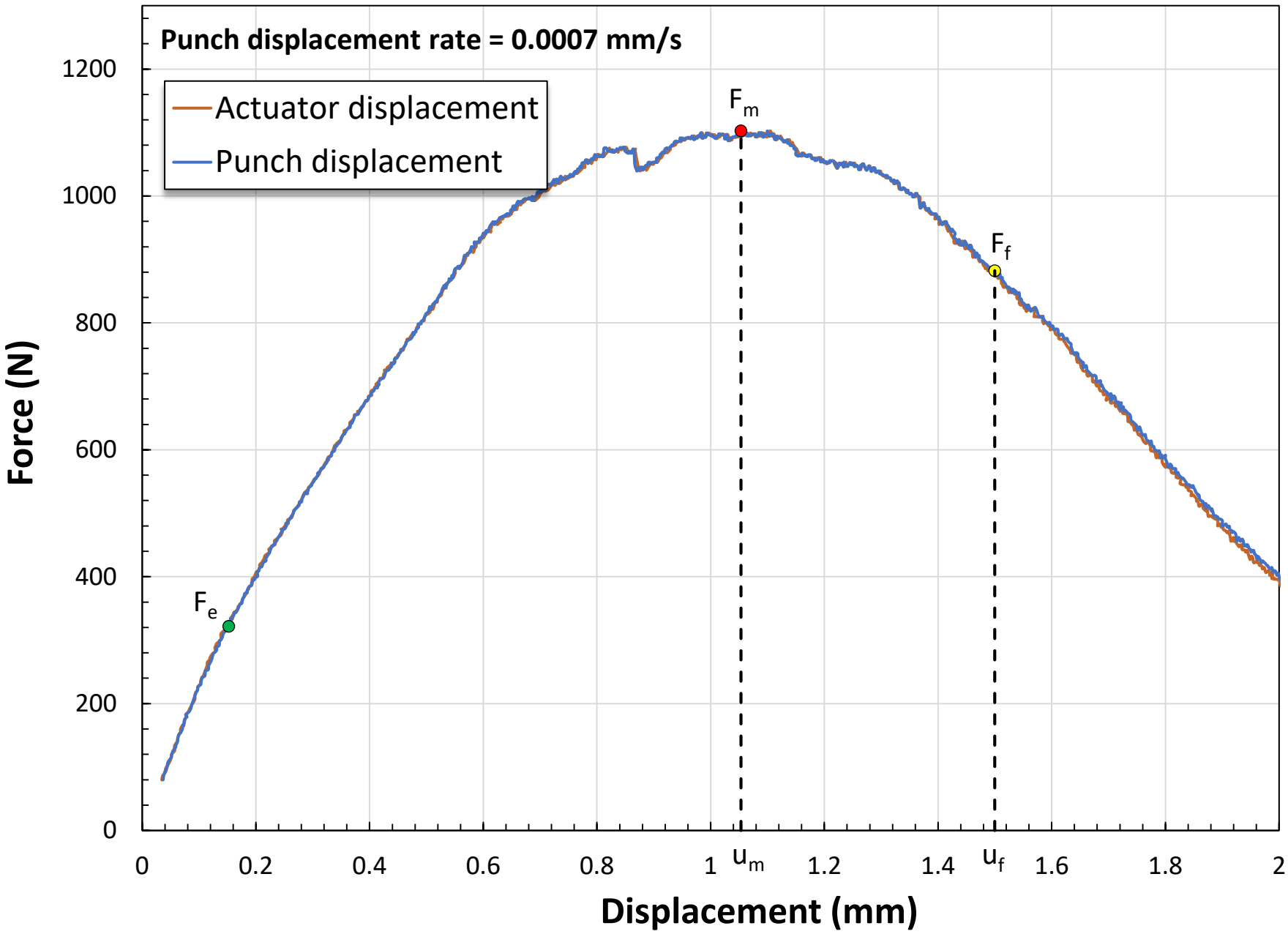

Punch displacement rate = 0.0007 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

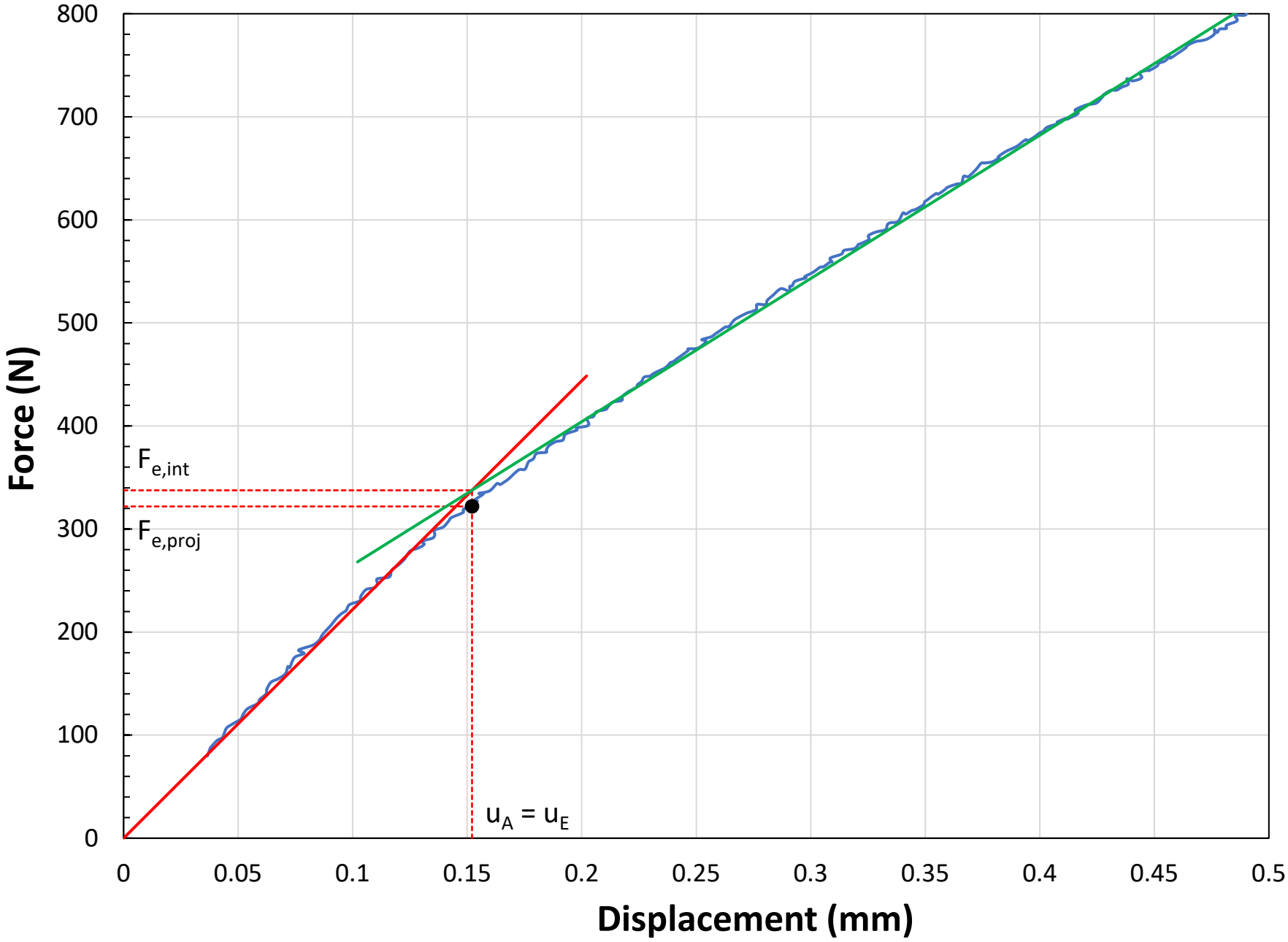

700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP2
Material: AM Ti-64
Test speed: 0.007052 mm/s
Max strain rate: 7.05E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	321.9	N
$F_{e,int}$ =	337.6	N
$F_{h0/10,off}$ =	532.4	N
$F_{0.1mm,off}$ =	714.6	N
$F_{0.1mm}$ =	226.5	N
$F_{0.48mm}$ =	785.1	N
$F_{0.5mm}$ =	814.2	N
$F_{0.65mm}$ =	977.1	N
$F_{0.9mm}$ =	1053.2	N
F_{ept} =	1069.2	N
$F_{e1.5}$ =	635.6	N
F_m =	1102.8	N
F_{infl} =	169.1	N
F_f =	882.2	N
Displacement values		
u_e =	0.152	mm
$u_{h0/10,off}$ =	0.291	mm
$u_{0.1mm,off}$ =	0.423	mm
$u_{e1.5}$ =	0.366	mm
u_m =	1.053	mm
u_{infl} =	2.299	mm
u_f =	1.500	mm
Initial linear slope		
$Slope_{ini}$ =	2219.10	N/mm
Energy values		
E_{SP} =	1.25	J
E_m =	0.79	J
E_{PL} =	0.52	J

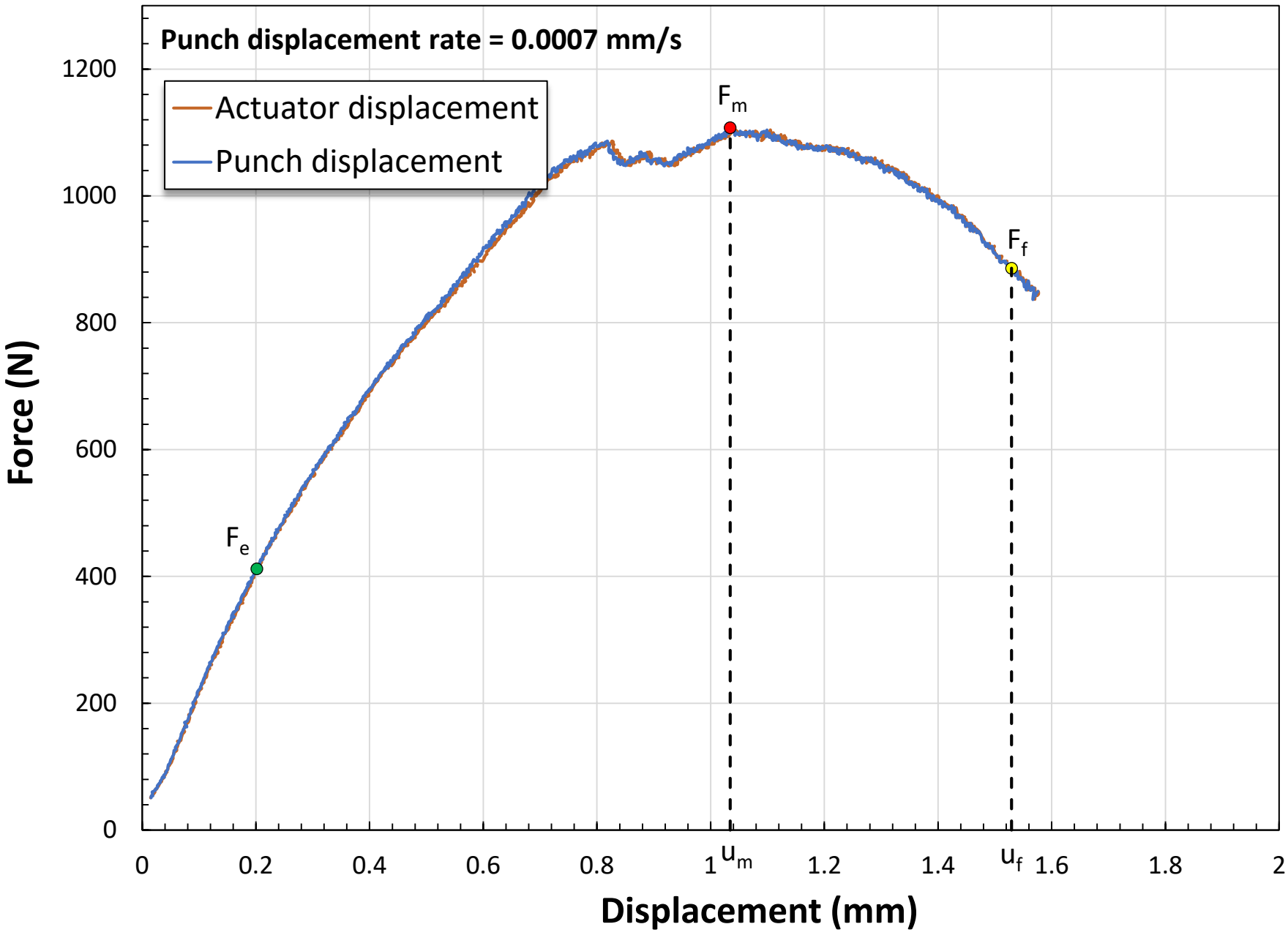

Punch displacement rate = 0.0007 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

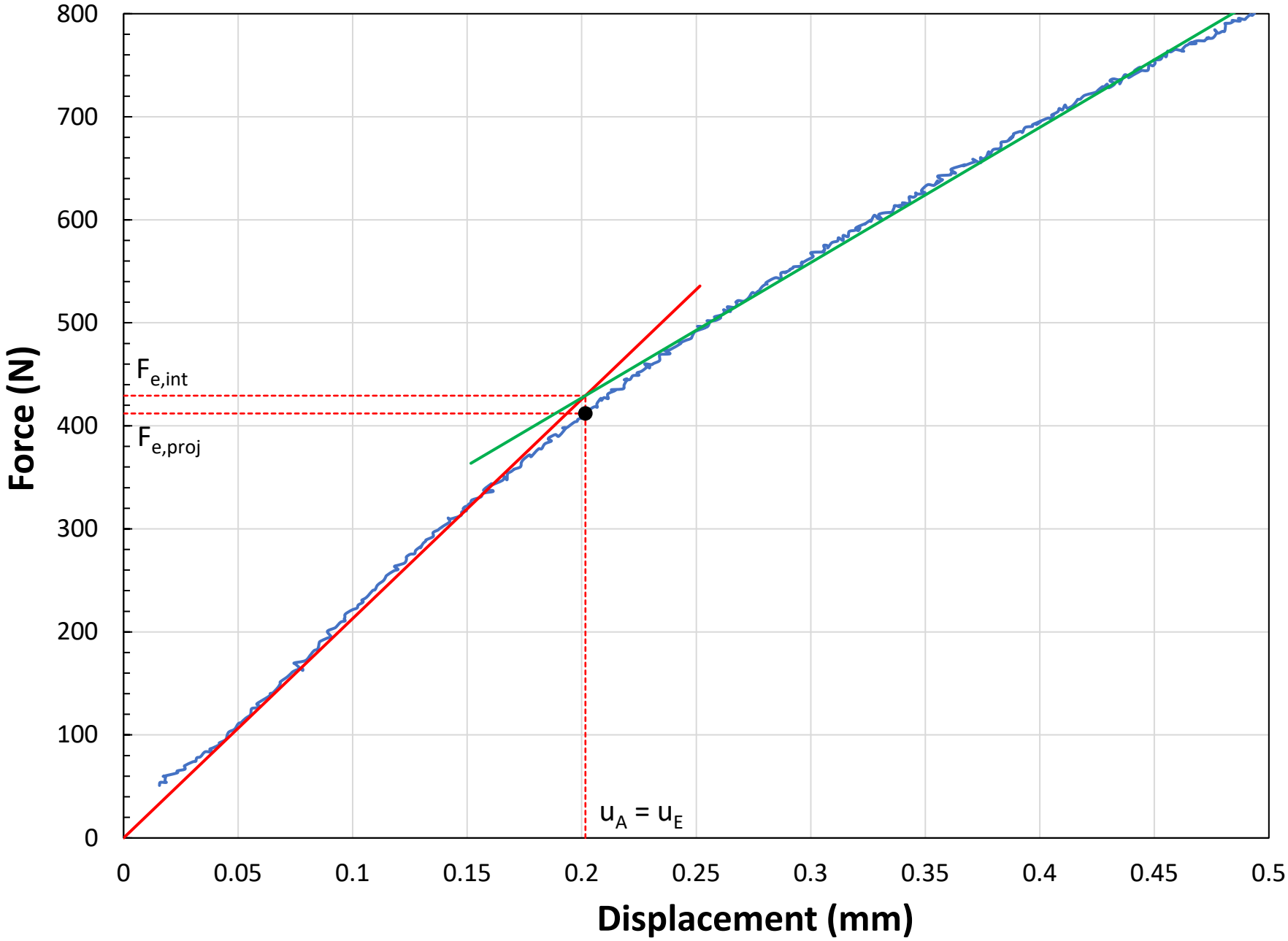

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP3
Material: AM Ti-64
Test speed: 0.002996 mm/s
Max strain rate: 3.00E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	412.0	N
$F_{e,int}$ =	429.3	N
$F_{h0/10,off}$ =	607.7	N
$F_{0.1mm,off}$ =	768.0	N
$F_{0.1mm}$ =	221.2	N
$F_{0.48mm}$ =	782.8	N
$F_{0.5mm}$ =	808.5	N
$F_{0.65mm}$ =	960.7	N
$F_{0.9mm}$ =	1057.7	N
F_{ept} =	856.8	N
$F_{e1.5}$ =	91.6	N
F_m =	1107.5	N
F_{infl} =	1080.9	N
F_f =	886.0	N
Displacement values		
u_e =	0.202	mm
$u_{h0/10,off}$ =	0.336	mm
$u_{0.1mm,off}$ =	0.463	mm
$u_{e1.5}$ =	0.042	mm
u_m =	1.034	mm
u_{infl} =	0.991	mm
u_f =	1.529	mm
Initial linear slope		
$Slope_{ini}$ =	2129.12	N/mm
Energy values		
E_{SP} =	1.28	J
E_m =	0.77	J
E_{PL} =	0.48	J

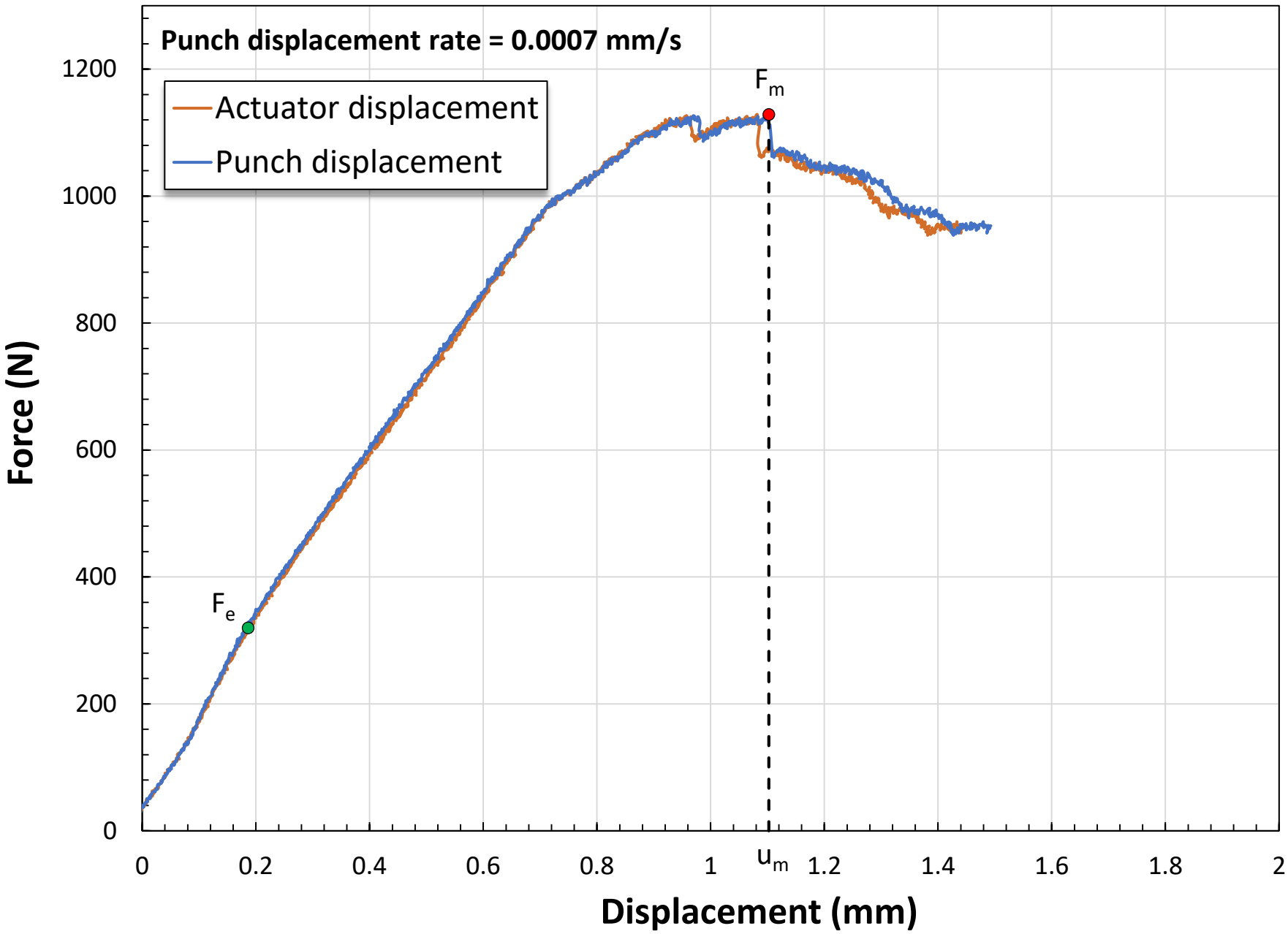

Punch displacement rate = 0.0007 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

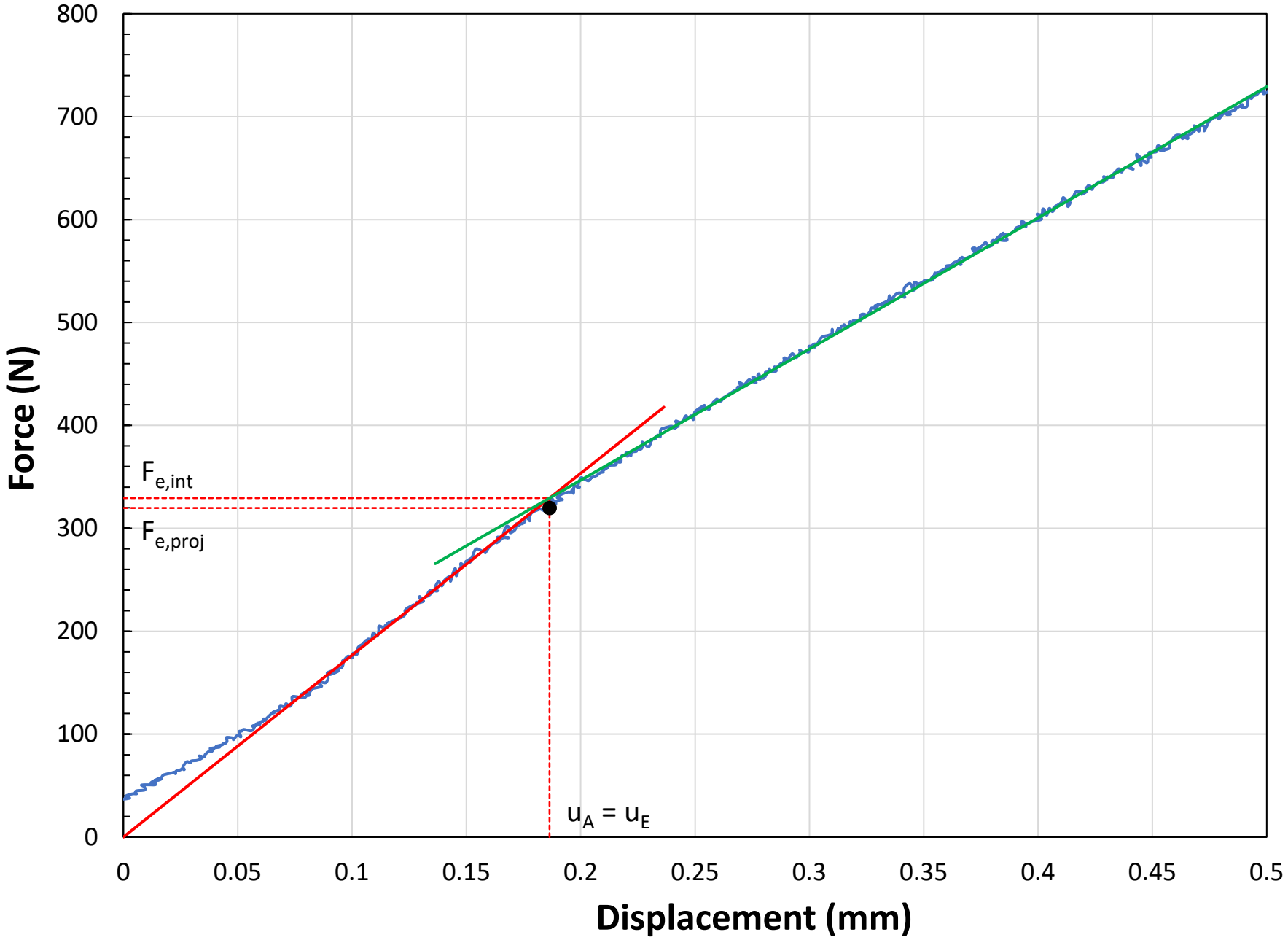

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP4
Material: AM Ti-64
Test speed: 0.000723 mm/s
Max strain rate: 7.23E-04 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	319.7	N
$F_{e,int}$ =	329.3	N
$F_{h0/10,off}$ =	557.7	N
$F_{0.1mm,off}$ =	760.7	N
$F_{0.1mm}$ =	174.1	N
$F_{0.48mm}$ =	697.7	N
$F_{0.5mm}$ =	722.3	N
$F_{0.65mm}$ =	904.2	N
$F_{0.9mm}$ =	1096.9	N
F_{ept} =	1117.1	N
$F_{e1.5}$ =	172.4	N
F_m =	1128.8	N
F_{infl} =	1122.8	N
F_f =	903.0	N
Displacement values		
u_e =	0.186	mm
$u_{h0/10,off}$ =	0.366	mm
$u_{0.1mm,off}$ =	0.532	mm
$u_{e1.5}$ =	0.097	mm
u_m =	1.102	mm
u_{infl} =	0.963	mm
u_f =		mm
Initial linear slope		
$Slope_{ini}$ =	1767.22	N/mm
Energy values		
E_{SP} =	#N/A	J
E_m =	0.80	J
E_{PL} =	0.44	J

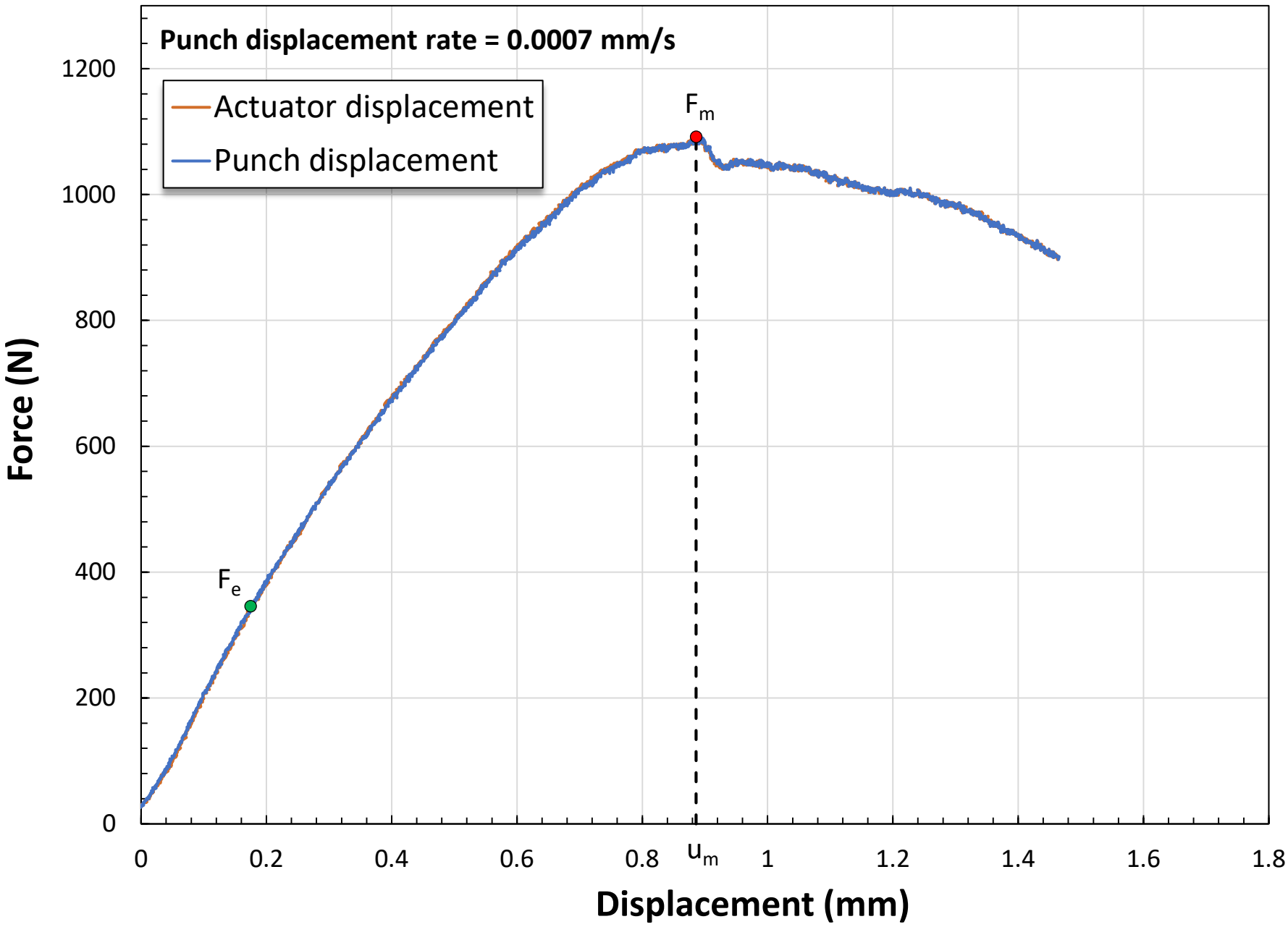

Punch displacement rate = 0.0007 mm/s
Actuator displacement
Punch displacement
F_m
F_e
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

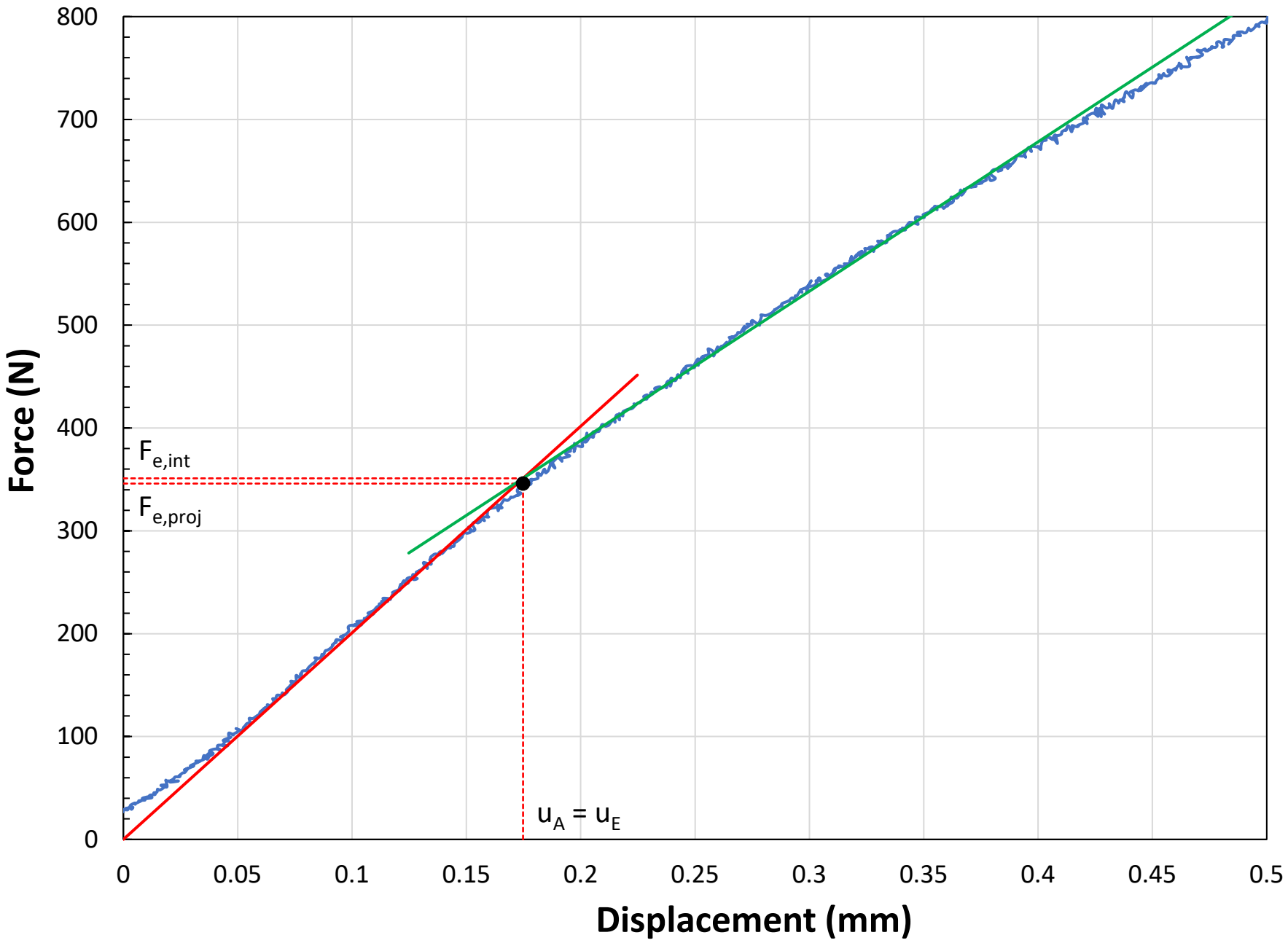

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP5
Material: AM Ti-64
Test speed: 0.007006 mm/s
Max strain rate: 7.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	346.0	N
$F_{e,int}$ =	351.1	N
$F_{h0/10,off}$ =	613.3	N
$F_{0.1mm,off}$ =	785.1	N
$F_{0.1mm}$ =	208.1	N
$F_{0.48mm}$ =	775.4	N
$F_{0.5mm}$ =	793.7	N
$F_{0.65mm}$ =	958.5	N
$F_{0.9mm}$ =	1087.4	N
F_{ept} =	543.1	N
$F_{e1.5}$ =	140.2	N
F_m =	1091.8	N
F_{infl} =	1082.4	N
F_f =	873.5	N
Displacement values		
u_e =	0.175	mm
$u_{h0/10,off}$ =	0.356	mm
$u_{0.1mm,off}$ =	0.491	mm
$u_{e1.5}$ =	0.067	mm
u_m =	0.886	mm
u_{infl} =	0.878	mm
u_f =		mm
Initial linear slope		
$Slope_{ini}$ =	2008.64	N/mm
Energy values		
E_{SP} =	#N/A	J
E_m =	0.60	J
E_{PL} =	0.30	J

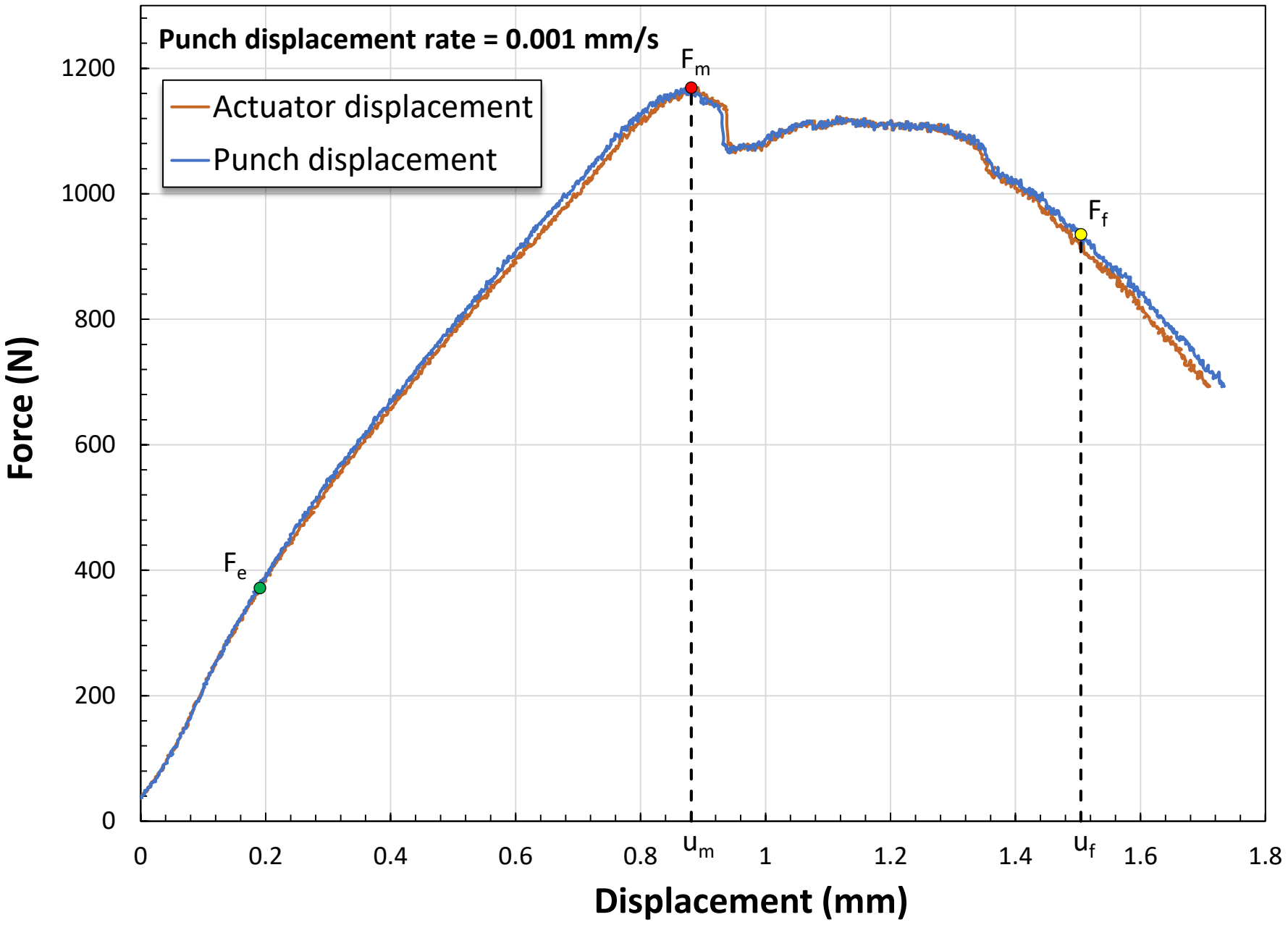

Punch displacement rate = 0.0007 mm/s
Actuator displacement
Punch displacement
F_m
F_e
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

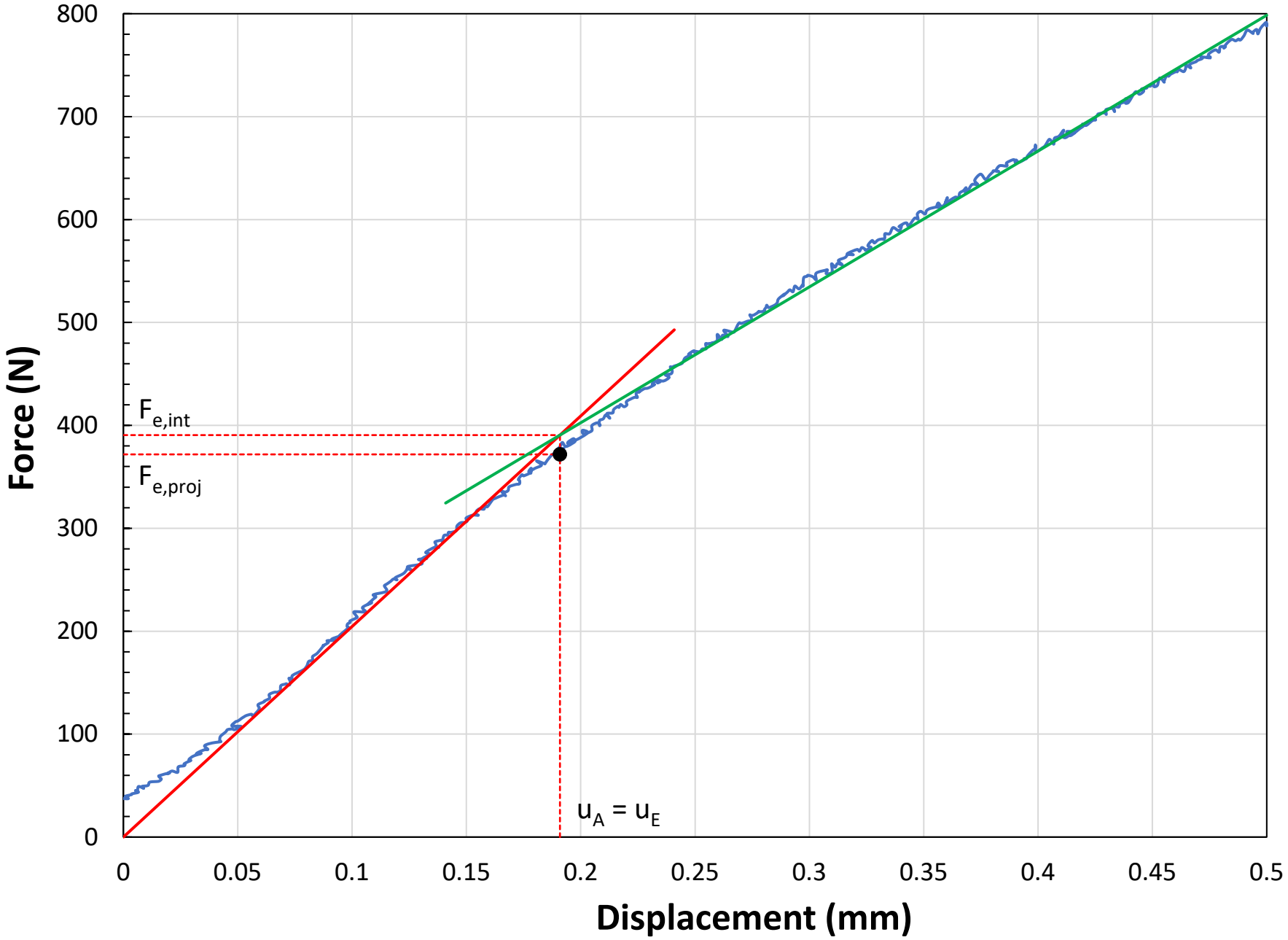

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP6
Material: AM Ti-64
Test speed: 0.001014 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	371.8	N
$F_{e,int}$ =	390.6	N
$F_{h0/10,off}$ =	590.3	N
$F_{0.1mm,off}$ =	743.8	N
$F_{0.1mm}$ =	209.9	N
$F_{0.48mm}$ =	767.7	N
$F_{0.5mm}$ =	788.2	N
$F_{0.65mm}$ =	964.4	N
$F_{0.9mm}$ =	1150.9	N
F_{ept} =	32.5	N
$F_{e1.5}$ =	170.6	N
F_m =	1169.2	N
F_{infl} =	693.0	N
F_f =	935.3	N
Displacement values		
u_e =	0.191	mm
$u_{h0/10,off}$ =	0.339	mm
$u_{0.1mm,off}$ =	0.464	mm
$u_{e1.5}$ =	0.081	mm
u_m =	0.881	mm
u_{infl} =	1.734	mm
u_f =	1.505	mm
Initial linear slope		
$Slope_{ini}$ =	2045.64	N/mm
Energy values		
E_{SP} =	1.28	J
E_m =	0.61	J
E_{PL} =	0.27	J

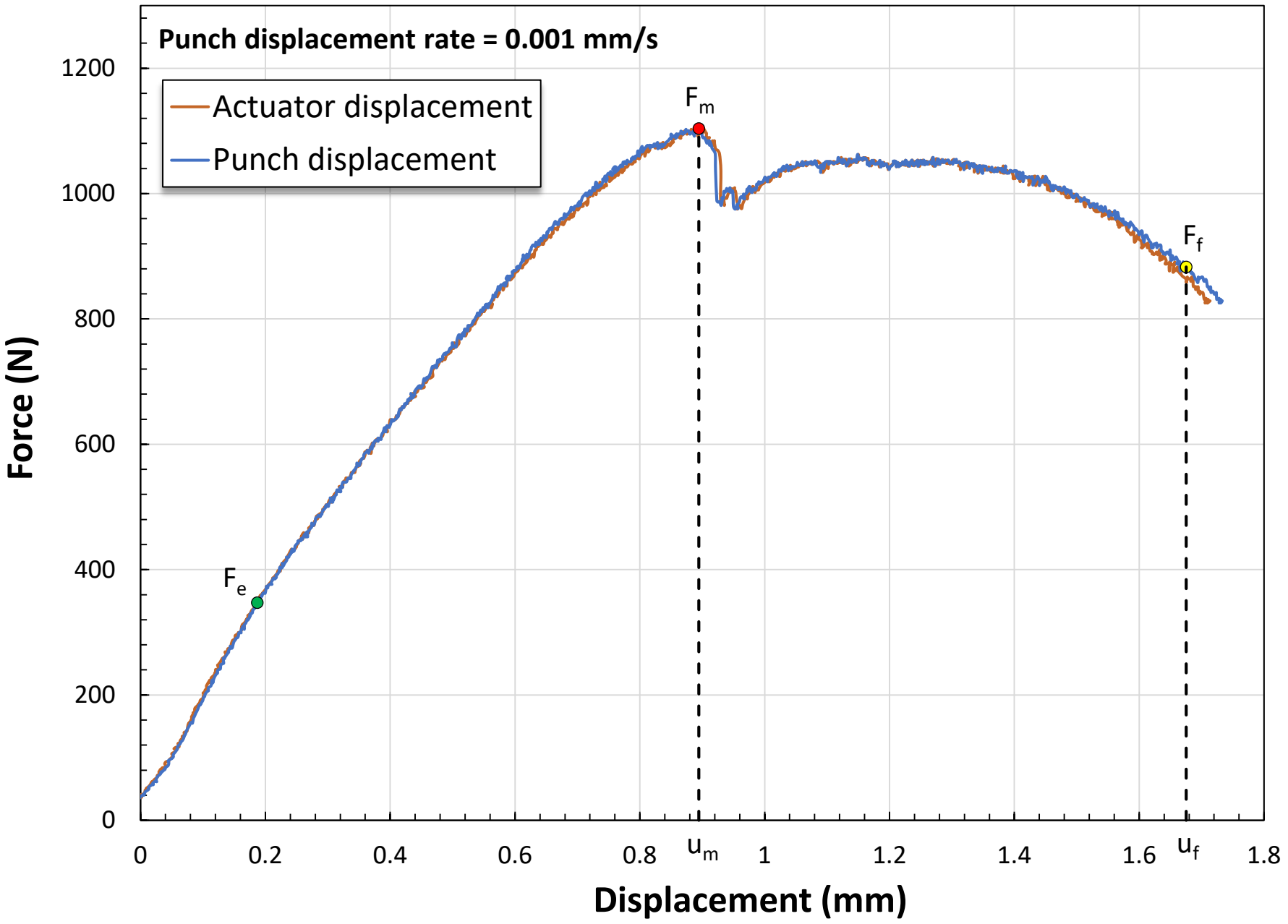

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

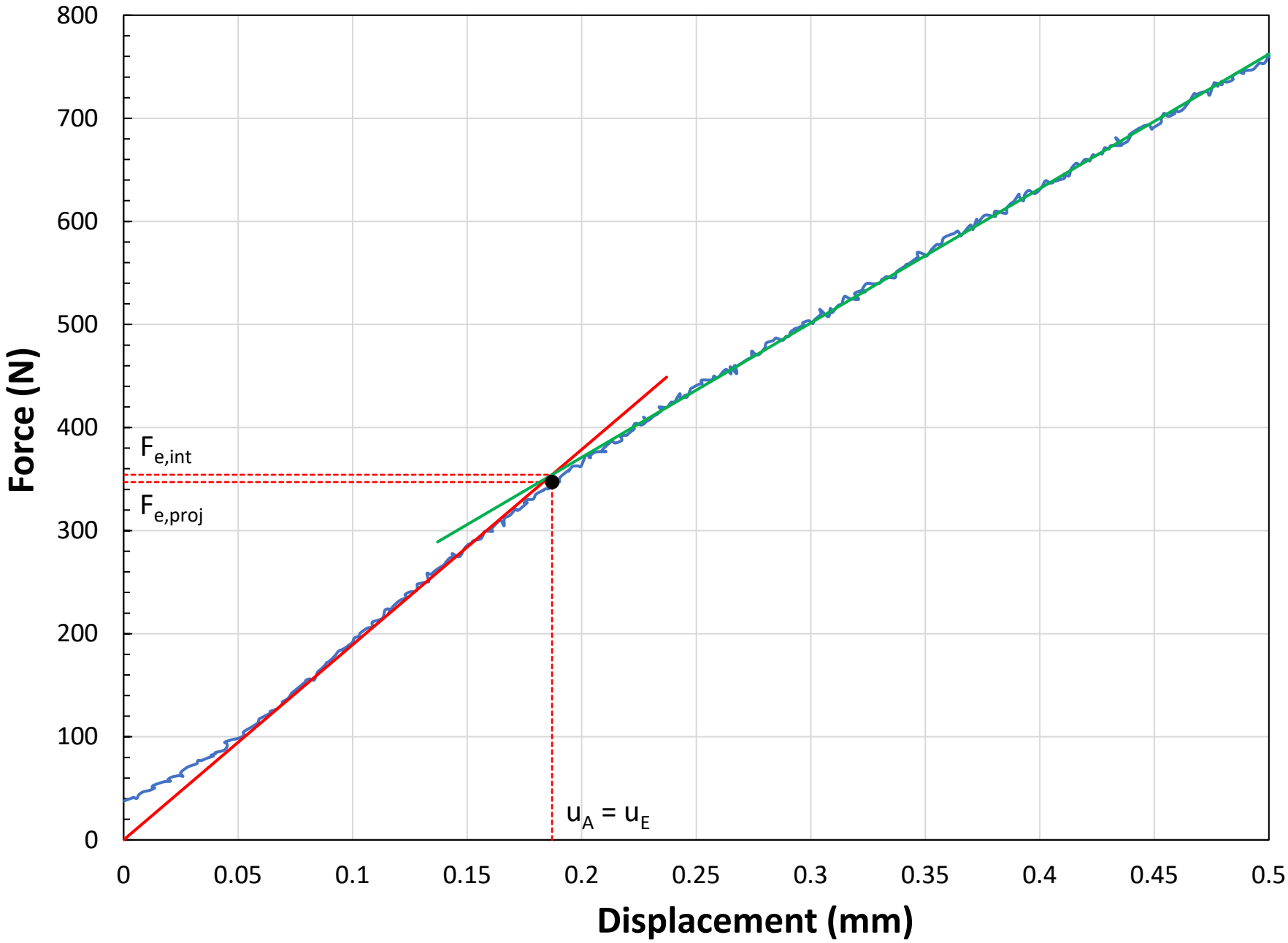

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP7
Material: AM Ti-64
Test speed: 0.001006 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	347.1	N
$F_{e,int}$ =	354.2	N
$F_{h0/10,off}$ =	567.8	N
$F_{0.1mm,off}$ =	753.2	N
$F_{0.1mm}$ =	191.7	N
$F_{0.48mm}$ =	735.9	N
$F_{0.5mm}$ =	762.0	N
$F_{0.65mm}$ =	929.8	N
$F_{0.9mm}$ =	1092.3	N
F_{ept} =	326.7	N
$F_{e1.5}$ =	164.9	N
F_m =	1103.7	N
F_{infl} =	446.2	N
F_f =	882.9	N
Displacement values		
u_e =	0.187	mm
$u_{h0/10,off}$ =	0.351	mm
$u_{0.1mm,off}$ =	0.498	mm
$u_{e1.5}$ =	0.086	mm
u_m =	0.894	mm
u_{infl} =	0.257	mm
u_f =	1.675	mm
Initial linear slope		
$Slope_{ini}$ =	1893.58	N/mm
Energy values		
E_{SP} =	1.38	J
E_m =	0.59	J
E_{PL} =	0.27	J

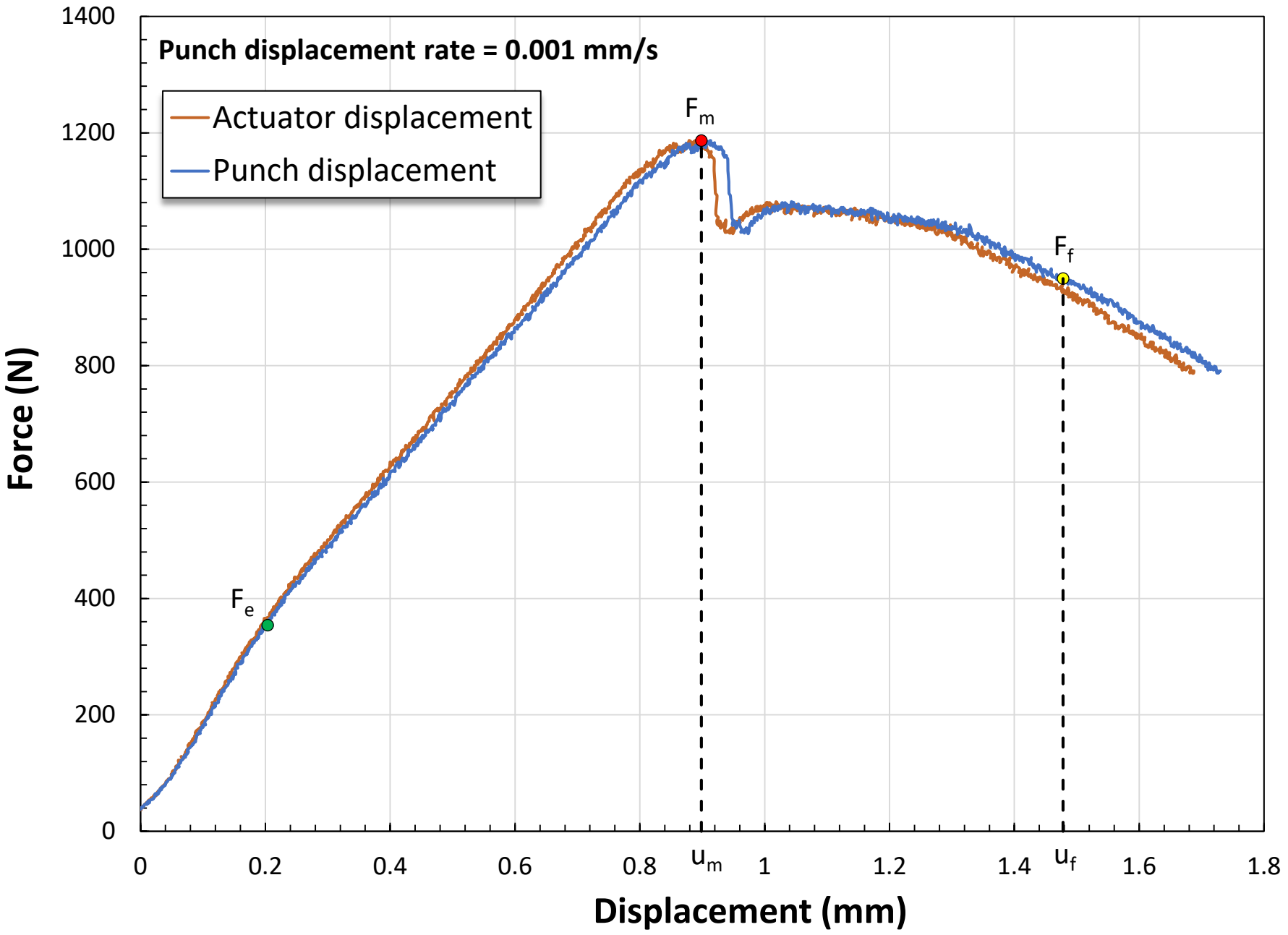

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

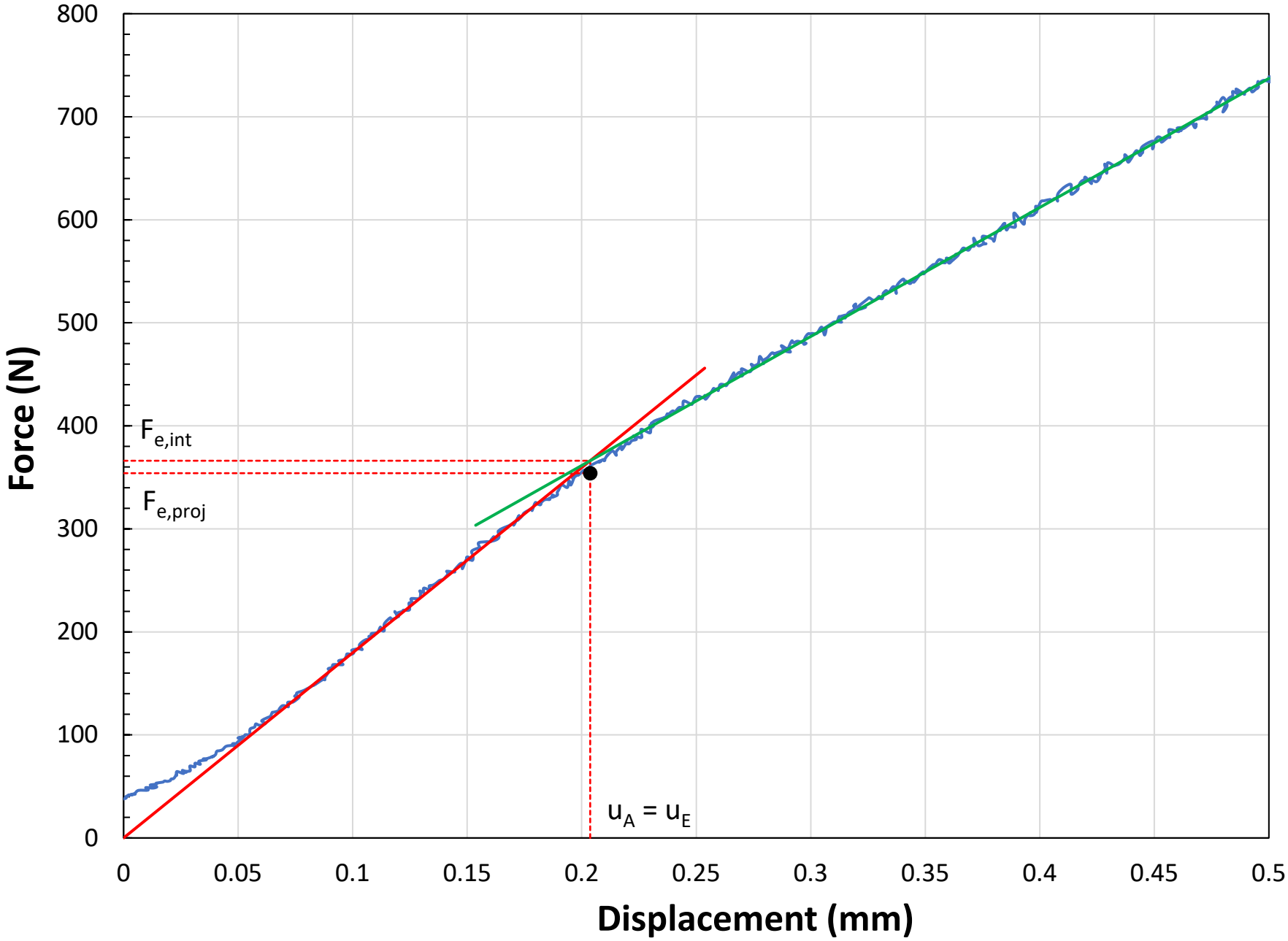

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP8
Material: AM Ti-64
Test speed: 0.001025 mm/s
Max strain rate: 1.02E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	354.0	N
$F_{e,int}$ =	366.1	N
$F_{h0/10,off}$ =	560.1	N
$F_{0.1mm,off}$ =	782.2	N
$F_{0.1mm}$ =	182.3	N
$F_{0.48mm}$ =	704.7	N
$F_{0.5mm}$ =	735.4	N
$F_{0.65mm}$ =	928.1	N
$F_{0.9mm}$ =	1186.9	N
F_{ept} =	855.9	N
$F_{e1.5}$ =	199.5	N
F_m =	1186.9	N
F_{infl} =	790.2	N
F_f =	949.5	N
Displacement values		
u_e =	0.204	mm
$u_{h0/10,off}$ =	0.362	mm
$u_{0.1mm,off}$ =	0.535	mm
$u_{e1.5}$ =	0.111	mm
u_m =	0.899	mm
u_{infl} =	1.729	mm
u_f =	1.478	mm
Initial linear slope		
$Slope_{ini}$ =	1797.35	N/mm
Energy values		
E_{SP} =	1.20	J
E_m =	0.59	J
E_{PL} =	0.20	J

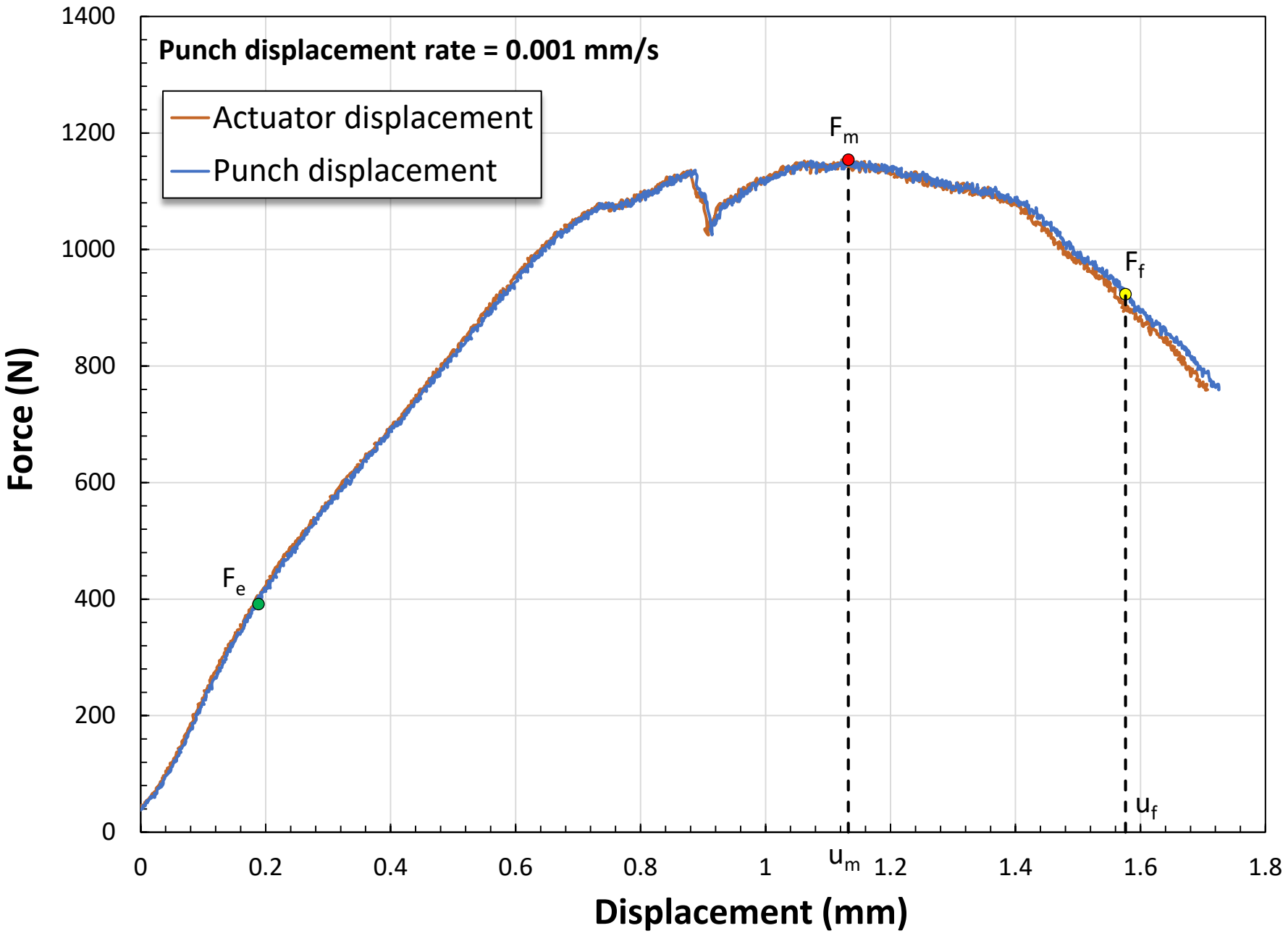

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
1400
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

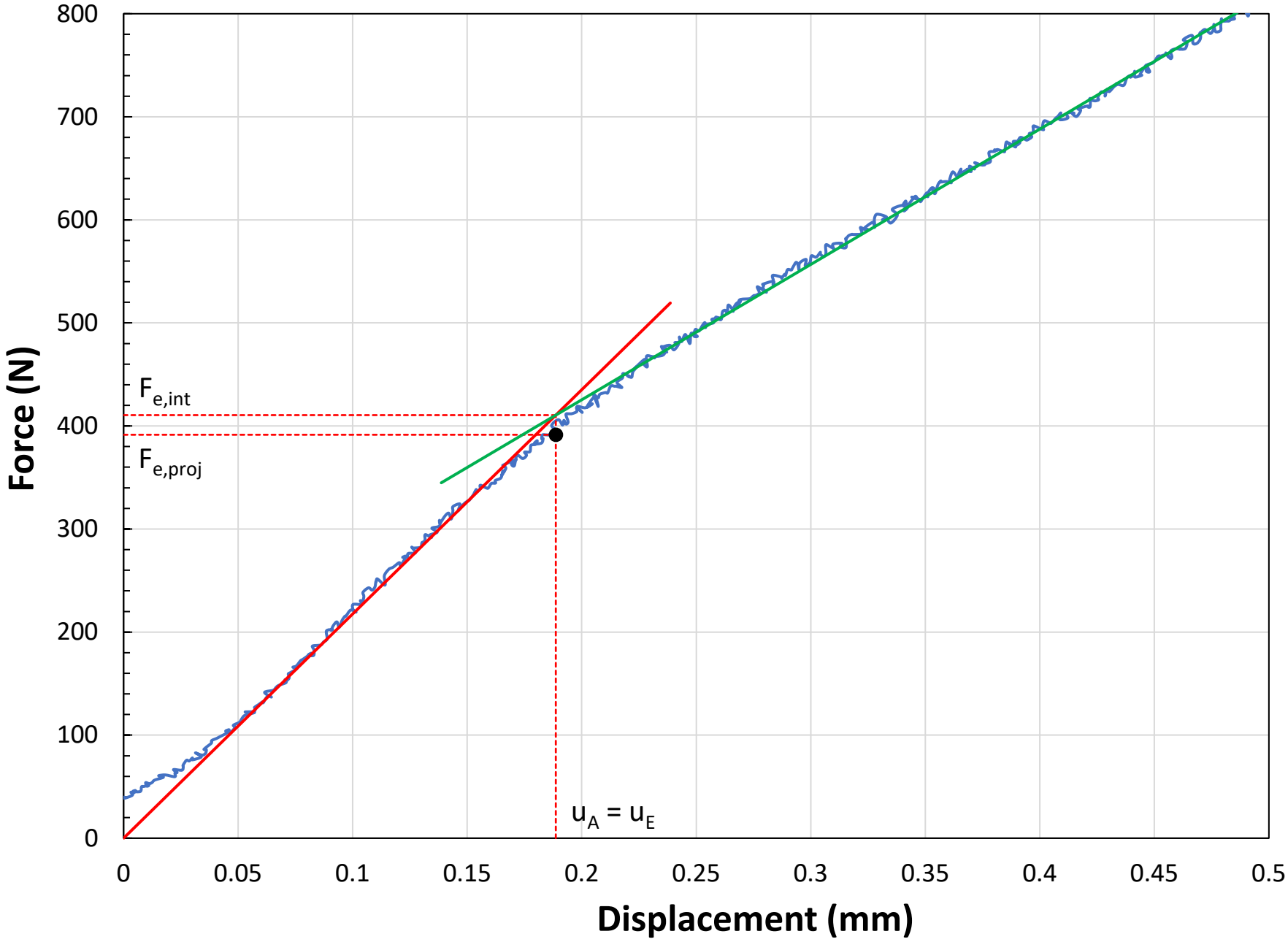

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP9
Material: AM Ti-64
Test speed: 0.001009 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	391.5	N
$F_{e,int}$ =	410.5	N
$F_{h0/10,off}$ =	575.3	N
$F_{0.1mm,off}$ =	730.7	N
$F_{0.1mm}$ =	221.4	N
$F_{0.48mm}$ =	792.9	N
$F_{0.5mm}$ =	816.7	N
$F_{0.65mm}$ =	1006.7	N
$F_{0.9mm}$ =	1094.7	N
F_{ept} =	1120.6	N
$F_{e1.5}$ =	187.6	N
F_m =	1154.0	N
F_{infl} =	1066.3	N
F_f =	923.2	N
Displacement values		
u_e =	0.189	mm
$u_{h0/10,off}$ =	0.315	mm
$u_{0.1mm,off}$ =	0.436	mm
$u_{e1.5}$ =	0.086	mm
u_m =	1.132	mm
u_{infl} =	1.428	mm
u_f =	1.576	mm
Initial linear slope		
$Slope_{ini}$ =	2175.63	N/mm
Energy values		
E_{SP} =	1.37	J
E_m =	0.90	J
E_{PL} =	0.59	J

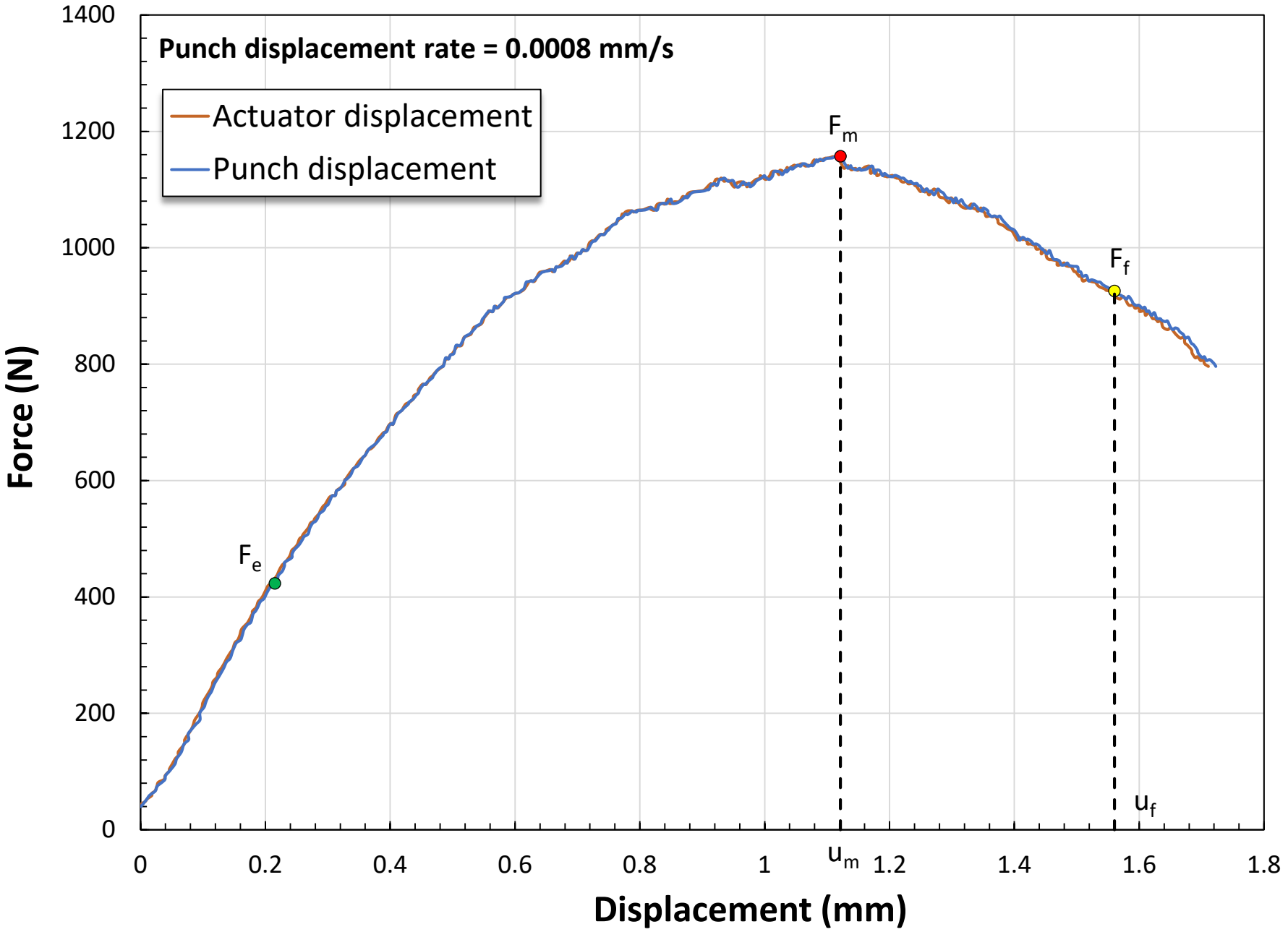

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
Force (N)
Displacement (mm)
1400
1200
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
F_m
F_f
F_e
u_f
u_m

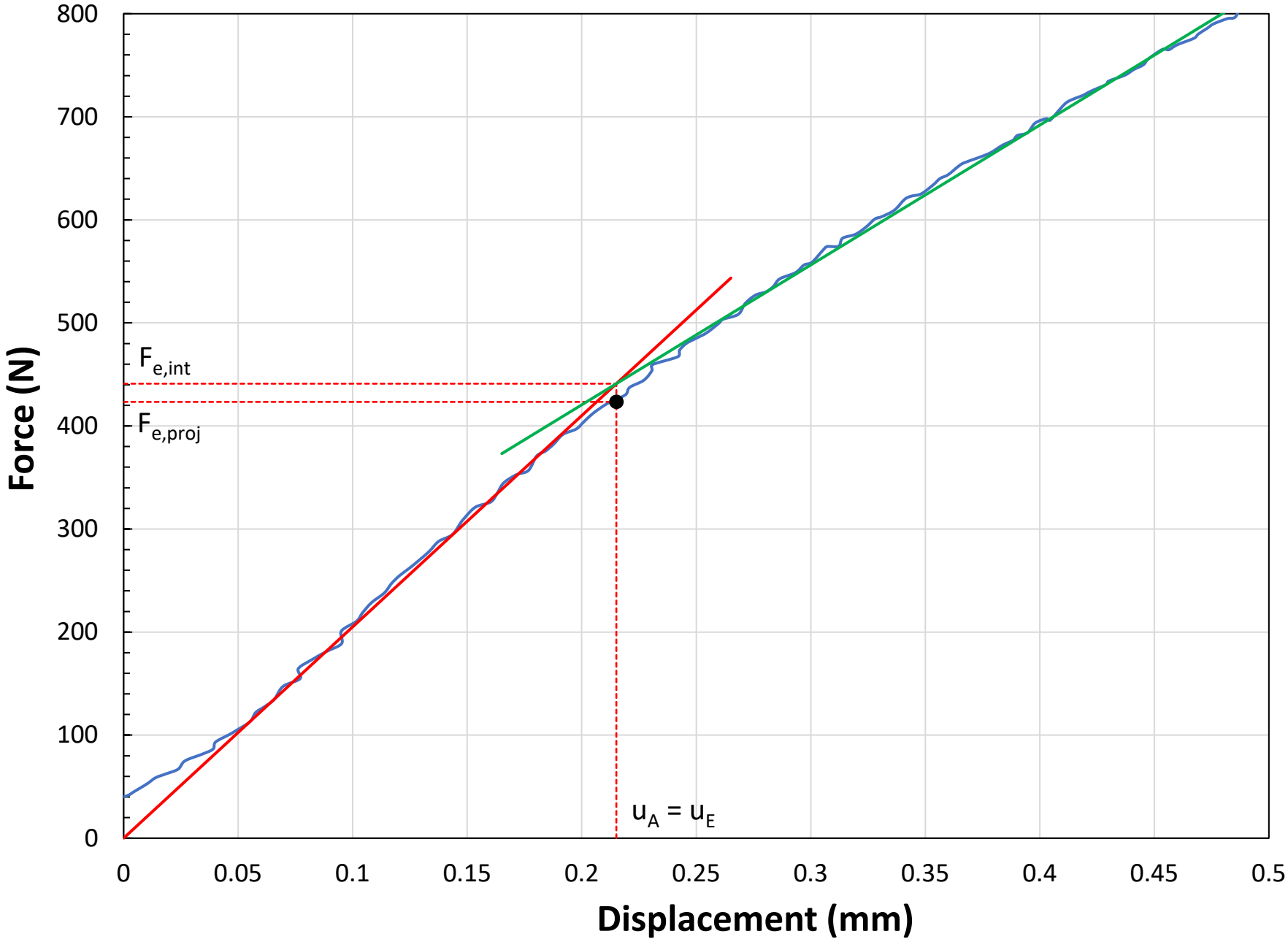

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_2_S_a_SP10
Material: AM Ti-64
Test speed: 0.008383 mm/s
Max strain rate: 8.38E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	423.4	N
$F_{e,int}$ =	441.0	N
$F_{h0/10,off}$ =	661.4	N
$F_{0.1mm,off}$ =	821.2	N
$F_{0.1mm}$ =	201.1	N
$F_{0.48mm}$ =	790.3	N
$F_{0.5mm}$ =	815.8	N
$F_{0.65mm}$ =	959.7	N
$F_{0.9mm}$ =	1097.1	N
F_{ept} =	977.1	N
$F_{e1.5}$ =	164.5	N
F_m =	1157.3	N
F_{infl} =	720.7	N
F_f =	925.8	N
Displacement values		
u_e =	0.215	mm
$u_{h0/10,off}$ =	0.373	mm
$u_{0.1mm,off}$ =	0.502	mm
$u_{e1.5}$ =	0.076	mm
u_m =	1.121	mm
u_{infl} =	0.419	mm
u_f =	1.560	mm
Initial linear slope		
$Slope_{ini}$ =	2050.10	N/mm
Energy values		
E_{SP} =	1.34	J
E_m =	0.87	J
E_{PL} =	0.55	J


Punch displacement rate = 0.0008 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
1400
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

ANNEX 2

SP Test Results for

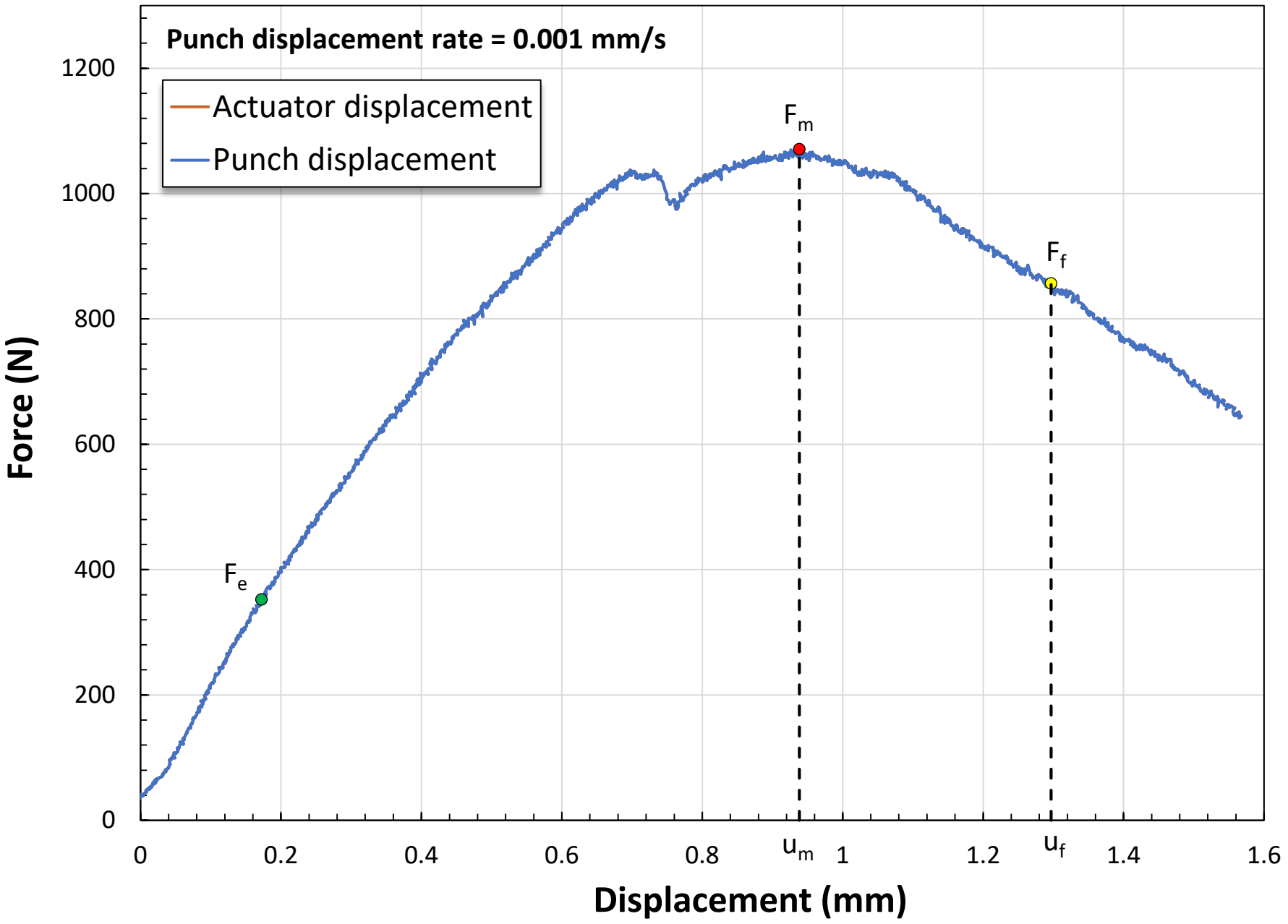
As built, scan length = 78 mm, non-supported

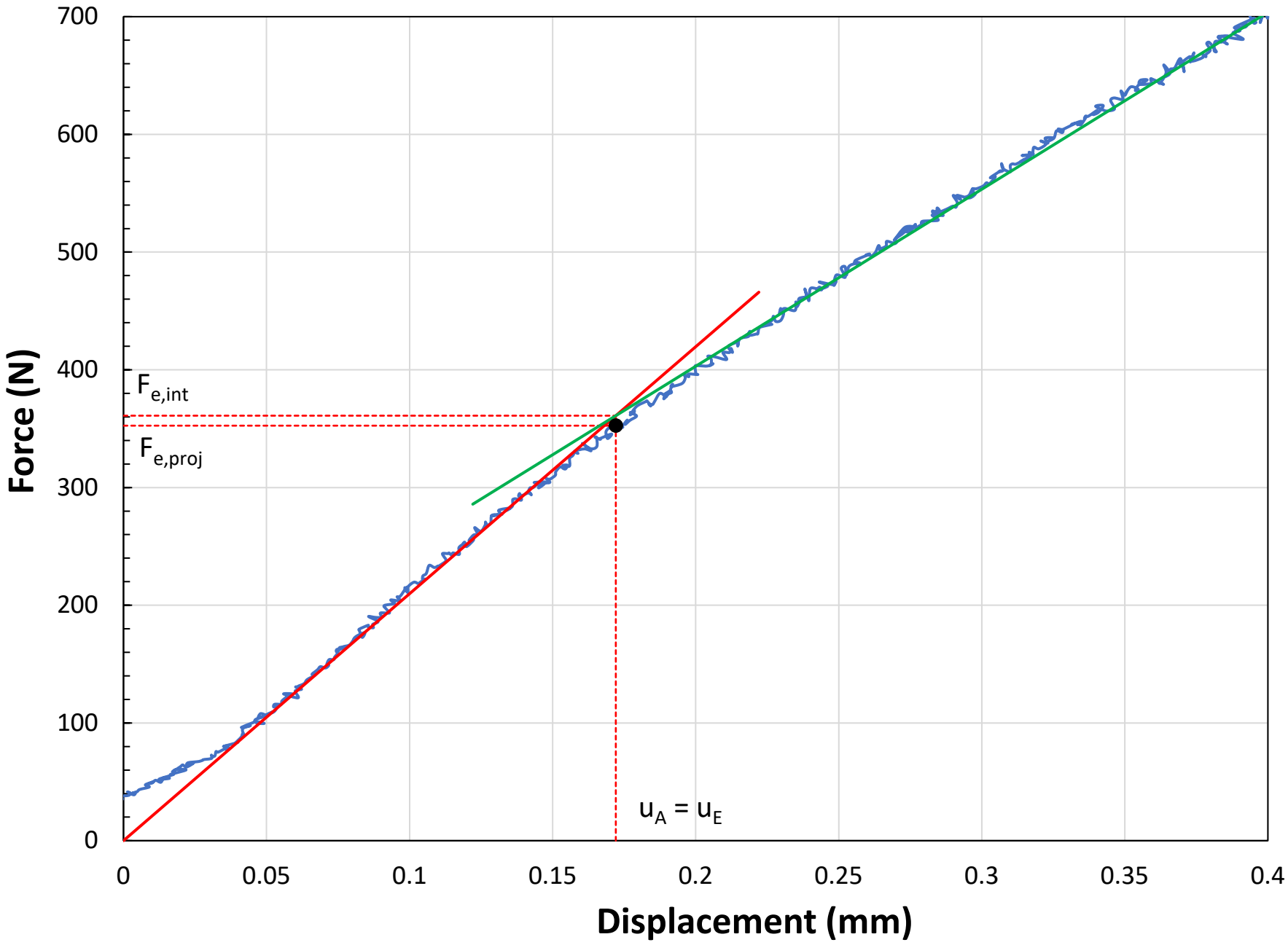
(“rough” specimens)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP1
Material: AM Ti-64
Test speed: 0.000934 mm/s
Max strain rate: 9.34E-04 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	352.6	N
$F_{e,int}$ =	361.0	N
$F_{h0/10,off}$ =	621.7	N
$F_{0.1mm,off}$ =	808.2	N
$F_{0.1mm}$ =	216.0	N
$F_{0.48mm}$ =	807.1	N
$F_{0.5mm}$ =	831.2	N
$F_{0.65mm}$ =	995.7	N
$F_{0.9mm}$ =	1057.2	N
F_{ept} =	23.9	N
$F_{e1.5}$ =	155.8	N
F_m =	1070.8	N
F_{infl} =	645.2	N
F_f =	856.7	N
Displacement values		
u_e =	0.172	mm
$u_{h0/10,off}$ =	0.346	mm
$u_{0.1mm,off}$ =	0.487	mm
$u_{e1.5}$ =	0.074	mm
u_m =	0.938	mm
u_{infl} =	1.568	mm
u_f =	1.297	mm
Initial linear slope		
$Slope_{ini}$ =	2098.05	N/mm
Energy values		
E_{SP} =	1.02	J
E_m =	0.67	J
E_{PL} =	0.39	J

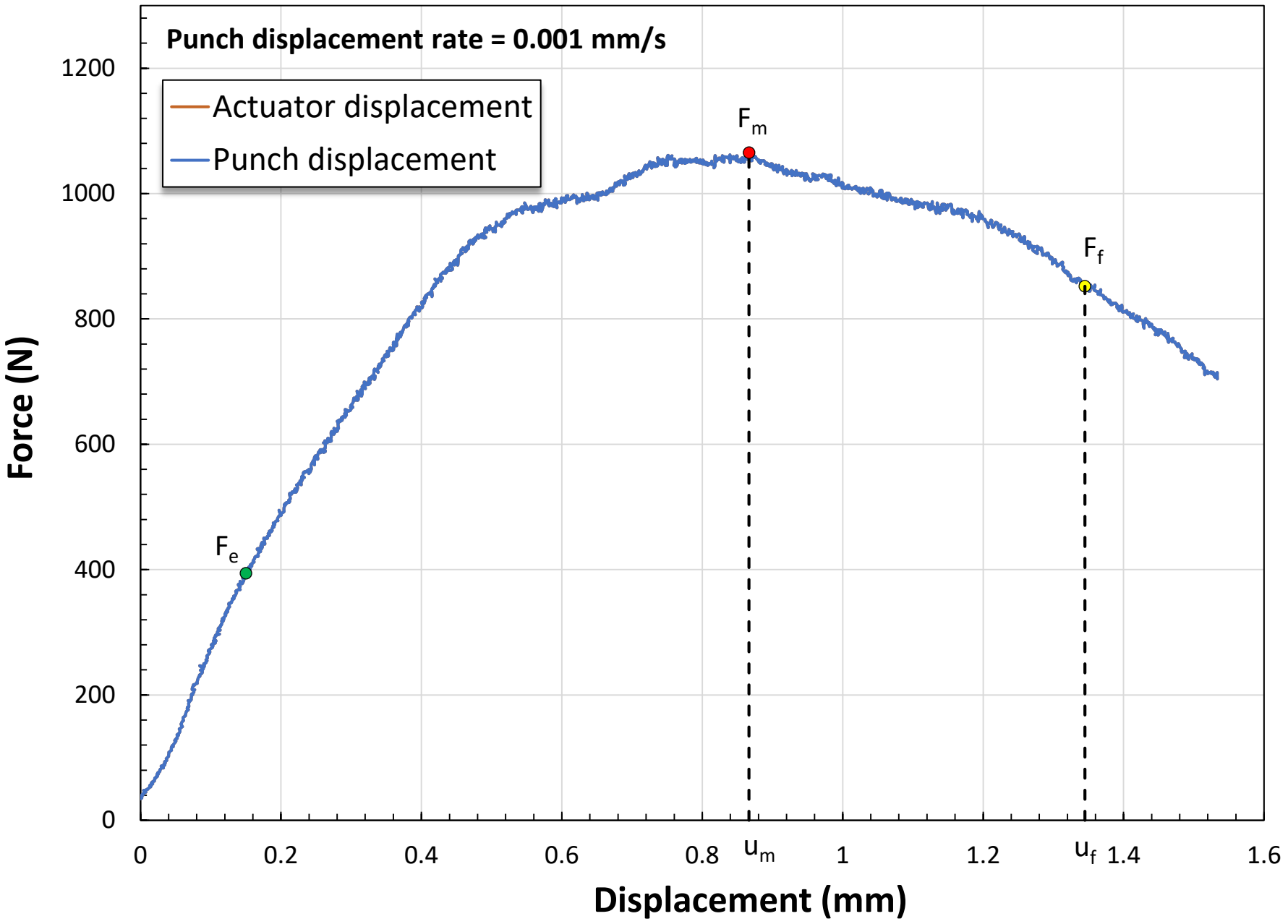

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

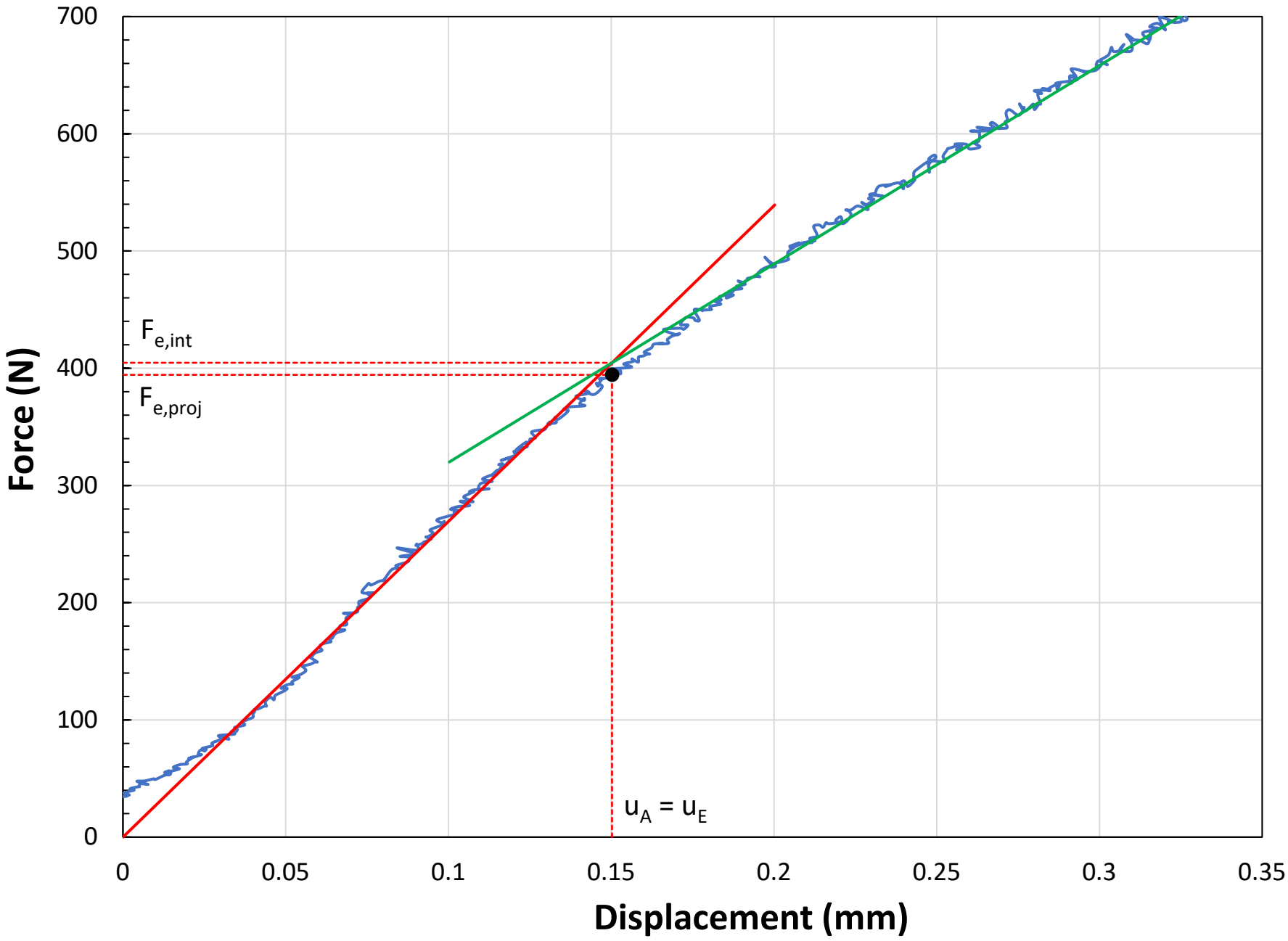

700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP2
Material: AM Ti-64
Test speed: 0.000927 mm/s
Max strain rate: 9.27E-04 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	394.4	N
$F_{e,int}$ =	404.7	N
$F_{h0/10,off}$ =	638.2	N
$F_{0.1mm,off}$ =	841.7	N
$F_{0.1mm}$ =	271.0	N
$F_{0.48mm}$ =	930.2	N
$F_{0.5mm}$ =	944.1	N
$F_{0.65mm}$ =	996.4	N
$F_{0.9mm}$ =	1047.2	N
F_{ept} =	704.5	N
$F_{e1.5}$ =	190.1	N
F_m =	1065.2	N
F_{infl} =	1038.6	N
F_f =	852.2	N
Displacement values		
u_e =	0.150	mm
$u_{h0/10,off}$ =	0.287	mm
$u_{0.1mm,off}$ =	0.413	mm
$u_{e1.5}$ =	0.070	mm
u_m =	0.866	mm
u_{infl} =	0.902	mm
u_f =	1.345	mm
Initial linear slope		
$Slope_{ini}$ =	2693.16	N/mm
Energy values		
E_{SP} =	1.11	J
E_m =	0.65	J
E_{PL} =	0.44	J

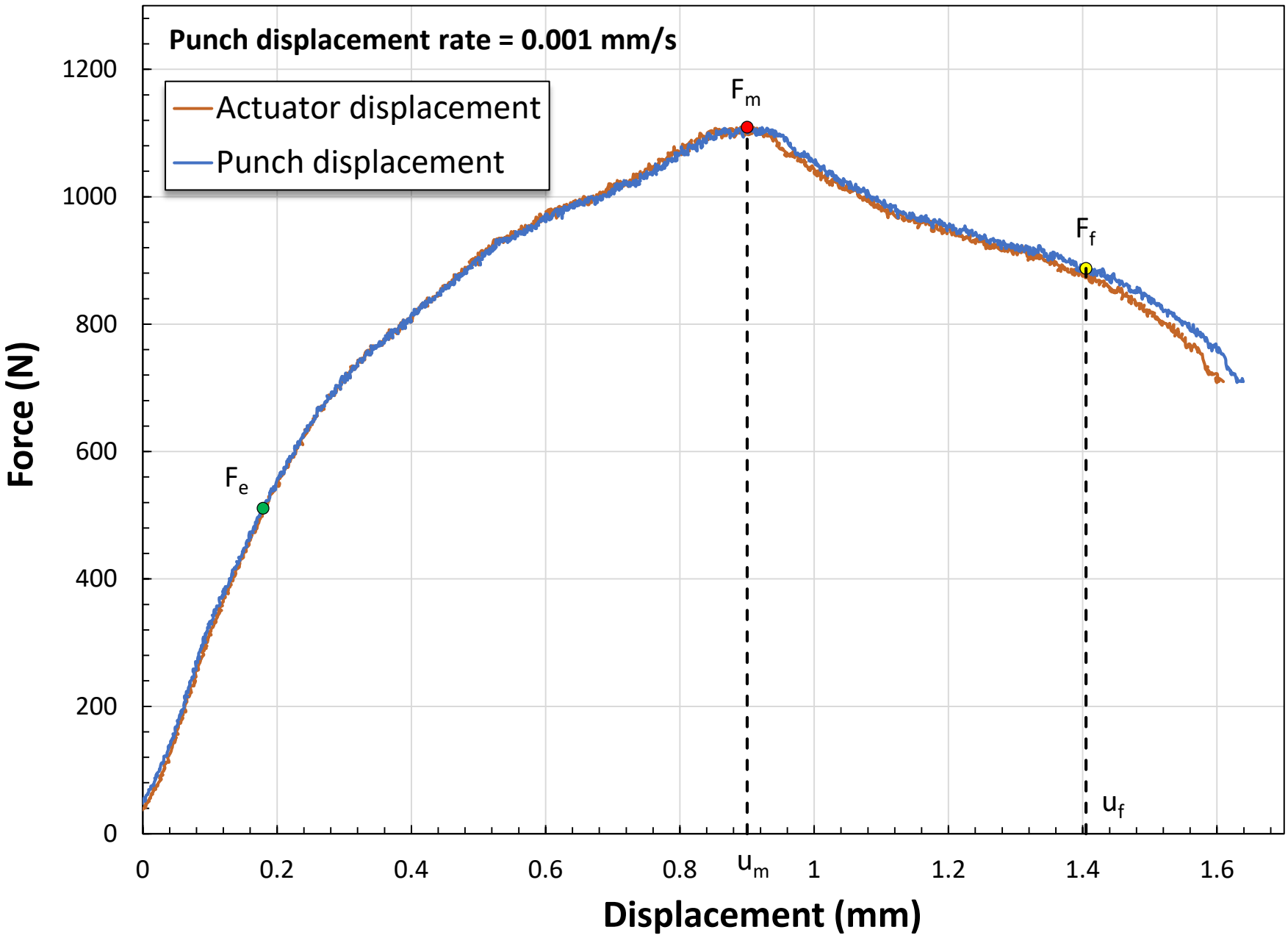

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
u_m
1
1.2
u_f
1.4
1.6

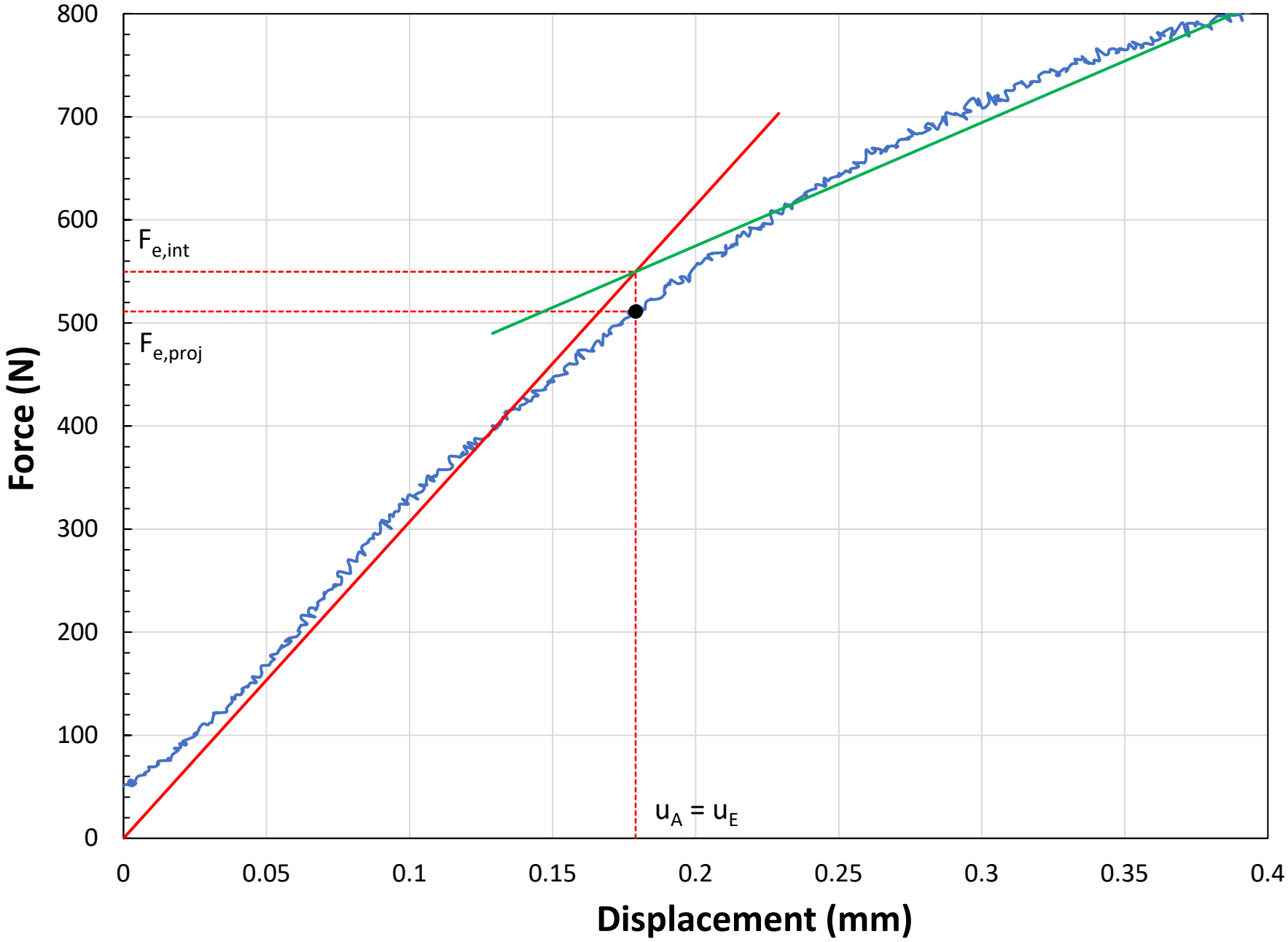

700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP4
Material: AM Ti-64
Test speed: 0.000964 mm/s
Max strain rate: 9.64E-04 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	511.2	N
$F_{e,int}$ =	549.7	N
$F_{h0/10,off}$ =	674.5	N
$F_{0.1mm,off}$ =	767.8	N
$F_{0.1mm}$ =	333.2	N
$F_{0.48mm}$ =	884.0	N
$F_{0.5mm}$ =	901.6	N
$F_{0.65mm}$ =	986.5	N
$F_{0.9mm}$ =	1103.1	N
F_{ept} =	792.6	N
$F_{e1.5}$ =	732.4	N
F_m =	1109.4	N
F_{infl} =	709.8	N
F_f =	887.5	N
Displacement values		
u_e =	0.179	mm
$u_{h0/10,off}$ =	0.271	mm
$u_{0.1mm,off}$ =	0.351	mm
$u_{e1.5}$ =	0.317	mm
u_m =	0.900	mm
u_{infl} =	1.639	mm
u_f =	1.405	mm
Initial linear slope		
$Slope_{ini}$ =	3070.90	N/mm
Energy values		
E_{SP} =	1.19	J
E_m =	0.69	J
E_{PL} =	0.49	J

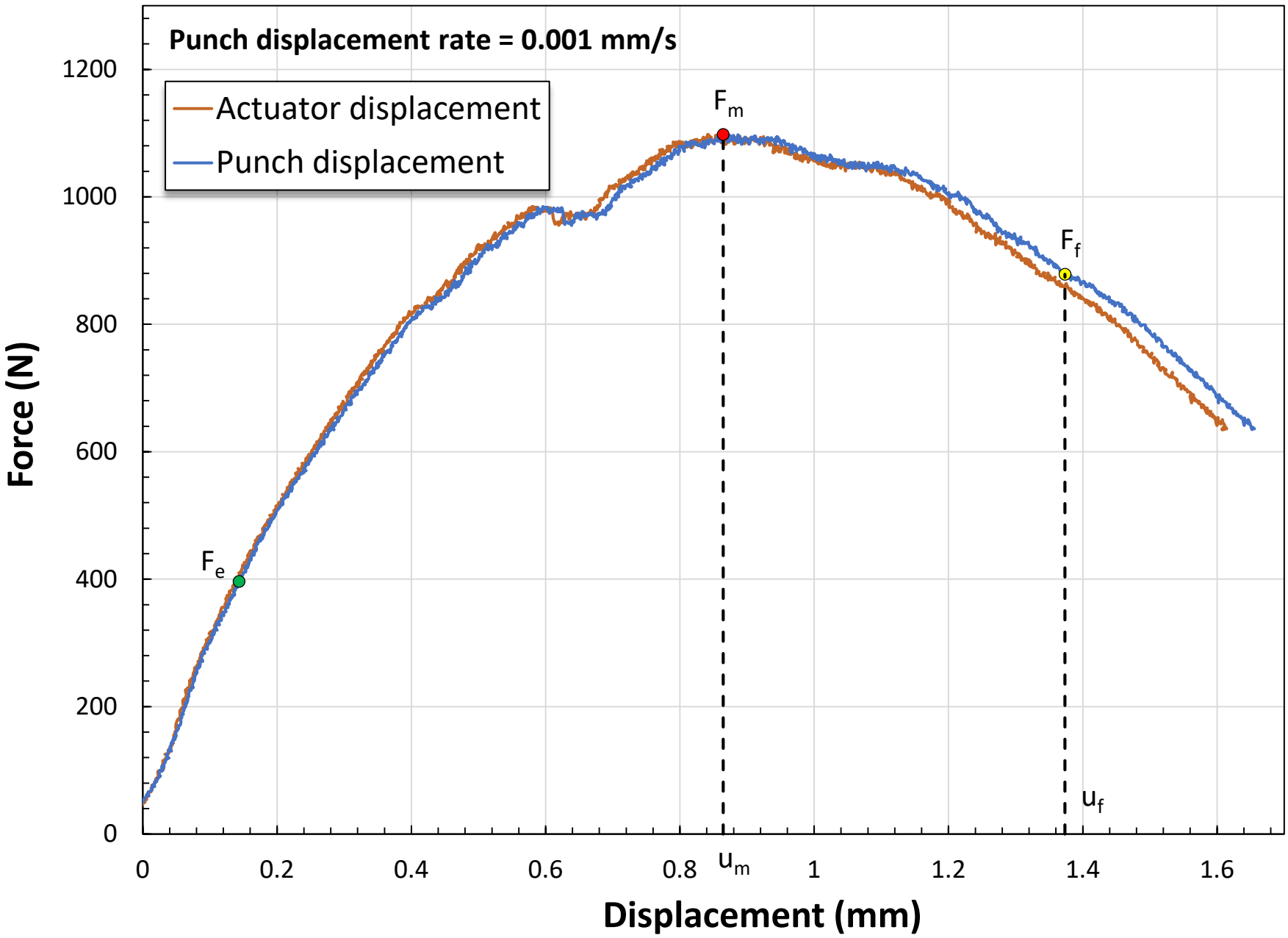

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

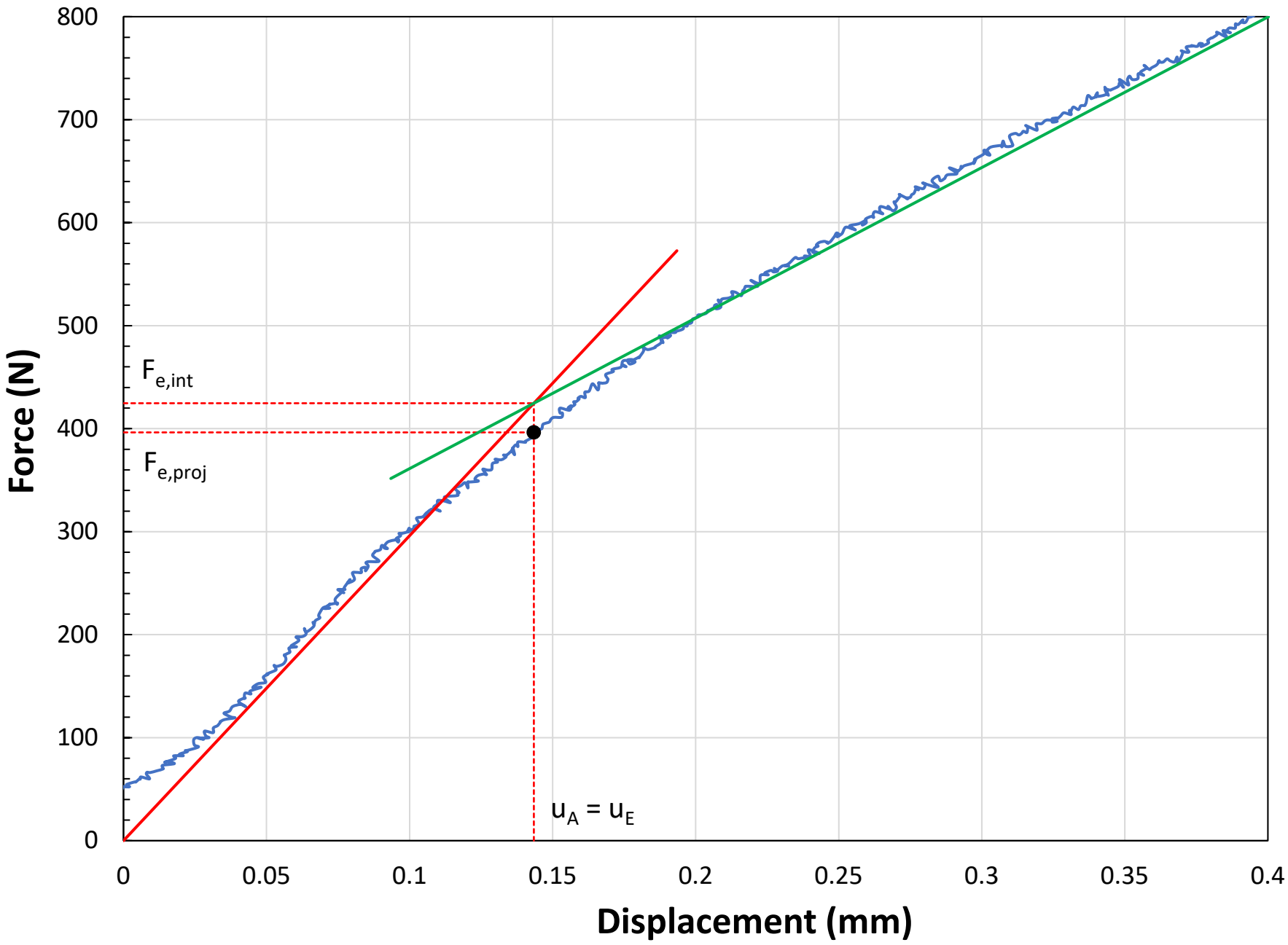

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP5
Material: AM Ti-64
Test speed: 0.000964 mm/s
Max strain rate: 9.64E-04 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	396.4	N
$F_{e,int}$ =	424.7	N
$F_{h0/10,off}$ =	571.1	N
$F_{0.1mm,off}$ =	732.9	N
$F_{0.1mm}$ =	299.7	N
$F_{0.48mm}$ =	879.4	N
$F_{0.5mm}$ =	899.0	N
$F_{0.65mm}$ =	973.8	N
$F_{0.9mm}$ =	1088.7	N
F_{ept} =	887.5	N
$F_{e1.5}$ =	261.9	N
F_m =	1098.1	N
F_{infl} =	635.9	N
F_f =	878.4	N
Displacement values		
u_e =	0.143	mm
$u_{h0/10,off}$ =	0.243	mm
$u_{0.1mm,off}$ =	0.348	mm
$u_{e1.5}$ =	0.085	mm
u_m =	0.864	mm
u_{infl} =	1.656	mm
u_f =	1.373	mm
Initial linear slope		
$Slope_{ini}$ =	2960.92	N/mm
Energy values		
E_{SP} =	1.16	J
E_m =	0.64	J
E_{PL} =	0.44	J

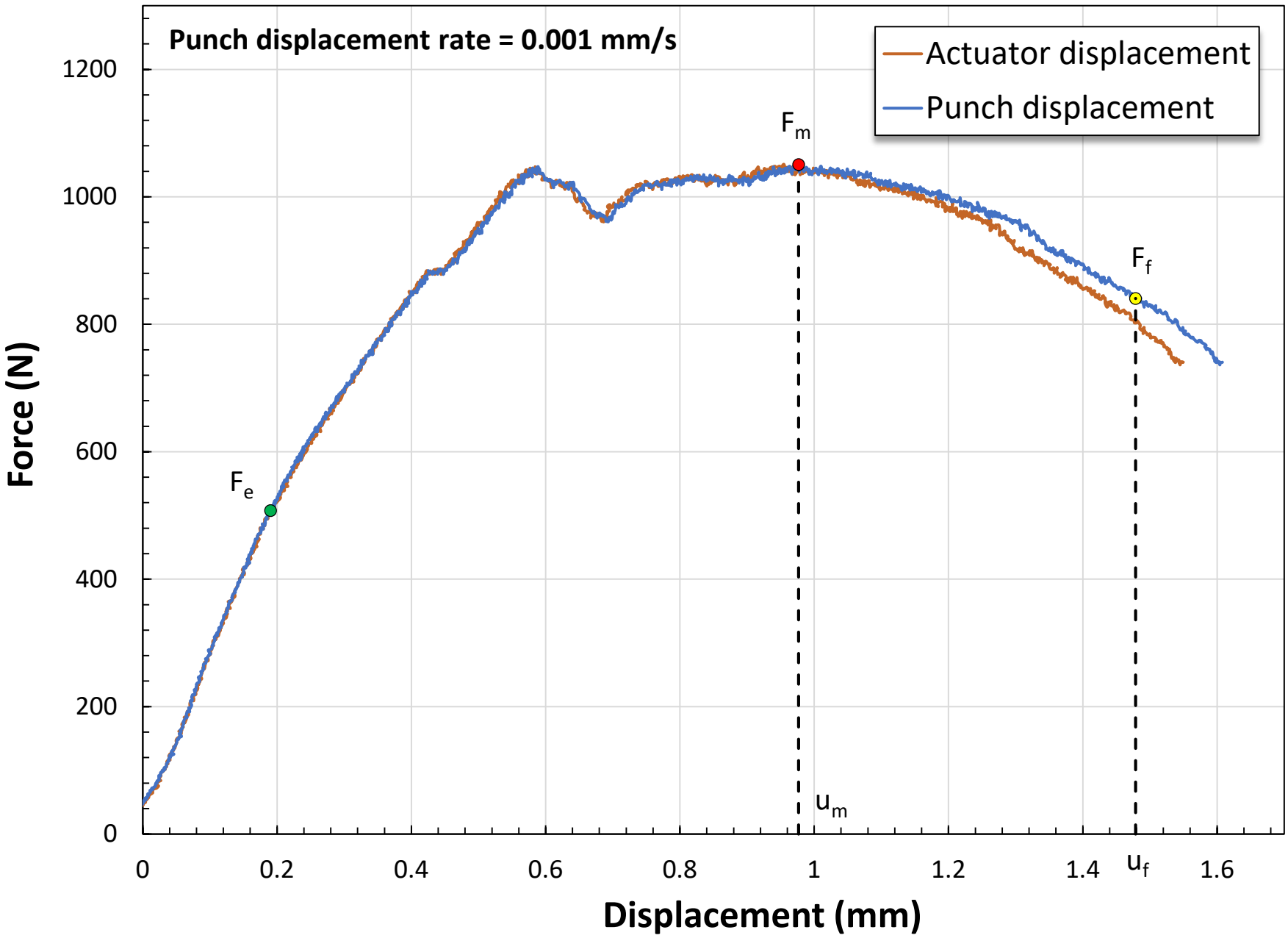

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
F_m
F_f
F_e
u_m
u_f

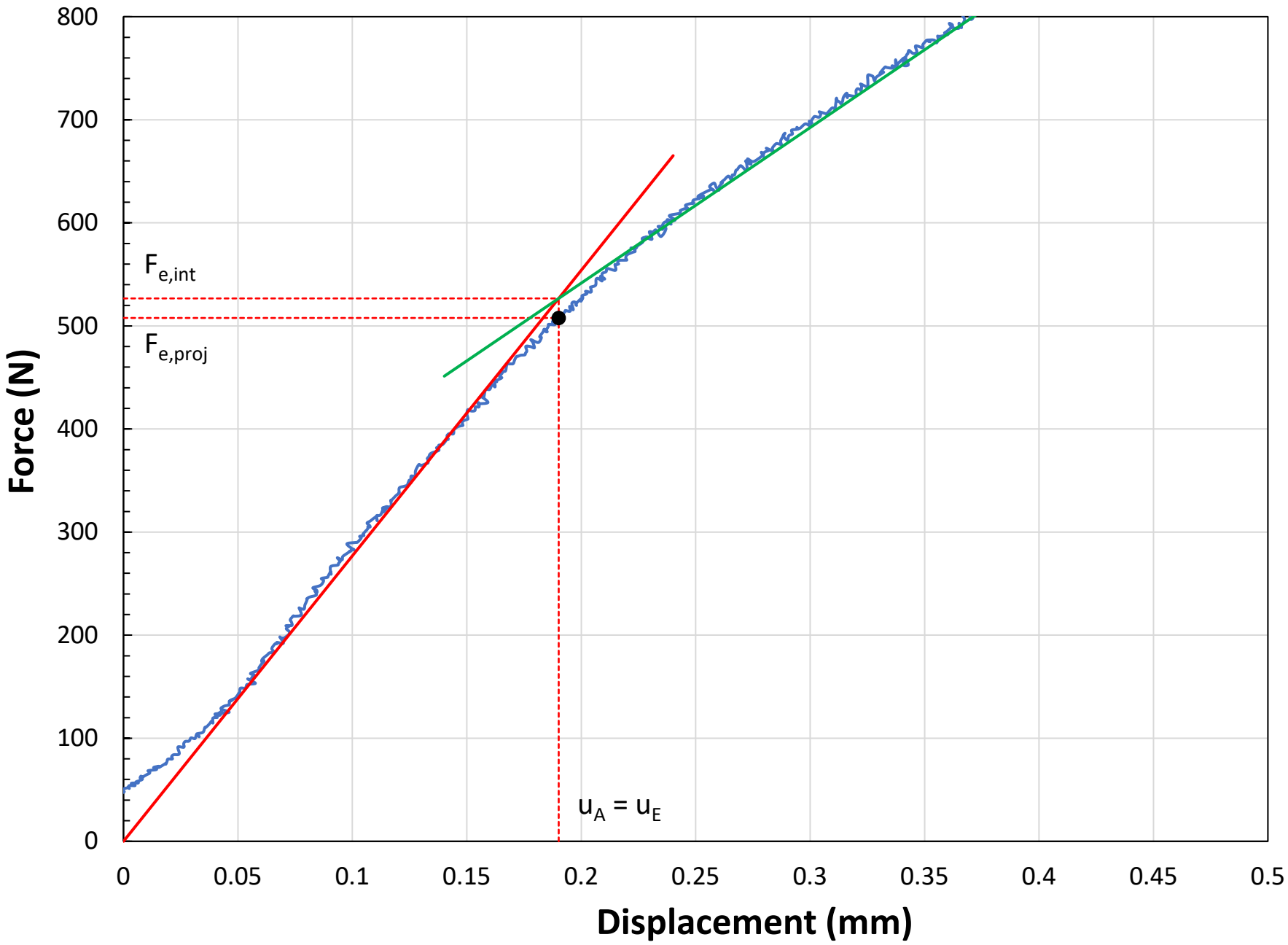

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP6
Material: AM Ti-64
Test speed: 0.000969 mm/s
Max strain rate: 9.69E-04 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	507.7	N
$F_{e,int}$ =	526.7	N
$F_{h0/10,off}$ =	703.1	N
$F_{0.1mm,off}$ =	851.9	N
$F_{0.1mm}$ =	288.5	N
$F_{0.48mm}$ =	919.3	N
$F_{0.5mm}$ =	951.0	N
$F_{0.65mm}$ =	1009.7	N
$F_{0.9mm}$ =	1024.5	N
F_{ept} =	410.0	N
$F_{e1.5}$ =	983.5	N
F_{m} =	1050.7	N
F_{infl} =	740.5	N
F_{f} =	840.6	N
Displacement values		
u_{e} =	0.190	mm
$u_{h0/10,off}$ =	0.304	mm
$u_{0.1mm,off}$ =	0.408	mm
$u_{e1.5}$ =	0.525	mm
u_{m} =	0.977	mm
u_{infl} =	1.608	mm
u_{f} =	1.479	mm
Initial linear slope		
$Slope_{ini}$ =	2769.78	N/mm
Energy values		
E_{SP} =	1.26	J
E_{m} =	0.77	J
E_{PL} =	0.57	J

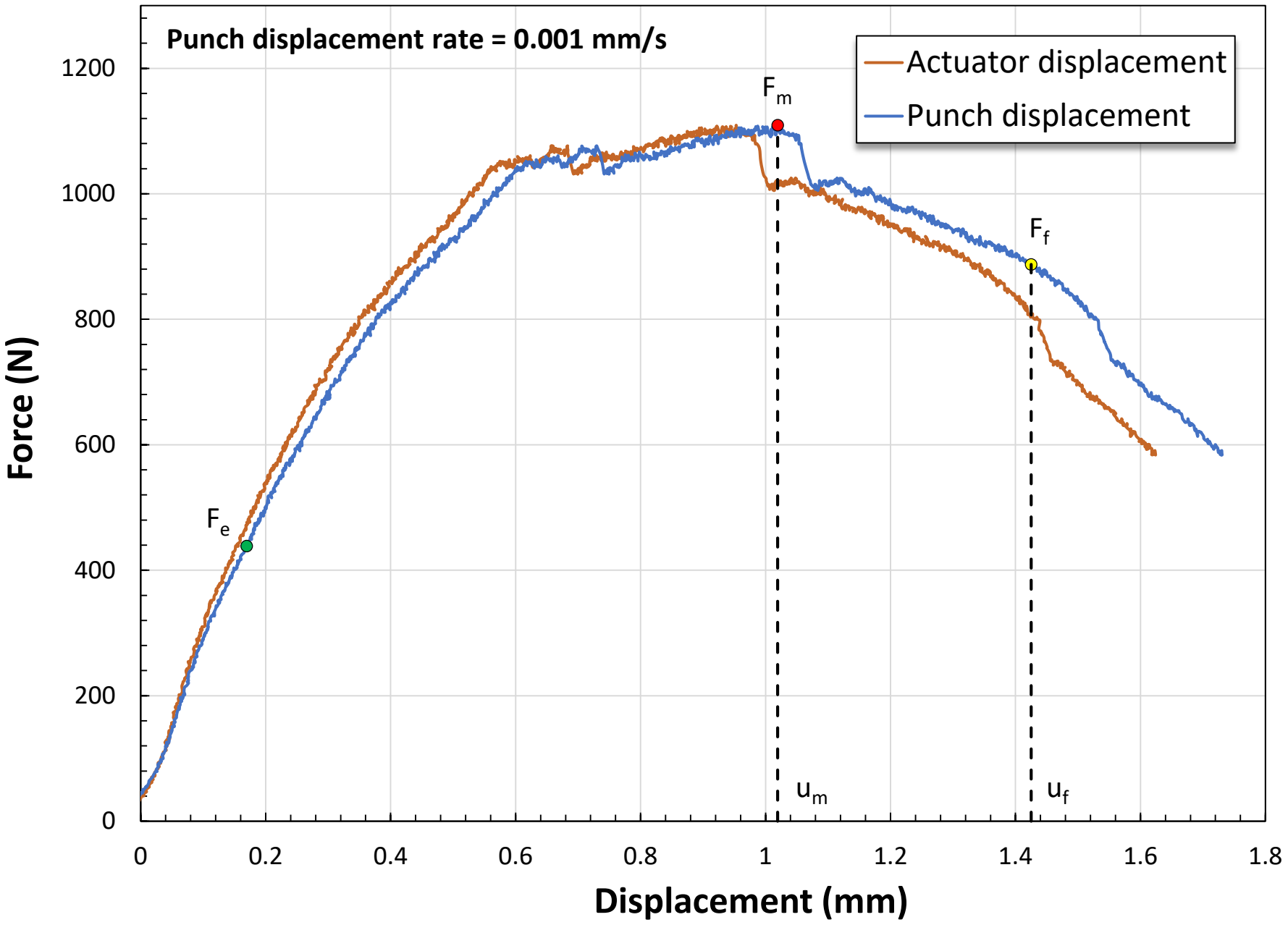

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

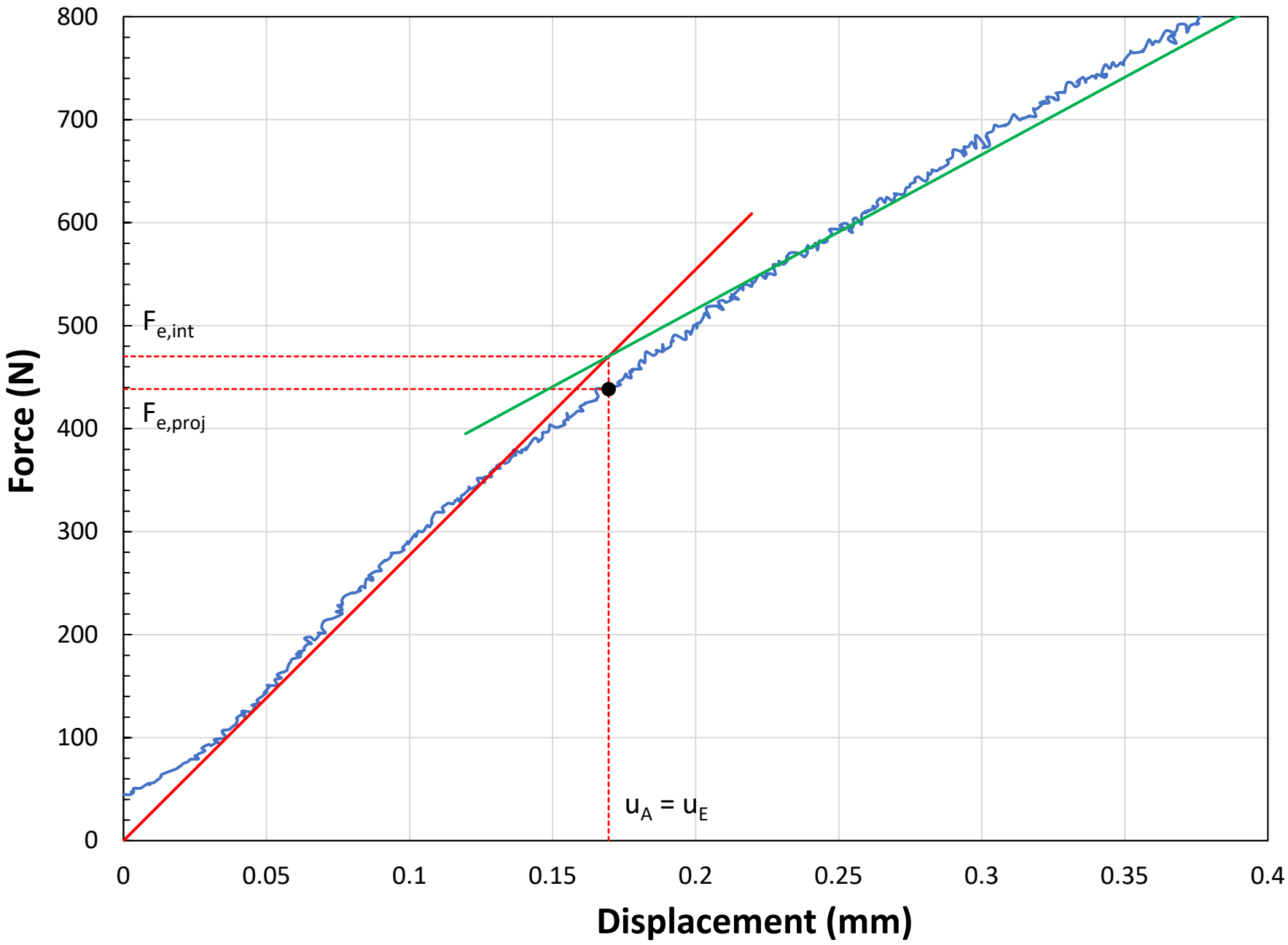

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP7
Material: AM Ti-64
Test speed: 0.001011 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	438.4	N
$F_{e,int}$ =	470.2	N
$F_{h0/10,off}$ =	653.3	N
$F_{0.1mm,off}$ =	822.8	N
$F_{0.1mm}$ =	288.2	N
$F_{0.48mm}$ =	915.7	N
$F_{0.5mm}$ =	927.0	N
$F_{0.65mm}$ =	1059.5	N
$F_{0.9mm}$ =	1083.8	N
F_{ept} =	309.6	N
$F_{e1.5}$ =	187.5	N
F_m =	1109.3	N
F_{infl} =	703.4	N
F_f =	887.4	N
Displacement values		
u_e =	0.170	mm
$u_{h0/10,off}$ =	0.286	mm
$u_{0.1mm,off}$ =	0.398	mm
$u_{e1.5}$ =	0.063	mm
u_m =	1.019	mm
u_{infl} =	1.592	mm
u_f =	1.425	mm
Initial linear slope		
$Slope_{ini}$ =	2772.76	N/mm
Energy values		
E_{SP} =	1.22	J
E_m =	0.83	J
E_{PL} =	0.60	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

ANNEX 3

SP Test Results for

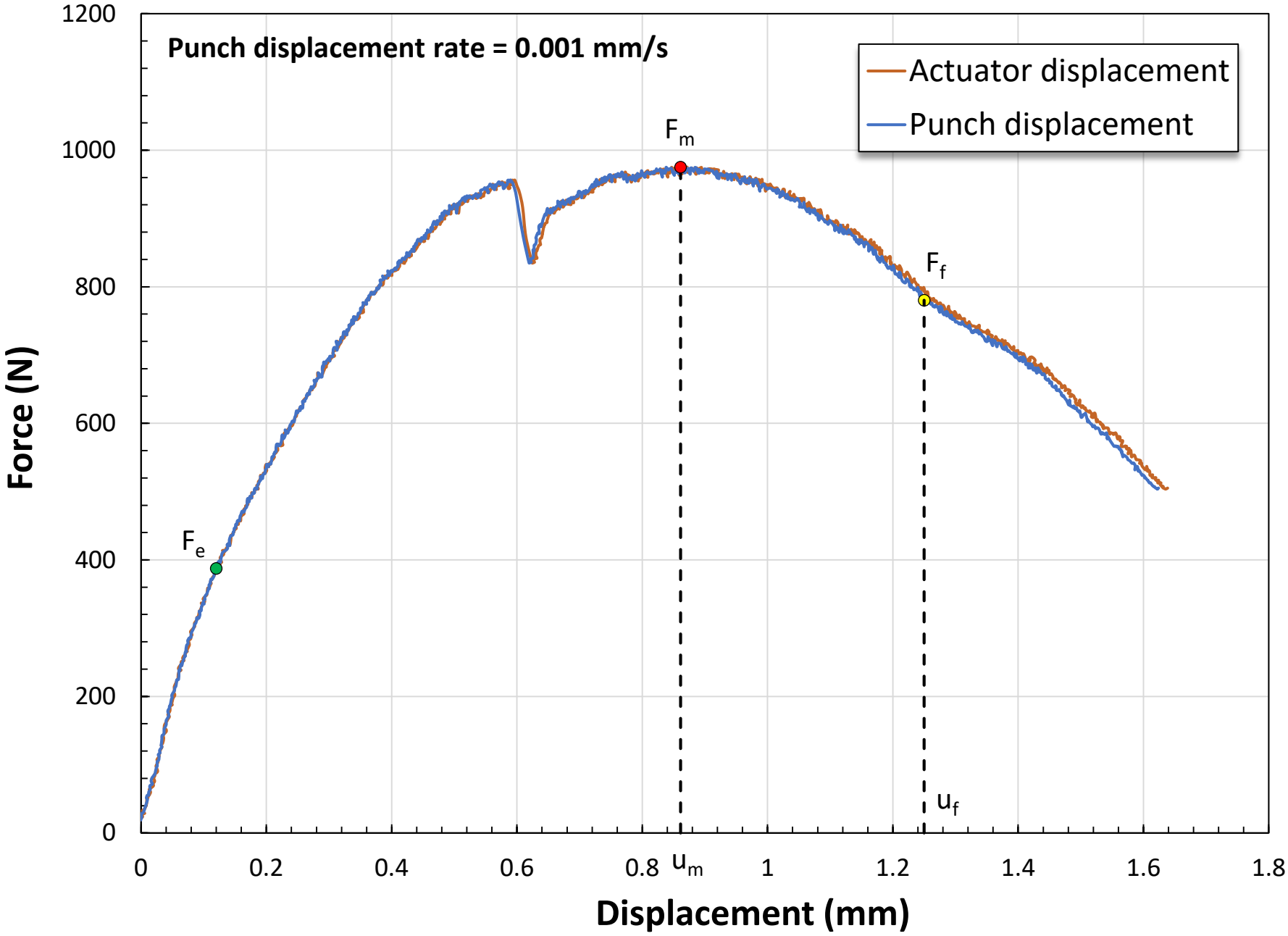
As built, scan length = 78 mm, non-supported

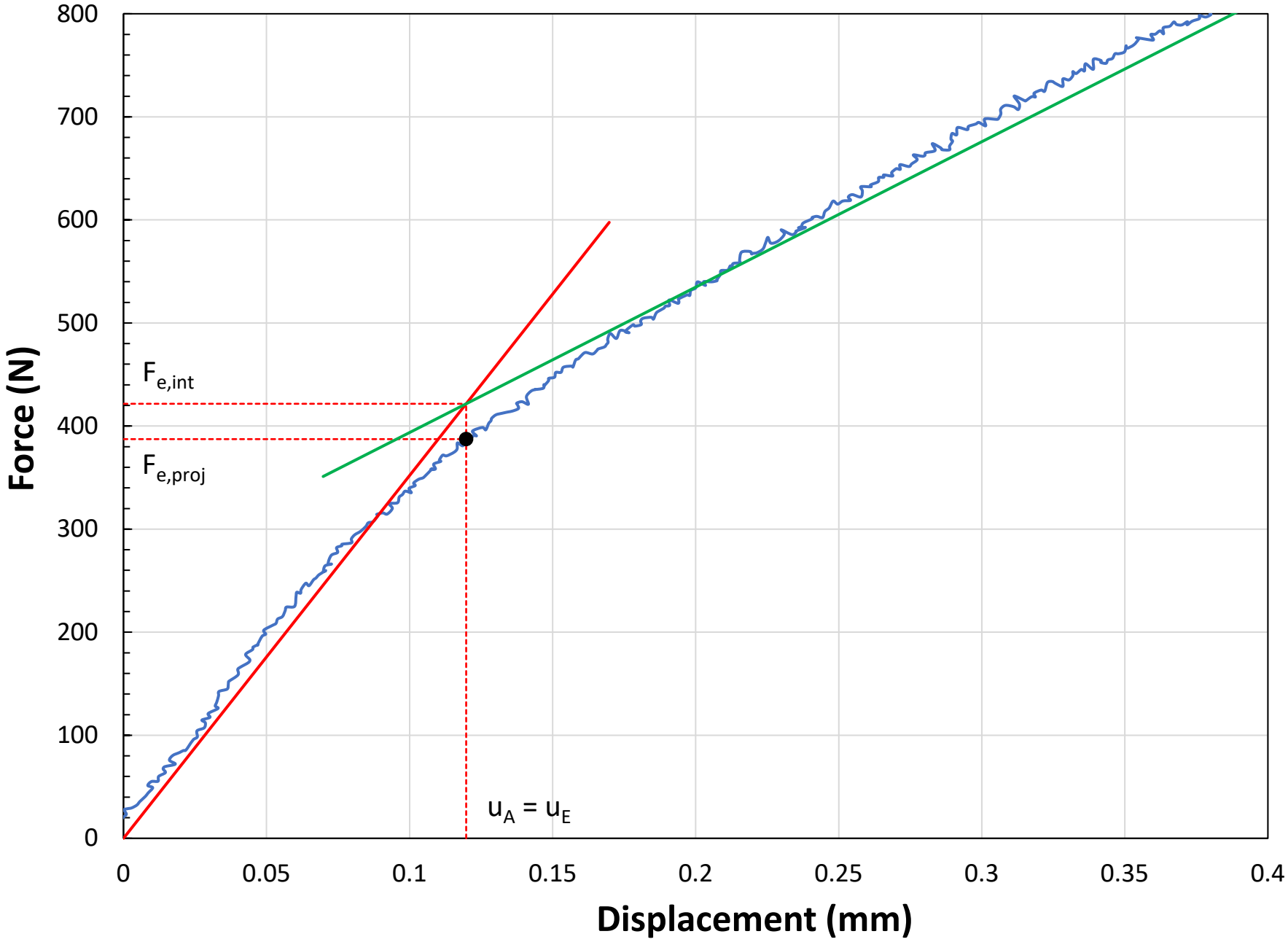
(polished specimens)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP8 (polish
Material: AM Ti-64
Test speed: 0.001436 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	387.3	N
$F_{e,int}$ =	421.6	N
$F_{h0/10,off}$ =	521.6	N
$F_{0.1mm,off}$ =	694.8	N
$F_{0.1mm}$ =	336.9	N
$F_{0.48mm}$ =	903.1	N
$F_{0.5mm}$ =	921.2	N
$F_{0.65mm}$ =	911.2	N
$F_{0.9mm}$ =	972.6	N
F_{ept} =	783.2	N
$F_{e1.5}$ =	736.8	N
F_m =	975.4	N
F_{infl} =	505.2	N
F_f =	780.3	N
Displacement values		
u_e =	0.120	mm
$u_{h0/10,off}$ =	0.194	mm
$u_{0.1mm,off}$ =	0.298	mm
$u_{e1.5}$ =	0.328	mm
u_m =	0.861	mm
u_{infl} =	1.624	mm
u_f =	1.250	mm
Initial linear slope		
$Slope_{ini}$ =	3519.91	N/mm
Energy values		
E_{SP} =	0.98	J
E_m =	0.63	J
E_{PL} =	0.49	J

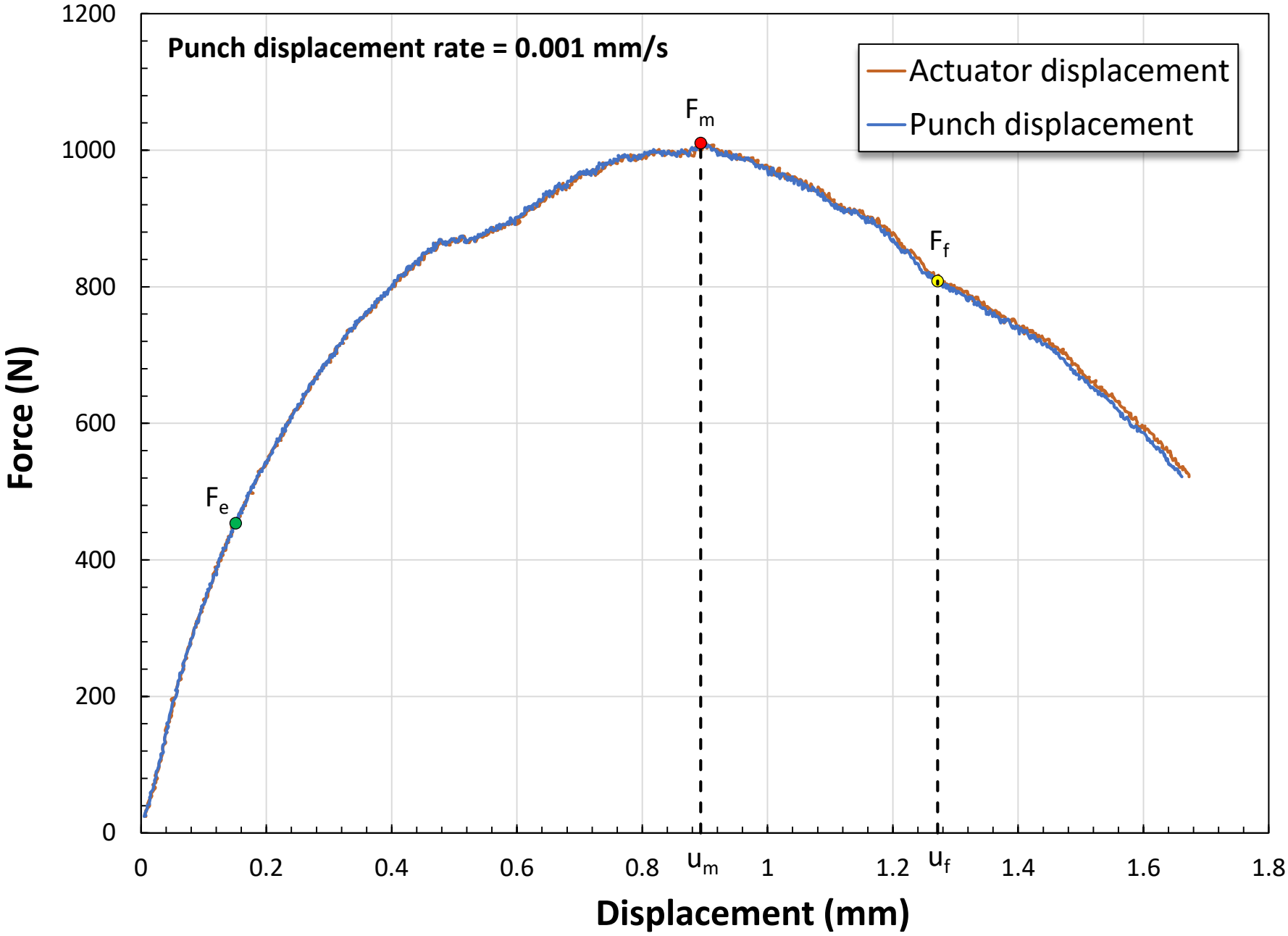

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

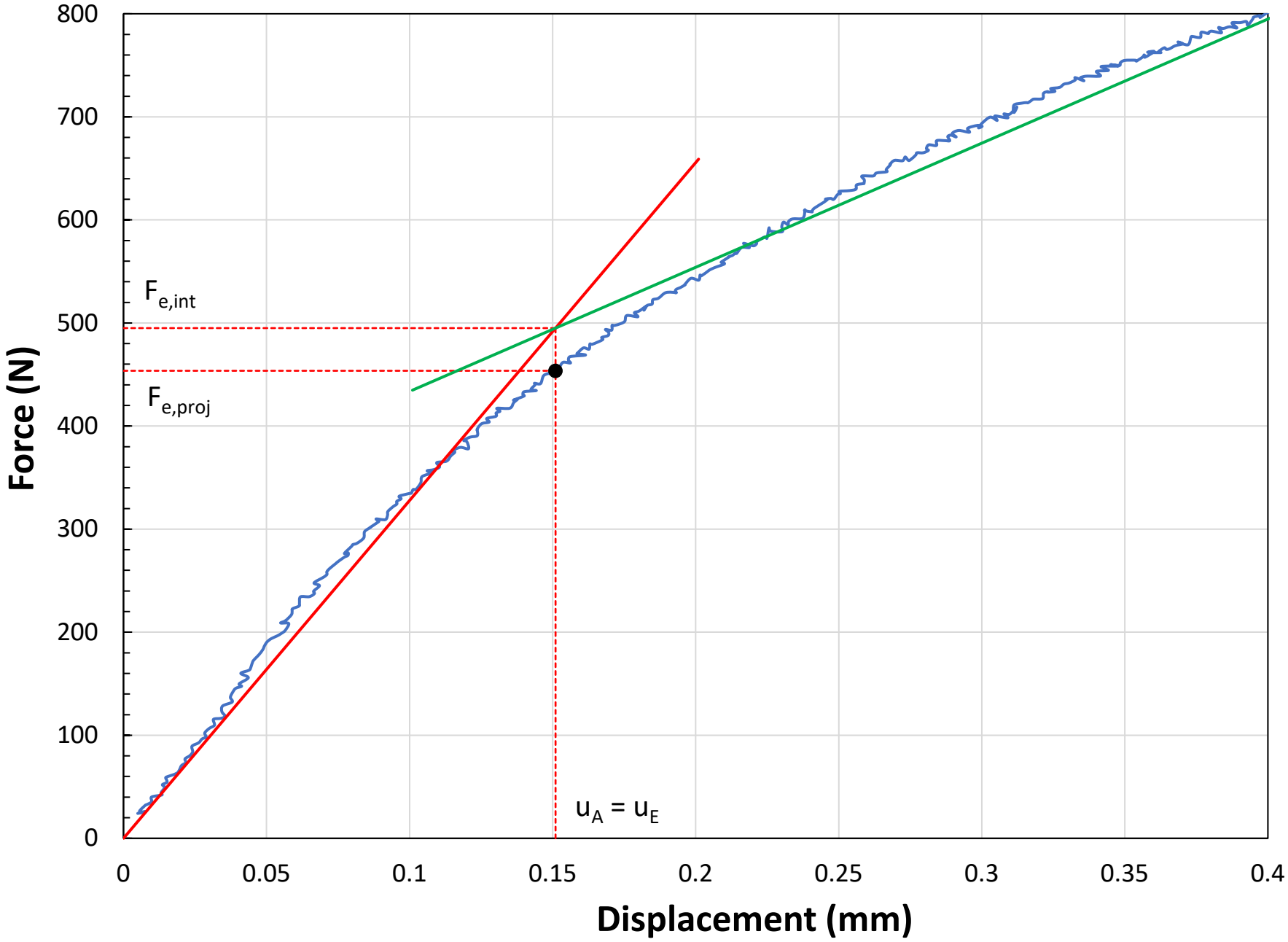

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP9 (polish
Material: AM Ti-64
Test speed: 0.001437 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	453.6	N
$F_{e,int}$ =	495.0	N
$F_{h0/10,off}$ =	577.5	N
$F_{0.1mm,off}$ =	721.5	N
$F_{0.1mm}$ =	334.5	N
$F_{0.48mm}$ =	868.3	N
$F_{0.5mm}$ =	870.6	N
$F_{0.65mm}$ =	939.4	N
$F_{0.9mm}$ =	1006.8	N
F_{ept} =	737.8	N
$F_{e1.5}$ =	711.4	N
F_m =	1010.7	N
F_{infl} =	970.1	N
F_f =	808.5	N
Displacement values		
u_e =	0.151	mm
$u_{h0/10,off}$ =	0.221	mm
$u_{0.1mm,off}$ =	0.321	mm
$u_{e1.5}$ =	0.311	mm
u_m =	0.893	mm
u_{infl} =	1.010	mm
u_f =	1.271	mm
Initial linear slope		
$Slope_{ini}$ =	3278.01	N/mm
Energy values		
E_{SP} =	1.01	J
E_m =	0.66	J
E_{PL} =	0.50	J

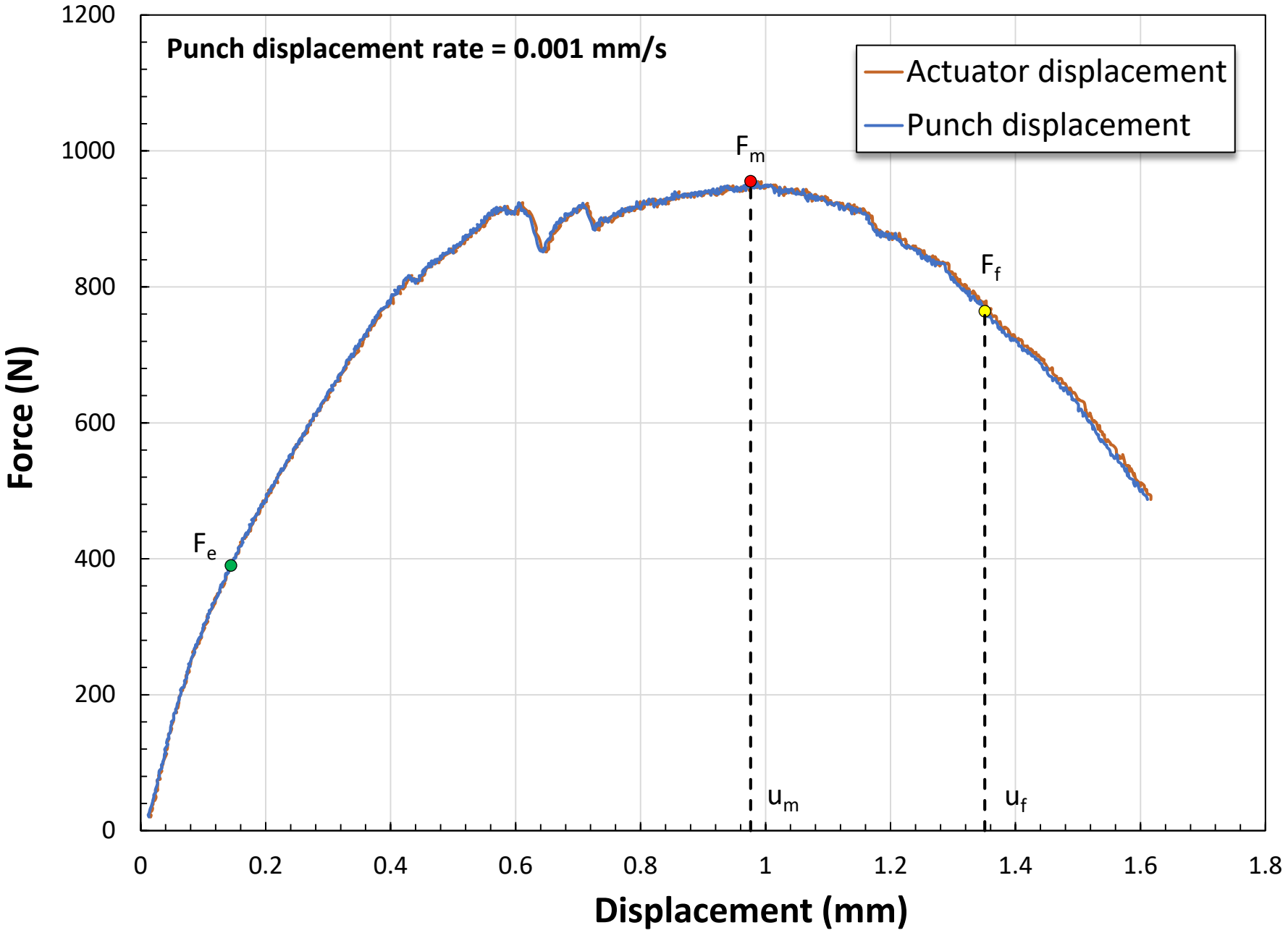

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

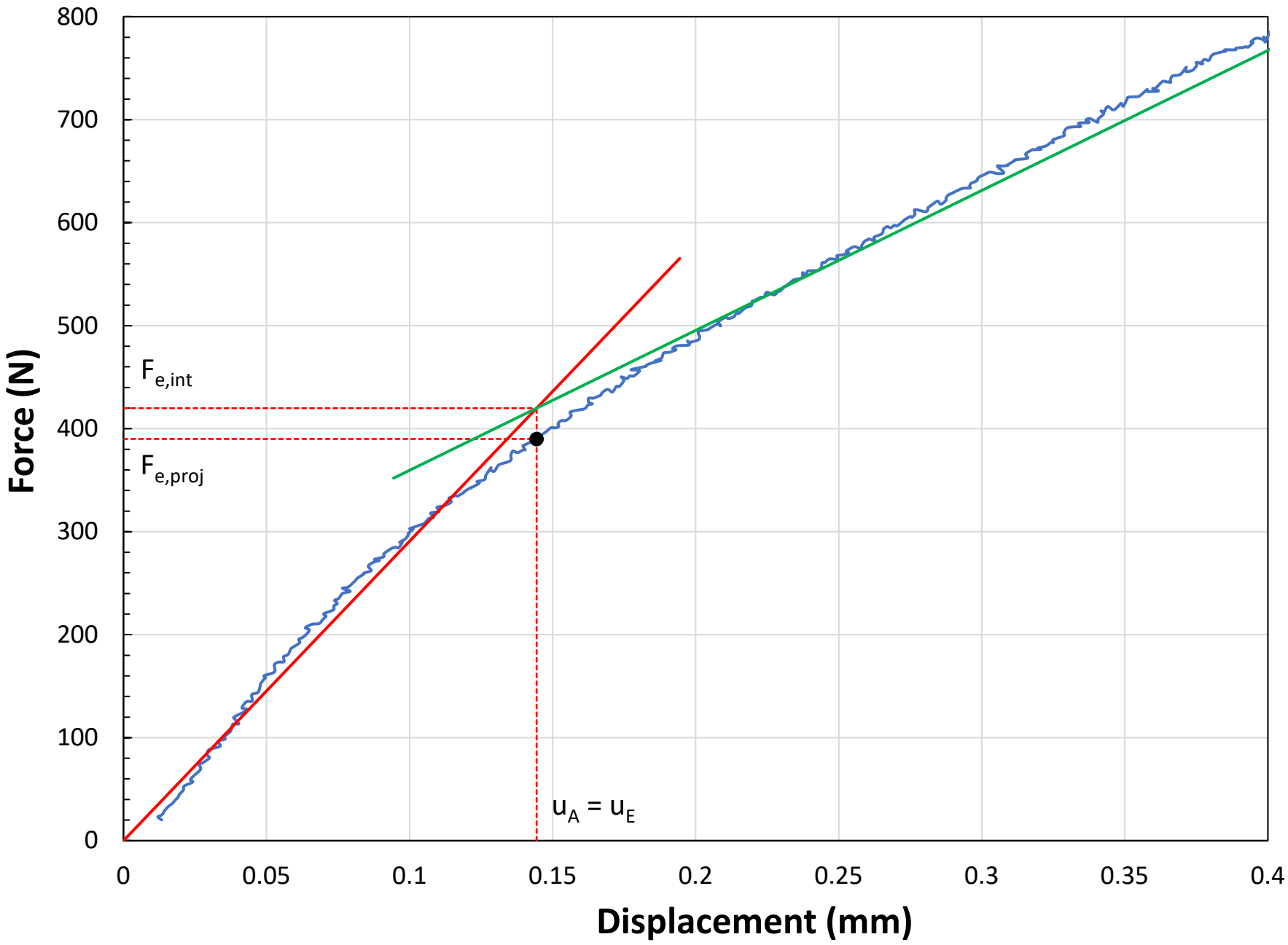

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_1_N_a_SP10 (polis
Material: AM Ti-64
Test speed: 0.00143 mm/s
Max strain rate: 1.43E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	390.0	N
$F_{e,int}$ =	419.9	N
$F_{h0/10,off}$ =	532.1	N
$F_{0.1mm,off}$ =	698.4	N
$F_{0.1mm}$ =	298.2	N
$F_{0.48mm}$ =	845.6	N
$F_{0.5mm}$ =	852.7	N
$F_{0.65mm}$ =	865.9	N
$F_{0.9mm}$ =	937.9	N
F_{ept} =	878.2	N
$F_{e1.5}$ =	775.3	N
F_m =	955.3	N
F_{infl} =	487.2	N
F_f =	764.3	N
Displacement values		
u_e =	0.144	mm
$u_{h0/10,off}$ =	0.228	mm
$u_{0.1mm,off}$ =	0.340	mm
$u_{e1.5}$ =	0.399	mm
u_m =	0.976	mm
u_{infl} =	1.611	mm
u_f =	1.351	mm
Initial linear slope		
$Slope_{ini}$ =	2907.81	N/mm
Energy values		
E_{SP} =	1.03	J
E_m =	0.70	J
E_{PL} =	0.54	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

ANNEX 4

SP Test Results for

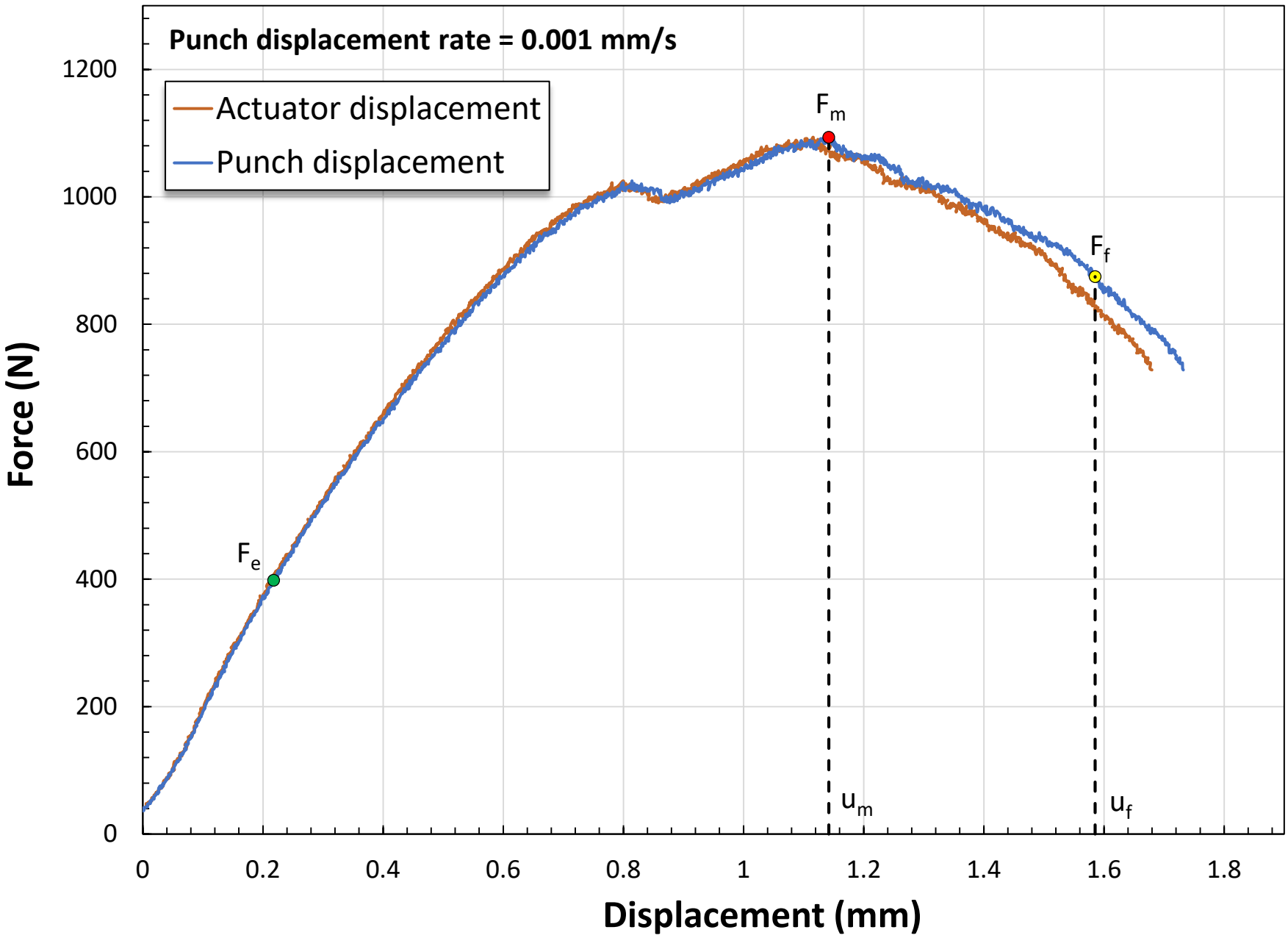
As built, scan length = 26 mm, non-supported

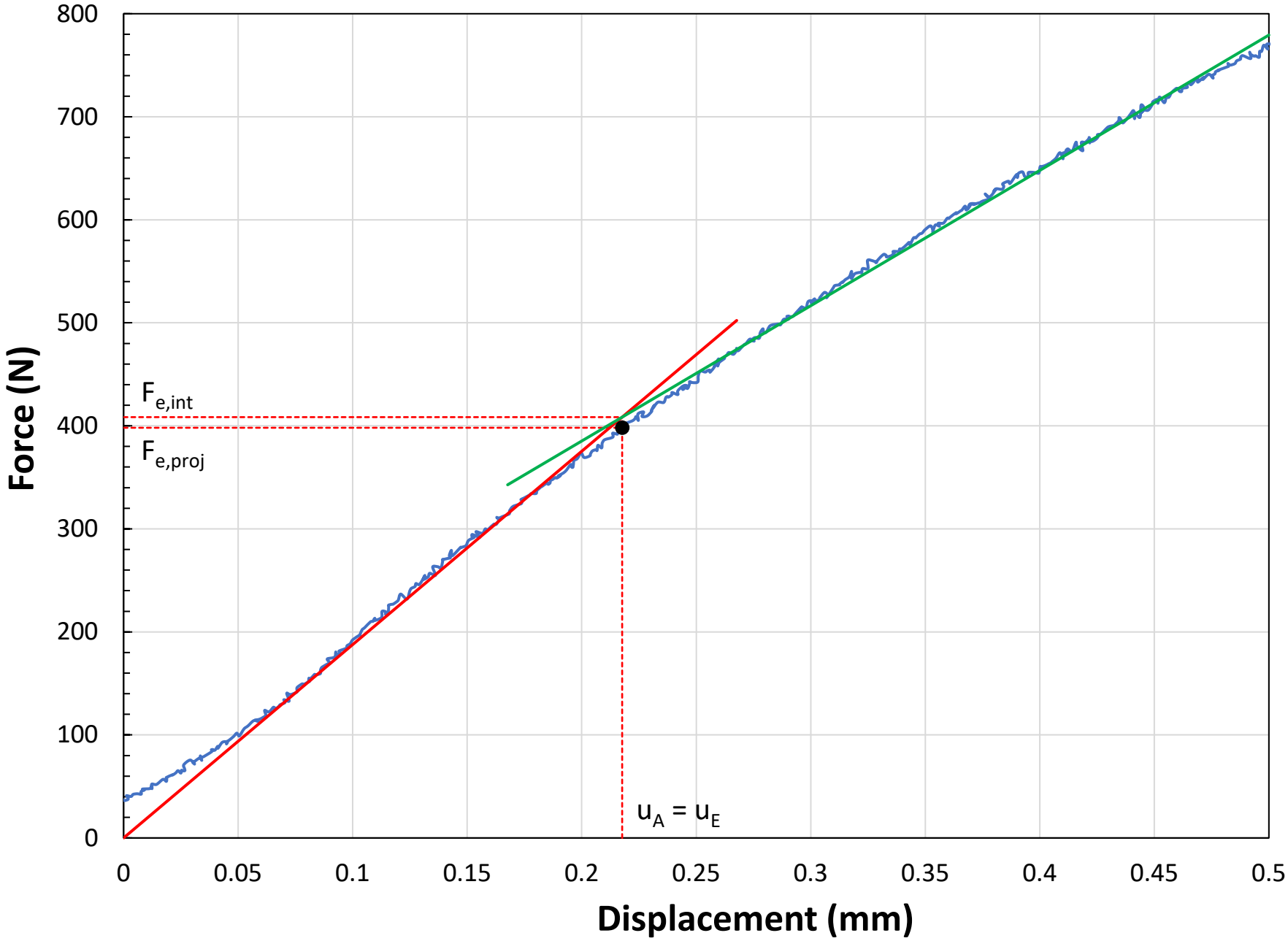
(“rough” specimens)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP1
Material: AM Ti-64
Test speed: 0.001031 mm/s
Max strain rate: 1.03E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	398.1	N
$F_{e,int}$ =	408.4	N
$F_{h0/10,off}$ =	643.2	N
$F_{0.1mm,off}$ =	787.6	N
$F_{0.1mm}$ =	188.5	N
$F_{0.48mm}$ =	745.2	N
$F_{0.5mm}$ =	770.4	N
$F_{0.65mm}$ =	920.4	N
$F_{0.9mm}$ =	1005.9	N
F_{ept} =	117.8	N
$F_{e1.5}$ =	192.6	N
F_m =	1093.5	N
F_{infl} =	1000.8	N
F_f =	874.8	N
Displacement values		
u_e =	0.218	mm
$u_{h0/10,off}$ =	0.393	mm
$u_{0.1mm,off}$ =	0.520	mm
$u_{e1.5}$ =	0.100	mm
u_m =	1.142	mm
u_{infl} =	0.774	mm
u_f =	1.585	mm
Initial linear slope		
$Slope_{ini}$ =	1876.53	N/mm
Energy values		
E_{SP} =	1.28	J
E_m =	0.84	J
E_{PL} =	0.52	J

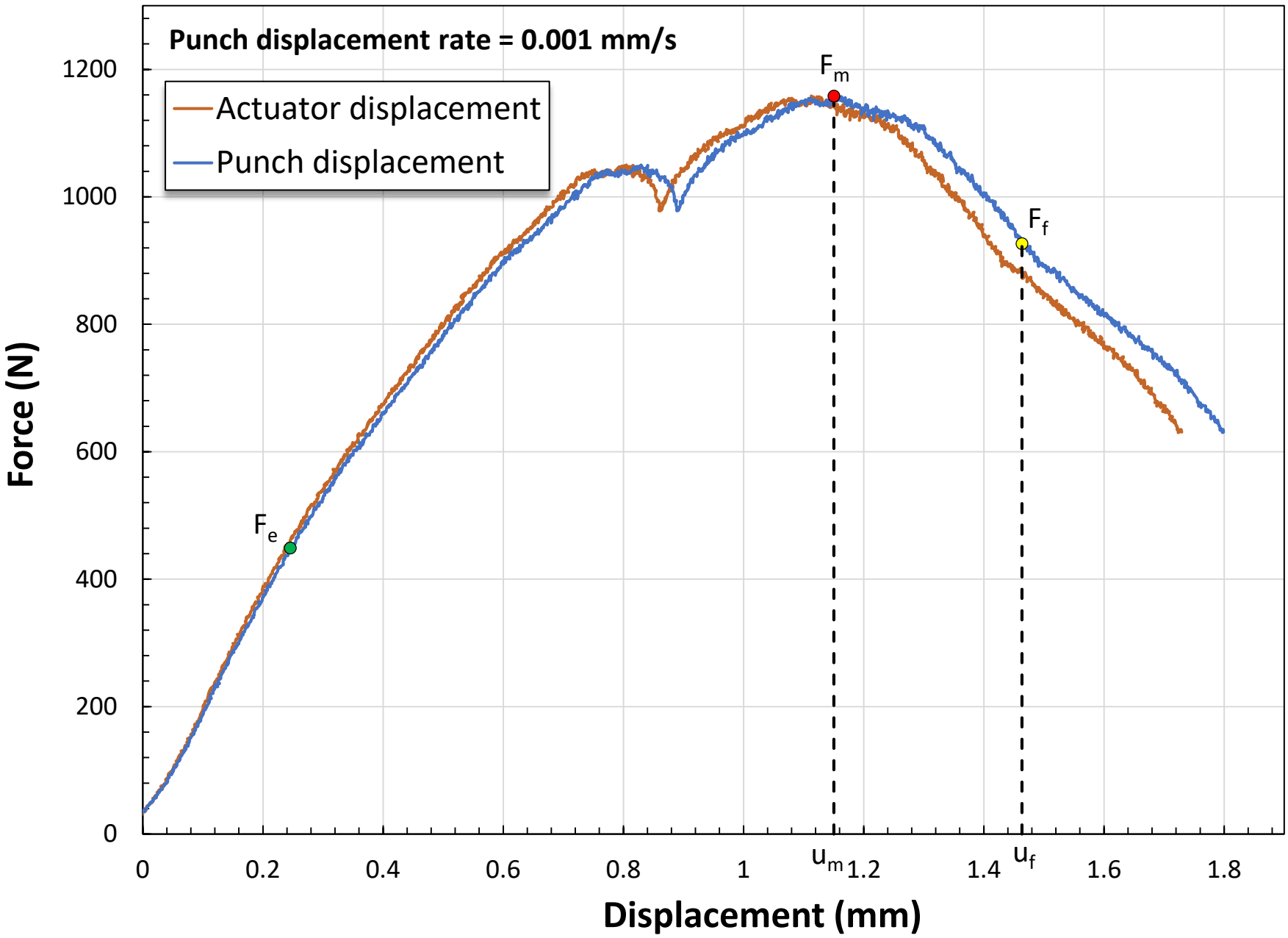

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

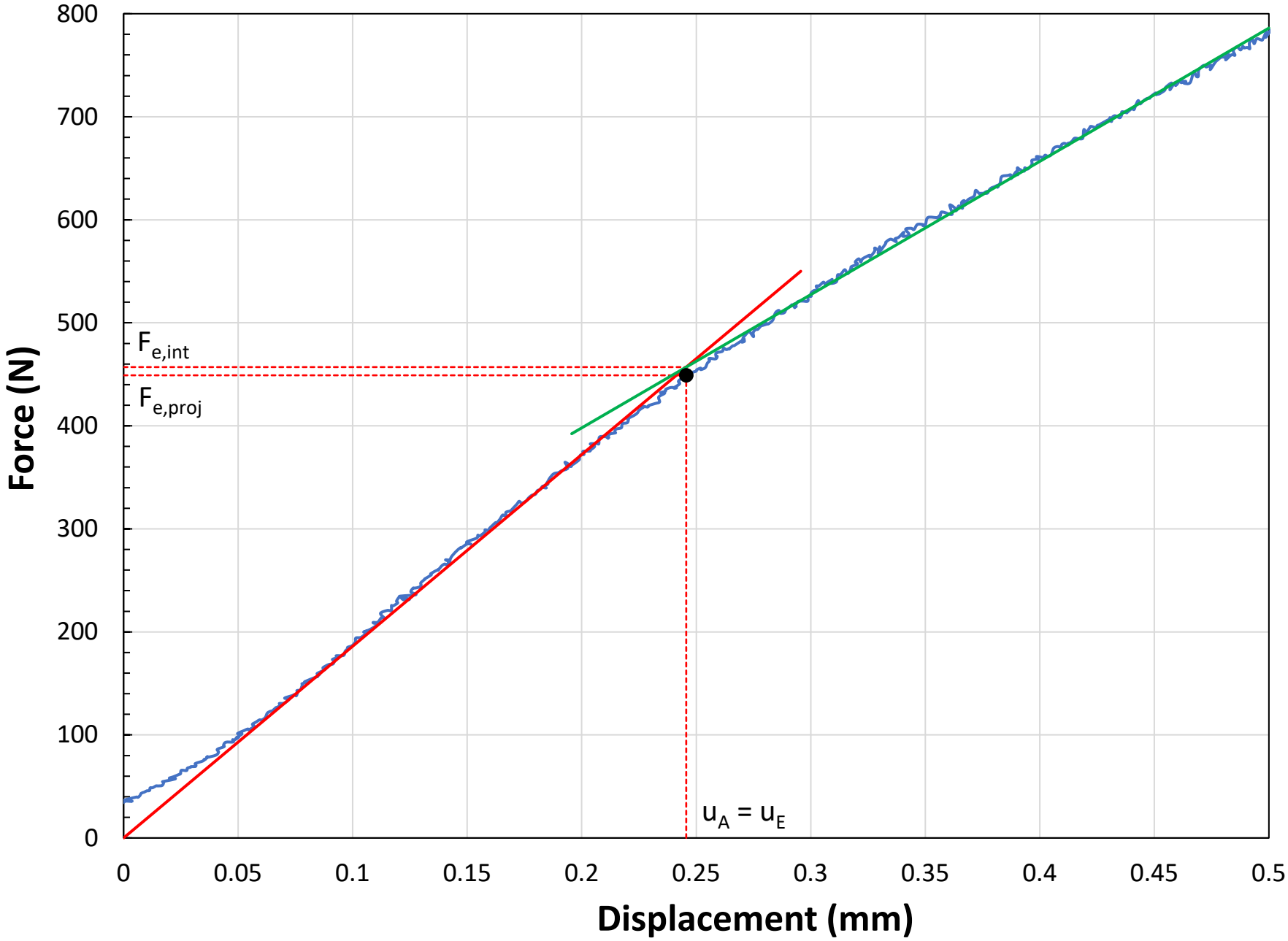

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP3
Material: AM Ti-64
Test speed: 0.00104 mm/s
Max strain rate: 1.04E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	449.1	N
$F_{e,int}$ =	457.0	N
$F_{h0/10,off}$ =	673.4	N
$F_{0.1mm,off}$ =	831.5	N
$F_{0.1mm}$ =	186.6	N
$F_{0.48mm}$ =	758.0	N
$F_{0.5mm}$ =	777.1	N
$F_{0.65mm}$ =	939.1	N
$F_{0.9mm}$ =	1002.7	N
F_{ept} =	609.0	N
$F_{e1.5}$ =	156.4	N
F_m =	1158.1	N
F_{infl} =	630.8	N
F_f =	926.5	N
Displacement values		
u_e =	0.246	mm
$u_{h0/10,off}$ =	0.412	mm
$u_{0.1mm,off}$ =	0.547	mm
$u_{e1.5}$ =	0.084	mm
u_m =	1.150	mm
u_{infl} =	1.799	mm
u_f =	1.463	mm
Initial linear slope		
$Slope_{ini}$ =	1860.63	N/mm
Energy values		
E_{SP} =	1.21	J
E_m =	0.88	J
E_{PL} =	0.51	J

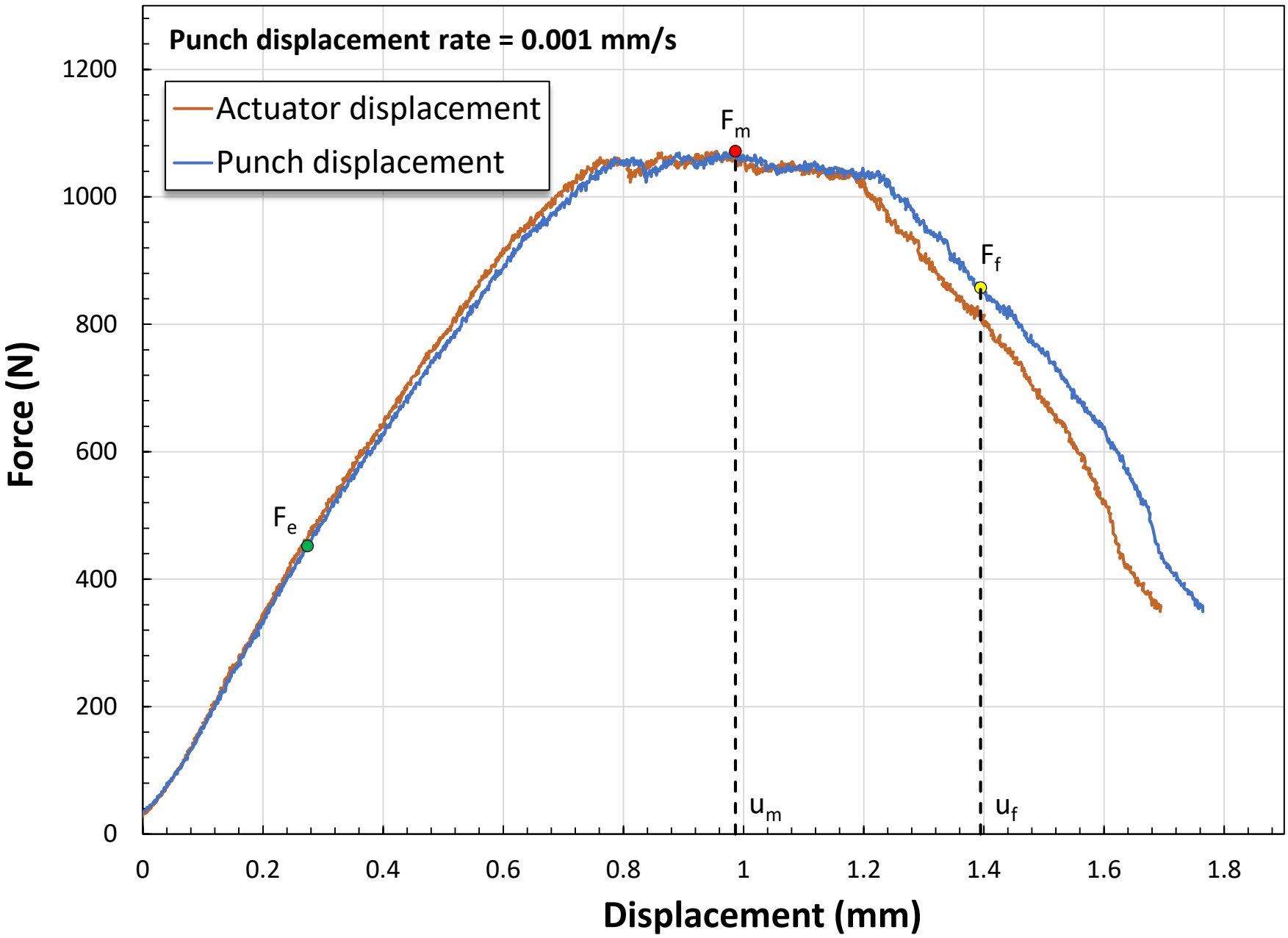

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

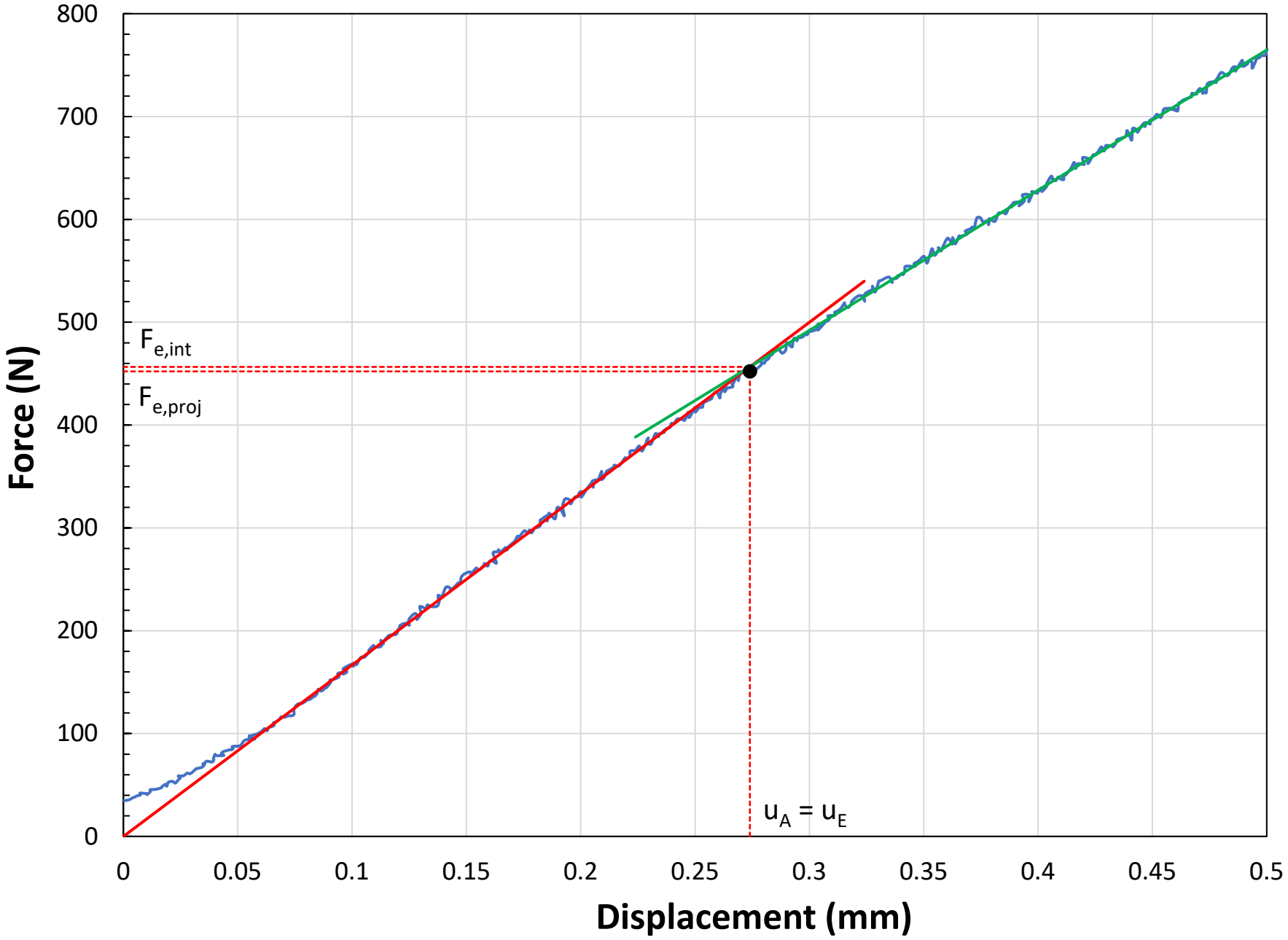

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP4
Material: AM Ti-64
Test speed: 0.001042 mm/s
Max strain rate: 1.04E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	452.2	N
$F_{e,int}$ =	456.5	N
$F_{h0/10,off}$ =	780.4	N
$F_{0.1mm,off}$ =	974.2	N
$F_{0.1mm}$ =	163.0	N
$F_{0.48mm}$ =	736.5	N
$F_{0.5mm}$ =	763.6	N
$F_{0.65mm}$ =	947.0	N
$F_{0.9mm}$ =	1060.2	N
F_{ept} =	942.2	N
$F_{e1.5}$ =	174.1	N
F_m =	1071.7	N
F_{infl} =	349.1	N
F_f =	857.3	N
Displacement values		
u_e =	0.274	mm
$u_{h0/10,off}$ =	0.519	mm
$u_{0.1mm,off}$ =	0.685	mm
$u_{e1.5}$ =	0.105	mm
u_m =	0.987	mm
u_{infl} =	1.765	mm
u_f =	1.395	mm
Initial linear slope		
$Slope_{ini}$ =	1666.44	N/mm
Energy values		
E_{SP} =	1.09	J
E_m =	0.68	J
E_{PL} =	0.33	J

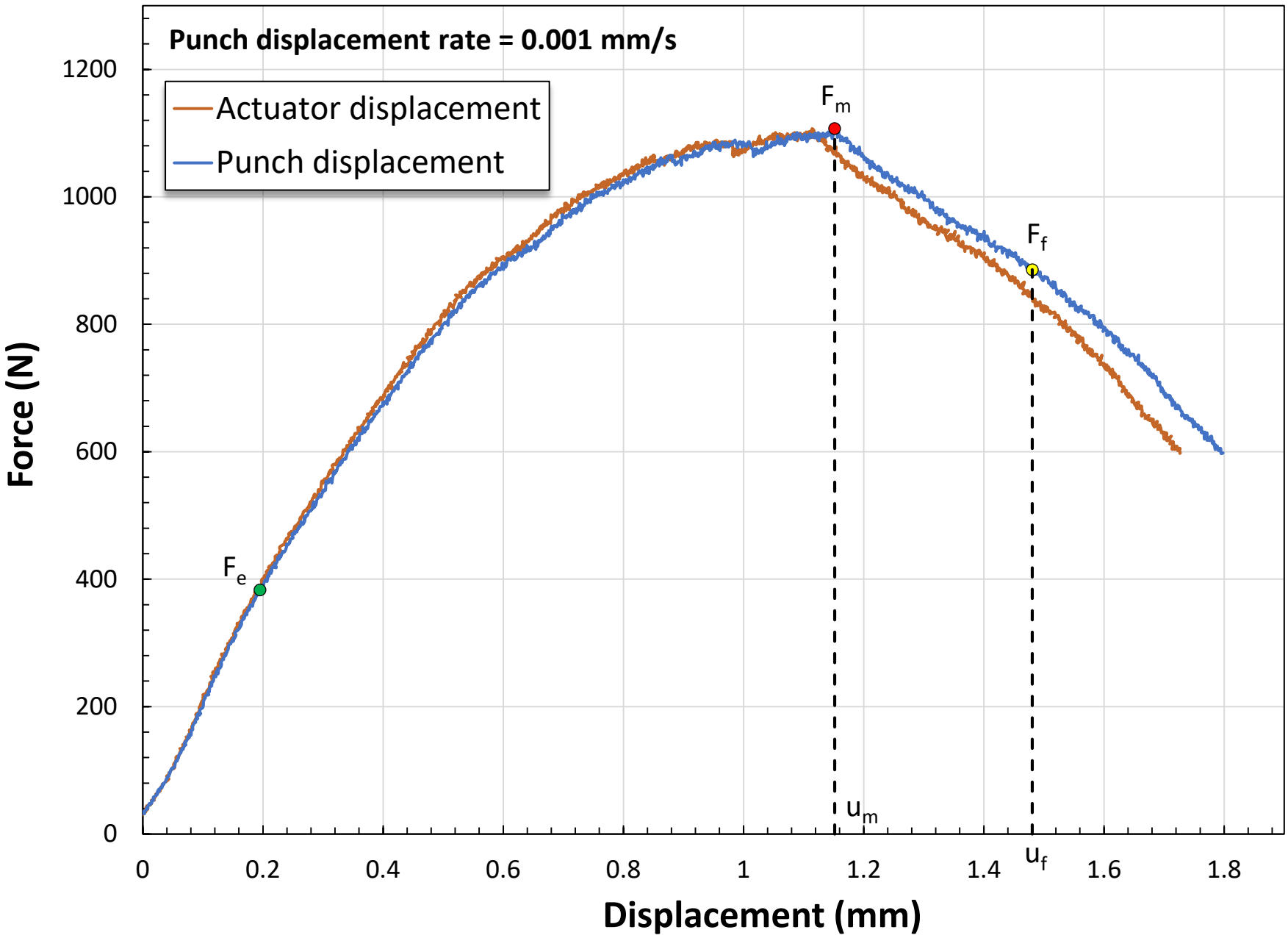

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

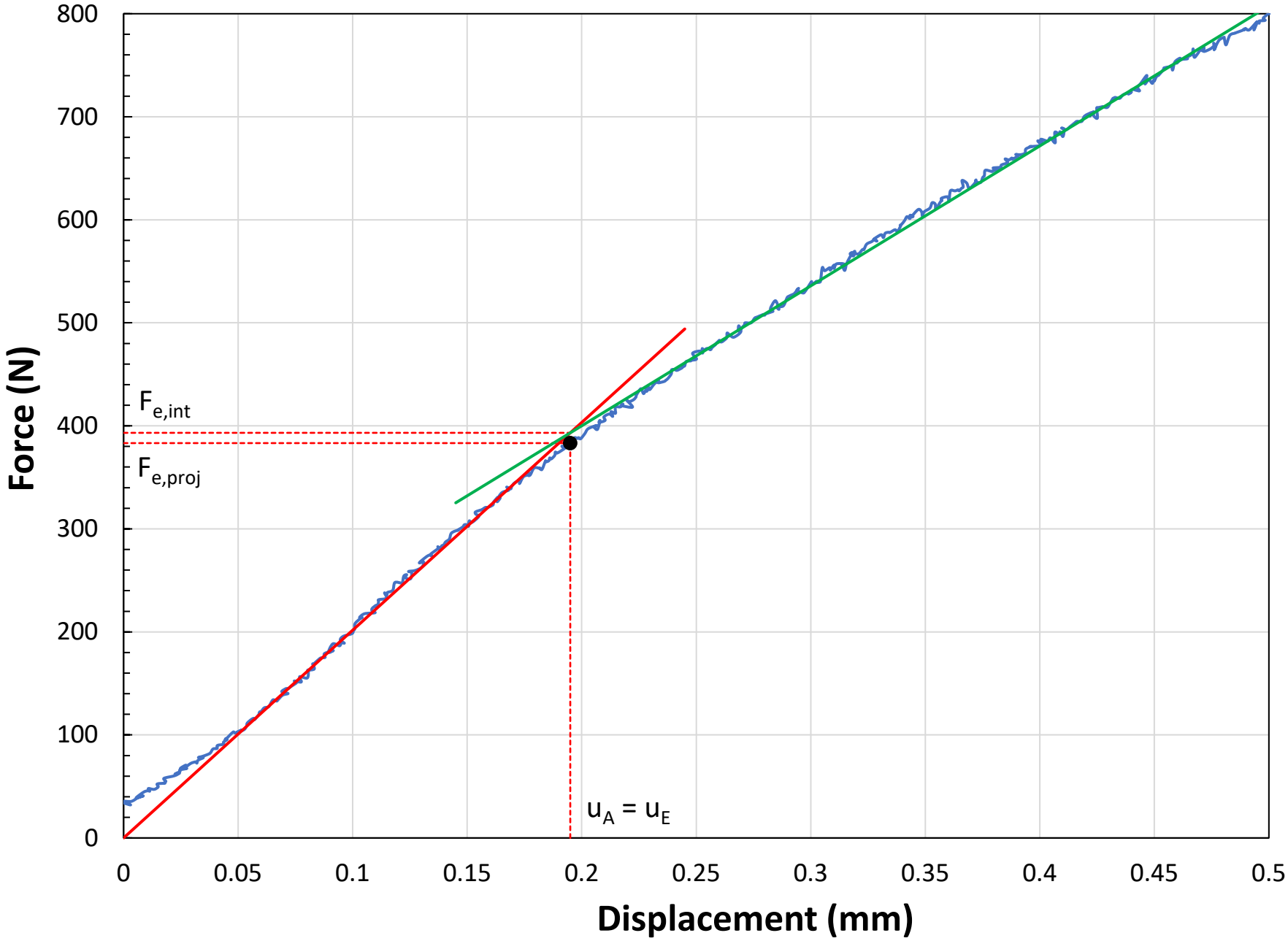

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP5
Material: AM Ti-64
Test speed: 0.00104 mm/s
Max strain rate: 1.04E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	383.2	N
$F_{e,int}$ =	393.2	N
$F_{h0/10,off}$ =	612.4	N
$F_{0.1mm,off}$ =	785.9	N
$F_{0.1mm}$ =	198.4	N
$F_{0.48mm}$ =	774.2	N
$F_{0.5mm}$ =	799.9	N
$F_{0.65mm}$ =	921.8	N
$F_{0.9mm}$ =	1061.4	N
F_{ept} =	613.7	N
$F_{e1.5}$ =	163.9	N
F_m =	1107.0	N
F_{infl} =	740.2	N
F_f =	885.6	N
Displacement values		
u_e =	0.195	mm
$u_{h0/10,off}$ =	0.355	mm
$u_{0.1mm,off}$ =	0.490	mm
$u_{e1.5}$ =	0.083	mm
u_m =	1.152	mm
u_{infl} =	0.452	mm
u_f =	1.481	mm
Initial linear slope		
$Slope_{ini}$ =	2016.45	N/mm
Energy values		
E_{SP} =	1.20	J
E_m =	0.88	J
E_{PL} =	0.57	J

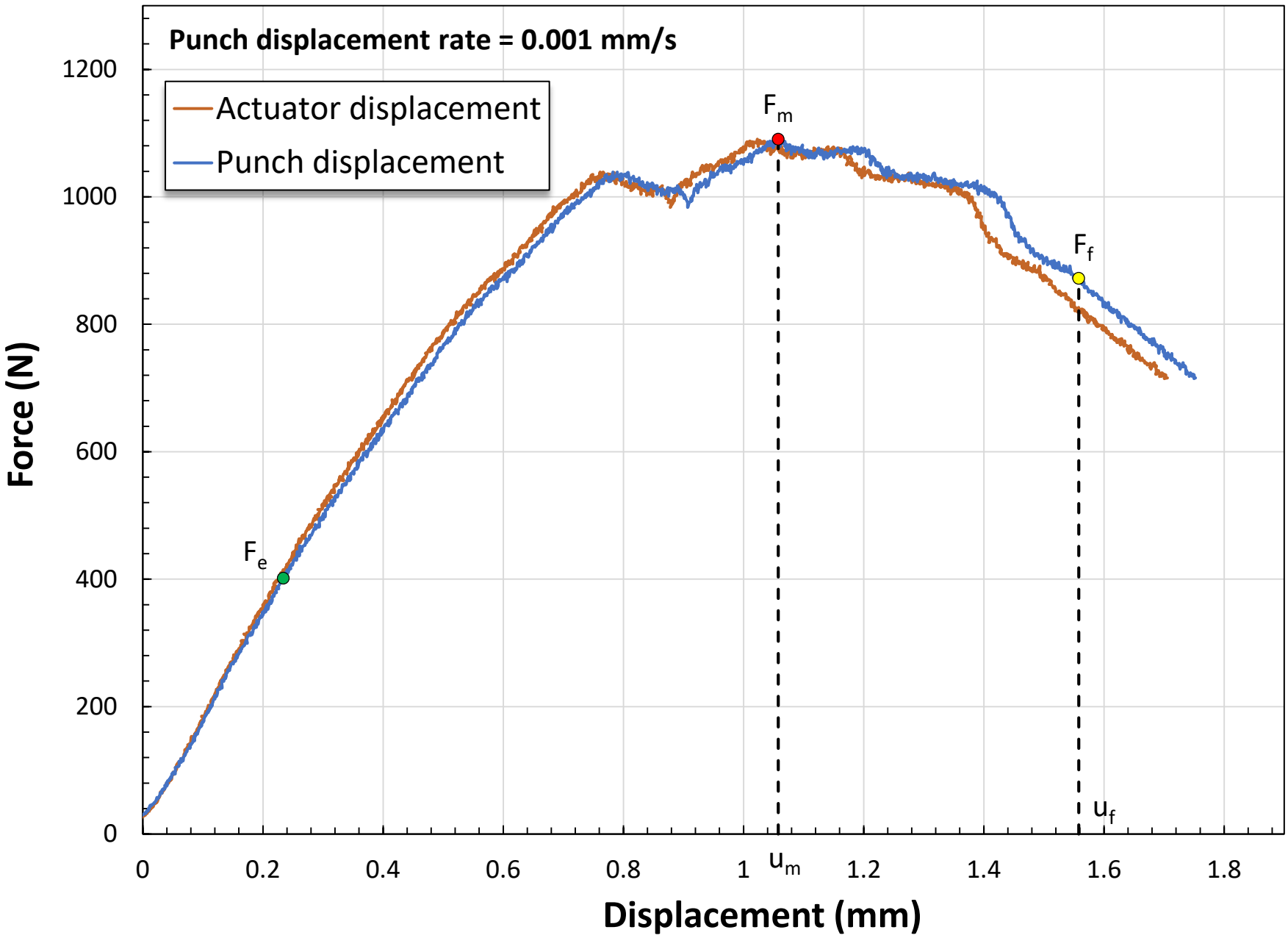

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

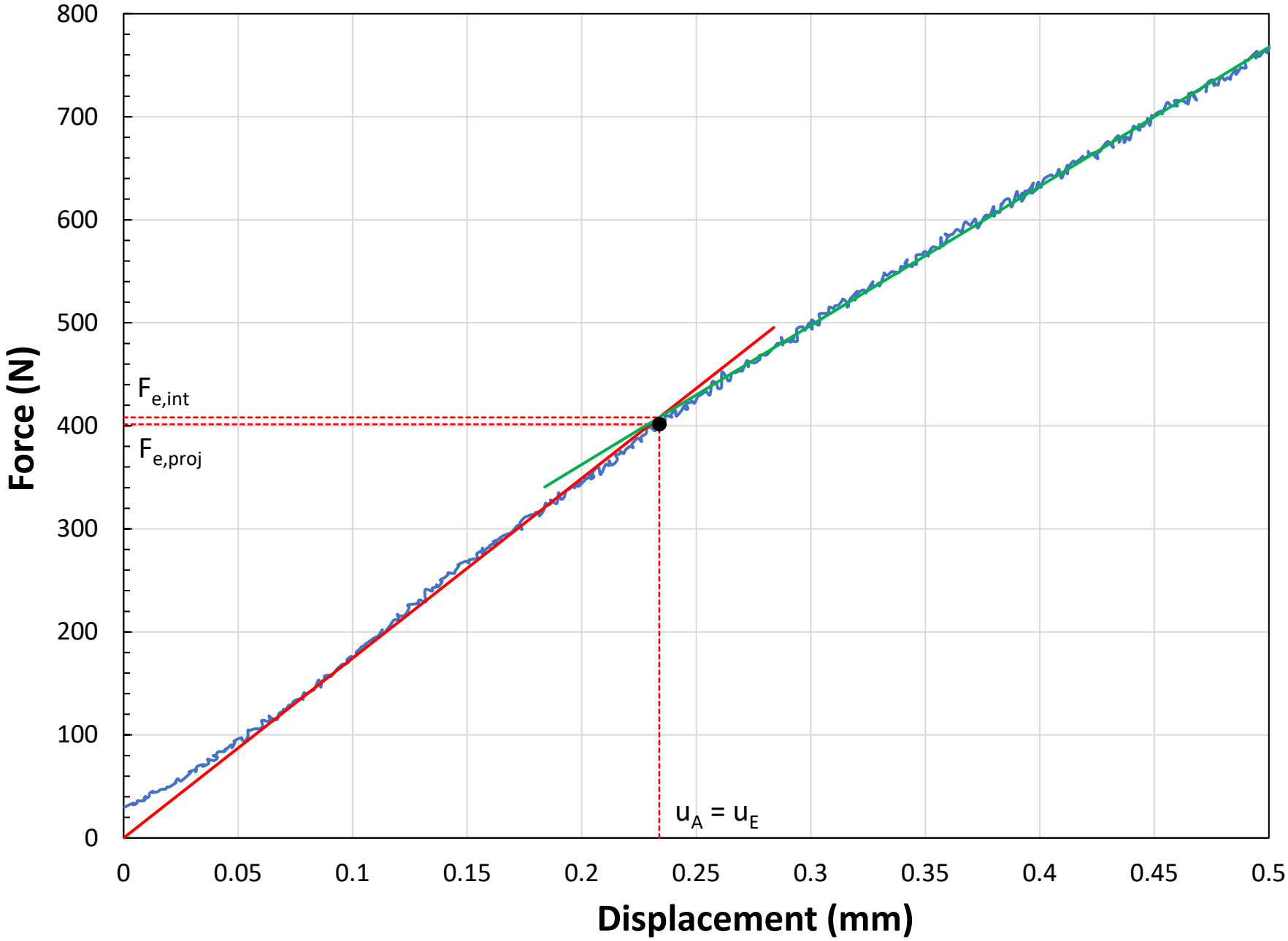

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP6
Material: AM Ti-64
Test speed: 0.001034 mm/s
Max strain rate: 1.03E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	401.5	N
$F_{e,int}$ =	408.2	N
$F_{h0/10,off}$ =	675.0	N
$F_{0.1mm,off}$ =	872.4	N
$F_{0.1mm}$ =	174.9	N
$F_{0.48mm}$ =	738.2	N
$F_{0.5mm}$ =	762.2	N
$F_{0.65mm}$ =	922.1	N
$F_{0.9mm}$ =	1003.1	N
F_{ept} =	756.4	N
$F_{e1.5}$ =	140.7	N
F_m =	1090.5	N
F_{infl} =	715.8	N
F_f =	872.4	N
Displacement values		
u_e =	0.234	mm
$u_{h0/10,off}$ =	0.437	mm
$u_{0.1mm,off}$ =	0.601	mm
$u_{e1.5}$ =	0.079	mm
u_m =	1.058	mm
u_{infl} =	1.752	mm
u_f =	1.558	mm
Initial linear slope		
$Slope_{ini}$ =	1745.38	N/mm
Energy values		
E_{SP} =	1.25	J
E_m =	0.75	J
E_{PL} =	0.41	J

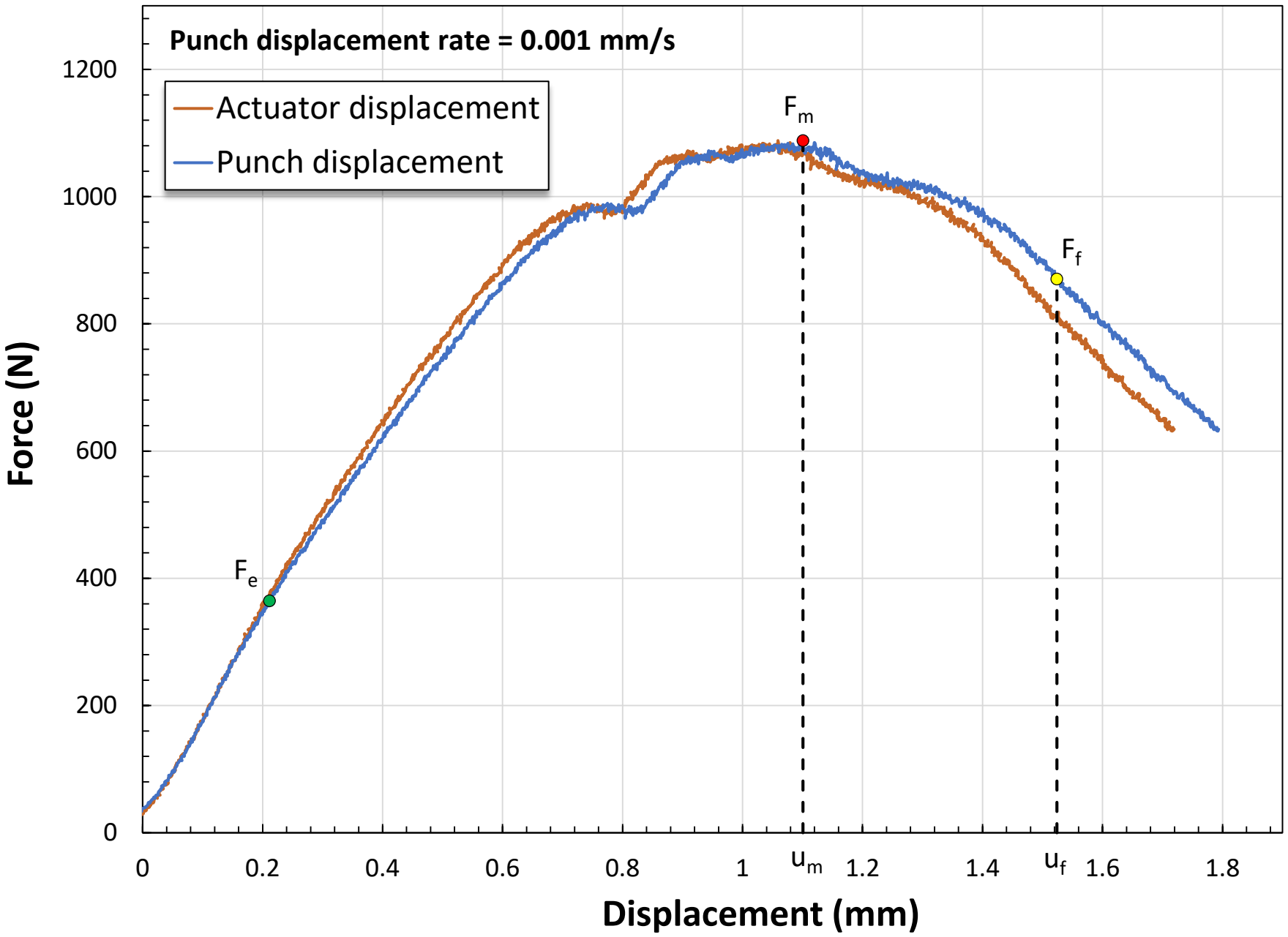

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

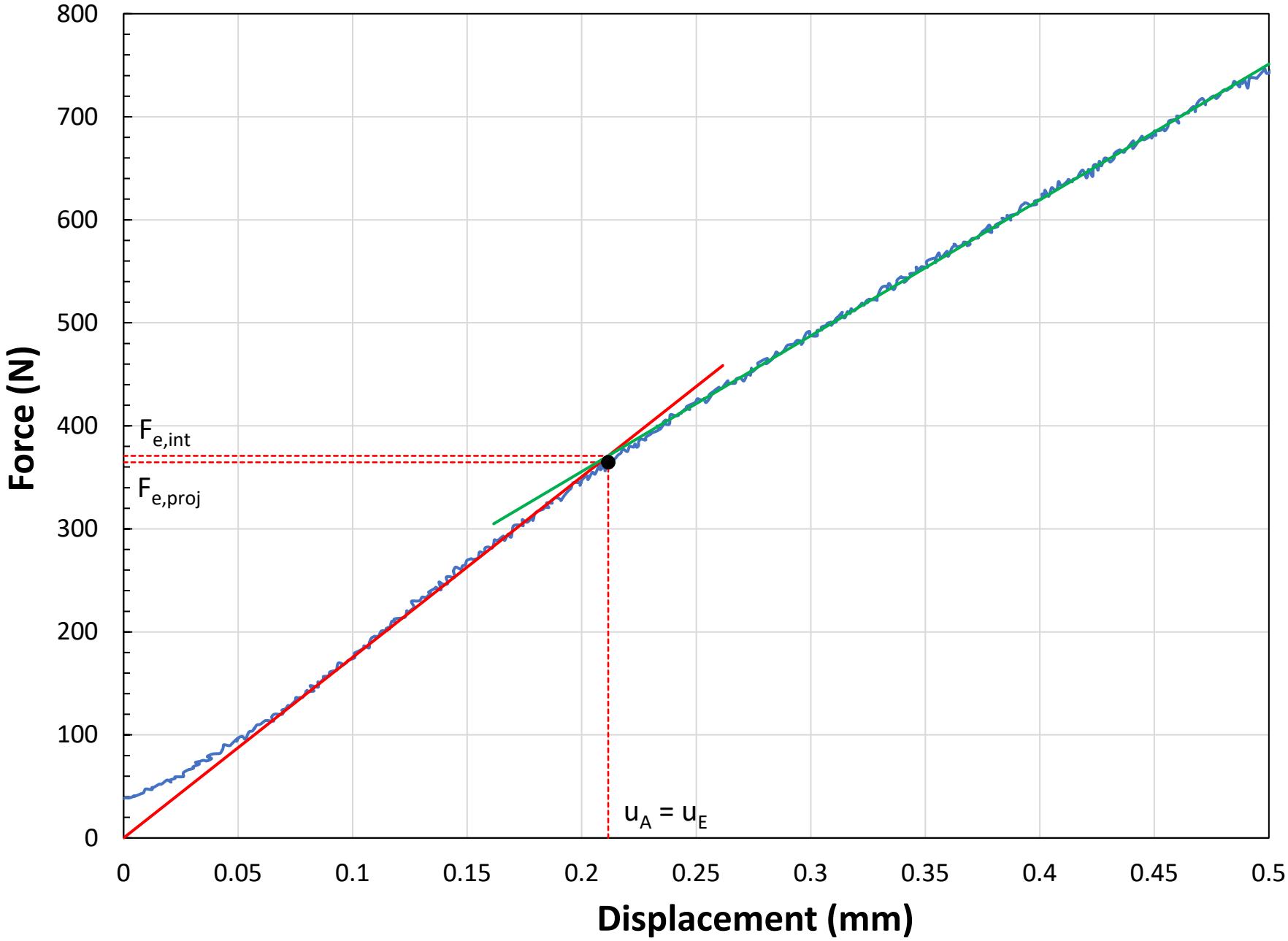

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP7
Material: AM Ti-64
Test speed: 0.001043 mm/s
Max strain rate: 1.04E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	364.6	N
$F_{e,int}$ =	370.9	N
$F_{h0/10,off}$ =	637.4	N
$F_{0.1mm,off}$ =	832.6	N
$F_{0.1mm}$ =	172.4	N
$F_{0.48mm}$ =	725.1	N
$F_{0.5mm}$ =	742.0	N
$F_{0.65mm}$ =	915.6	N
$F_{0.9mm}$ =	1055.6	N
F_{ept} =	241.5	N
$F_{e1.5}$ =	164.6	N
F_m =	1088.0	N
F_{infl} =	634.4	N
F_f =	870.4	N
Displacement values		
u_e =	0.212	mm
$u_{h0/10,off}$ =	0.414	mm
$u_{0.1mm,off}$ =	0.576	mm
$u_{e1.5}$ =	0.093	mm
u_m =	1.101	mm
u_{infl} =	1.794	mm
u_f =	1.524	mm
Initial linear slope		
$Slope_{ini}$ =	1752.85	N/mm
Energy values		
E_{SP} =	1.21	J
E_m =	0.79	J
E_{PL} =	0.45	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

ANNEX 5

SP Test Results for

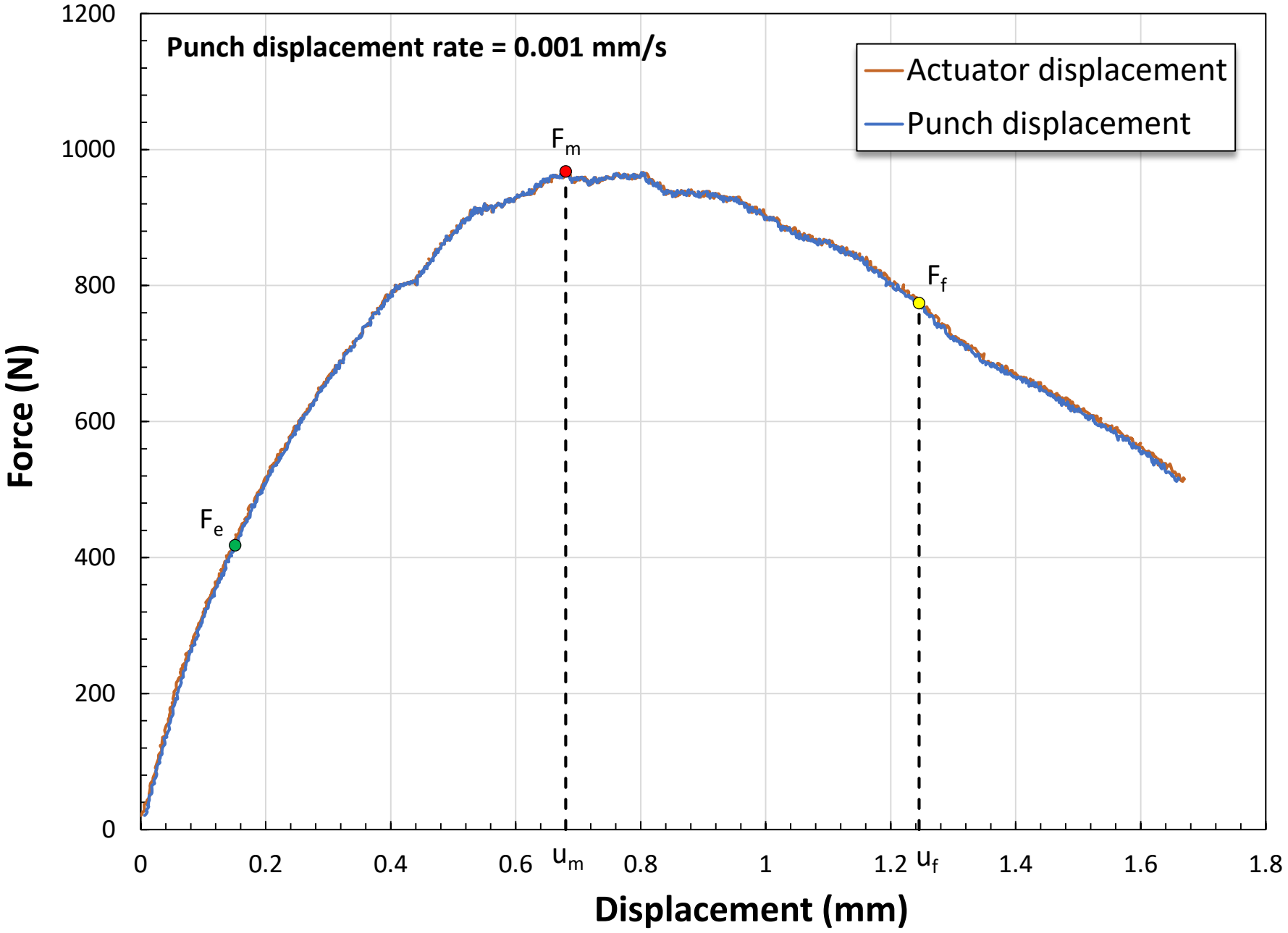
As built, scan length = 26 mm, non-supported

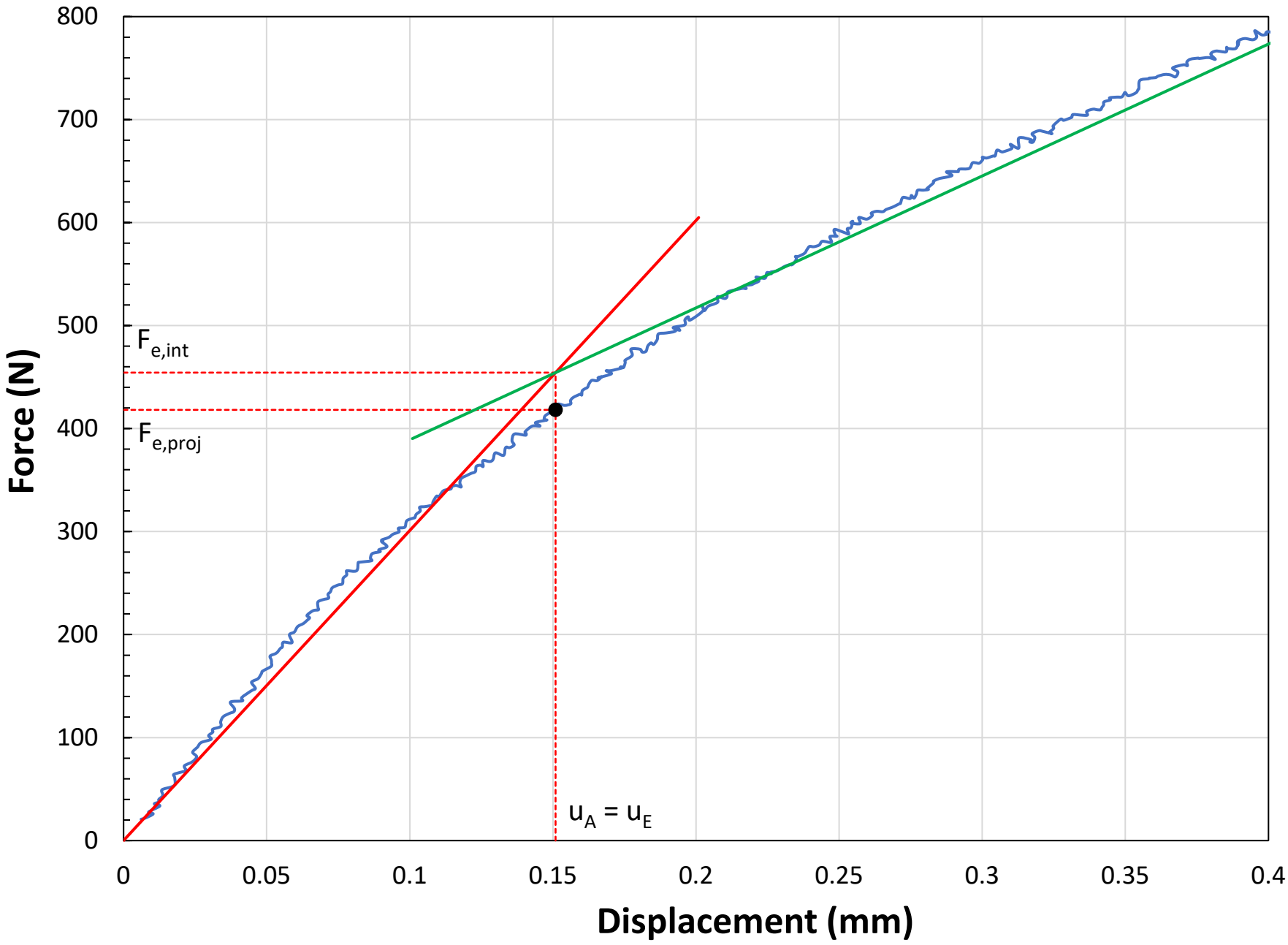
(polished specimens)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP8 (polish
Material: AM Ti-64
Test speed: 0.001444 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	418.2	N
$F_{e,int}$ =	454.3	N
$F_{h0/10,off}$ =	558.7	N
$F_{0.1mm,off}$ =	705.8	N
$F_{0.1mm}$ =	310.4	N
$F_{0.48mm}$ =	853.6	N
$F_{0.5mm}$ =	875.2	N
$F_{0.65mm}$ =	956.3	N
$F_{0.9mm}$ =	934.8	N
F_{ept} =	81.4	N
$F_{e1.5}$ =	760.3	N
F_m =	968.0	N
F_{infl} =	515.4	N
F_f =	774.4	N
Displacement values		
u_e =	0.151	mm
$u_{h0/10,off}$ =	0.231	mm
$u_{0.1mm,off}$ =	0.335	mm
$u_{e1.5}$ =	0.379	mm
u_m =	0.680	mm
u_{infl} =	1.661	mm
u_f =	1.245	mm
Initial linear slope		
$Slope_{ini}$ =	3010.25	N/mm
Energy values		
E_{SP} =	0.95	J
E_m =	0.44	J
E_{PL} =	0.28	J

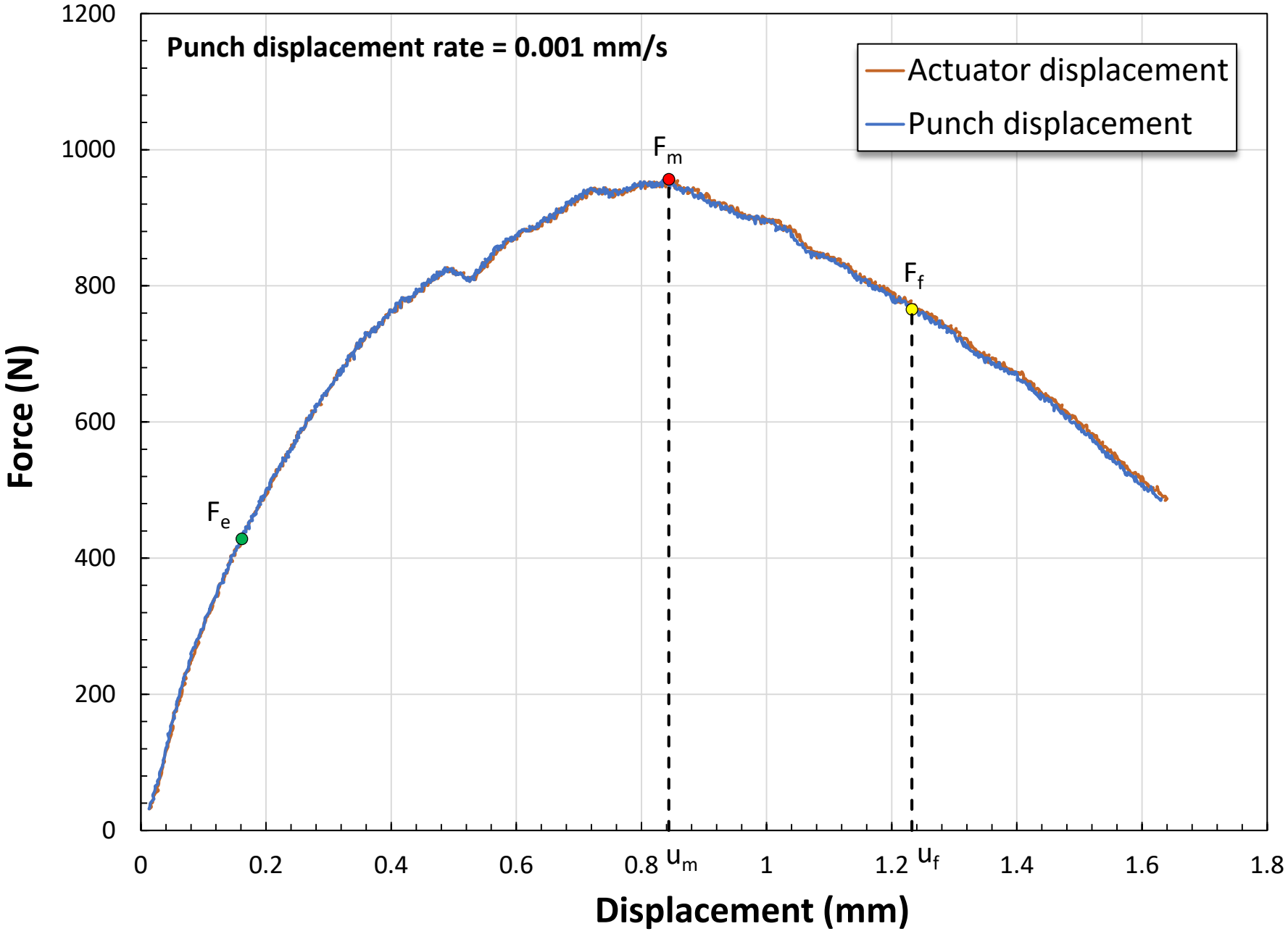

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

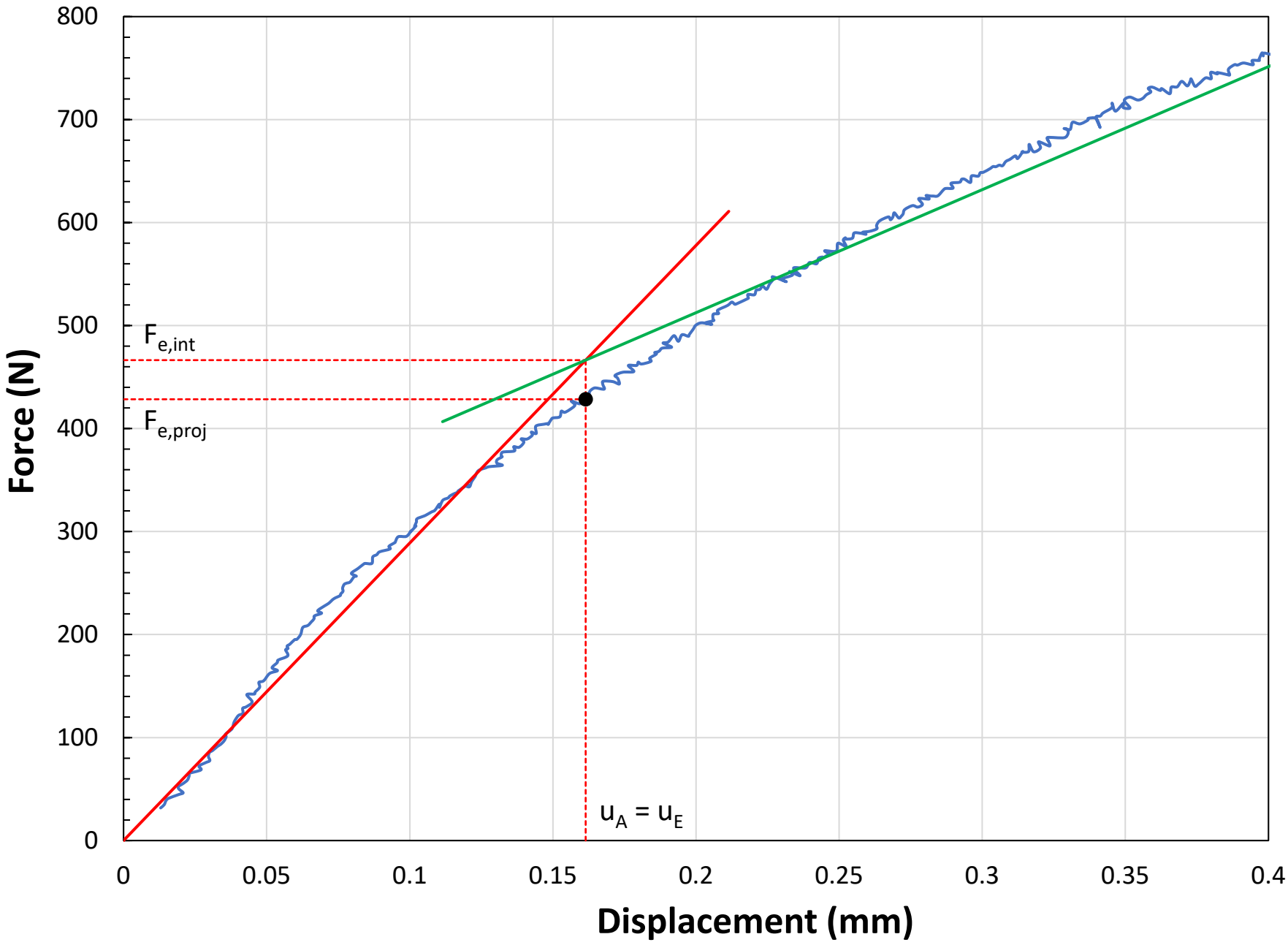

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP9 (polish
Material: AM Ti-64
Test speed: 0.001445 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	428.5	N
$F_{e,int}$ =	466.5	N
$F_{h0/10,off}$ =	552.1	N
$F_{0.1mm,off}$ =	694.6	N
$F_{0.1mm}$ =	295.4	N
$F_{0.48mm}$ =	818.5	N
$F_{0.5mm}$ =	818.5	N
$F_{0.65mm}$ =	897.2	N
$F_{0.9mm}$ =	926.0	N
F_{ept} =	702.3	N
$F_{e1.5}$ =	732.7	N
F_{m} =	956.8	N
F_{infl} =	487.4	N
F_{f} =	765.4	N
Displacement values		
u_{e} =	0.161	mm
$u_{h0/10,off}$ =	0.236	mm
$u_{0.1mm,off}$ =	0.341	mm
$u_{e1.5}$ =	0.372	mm
u_{m} =	0.844	mm
u_{infl} =	1.631	mm
u_{f} =	1.232	mm
Initial linear slope		
$Slope_{ini}$ =	2889.12	N/mm
Energy values		
E_{SP} =	0.91	J
E_{m} =	0.57	J
E_{PL} =	0.42	J

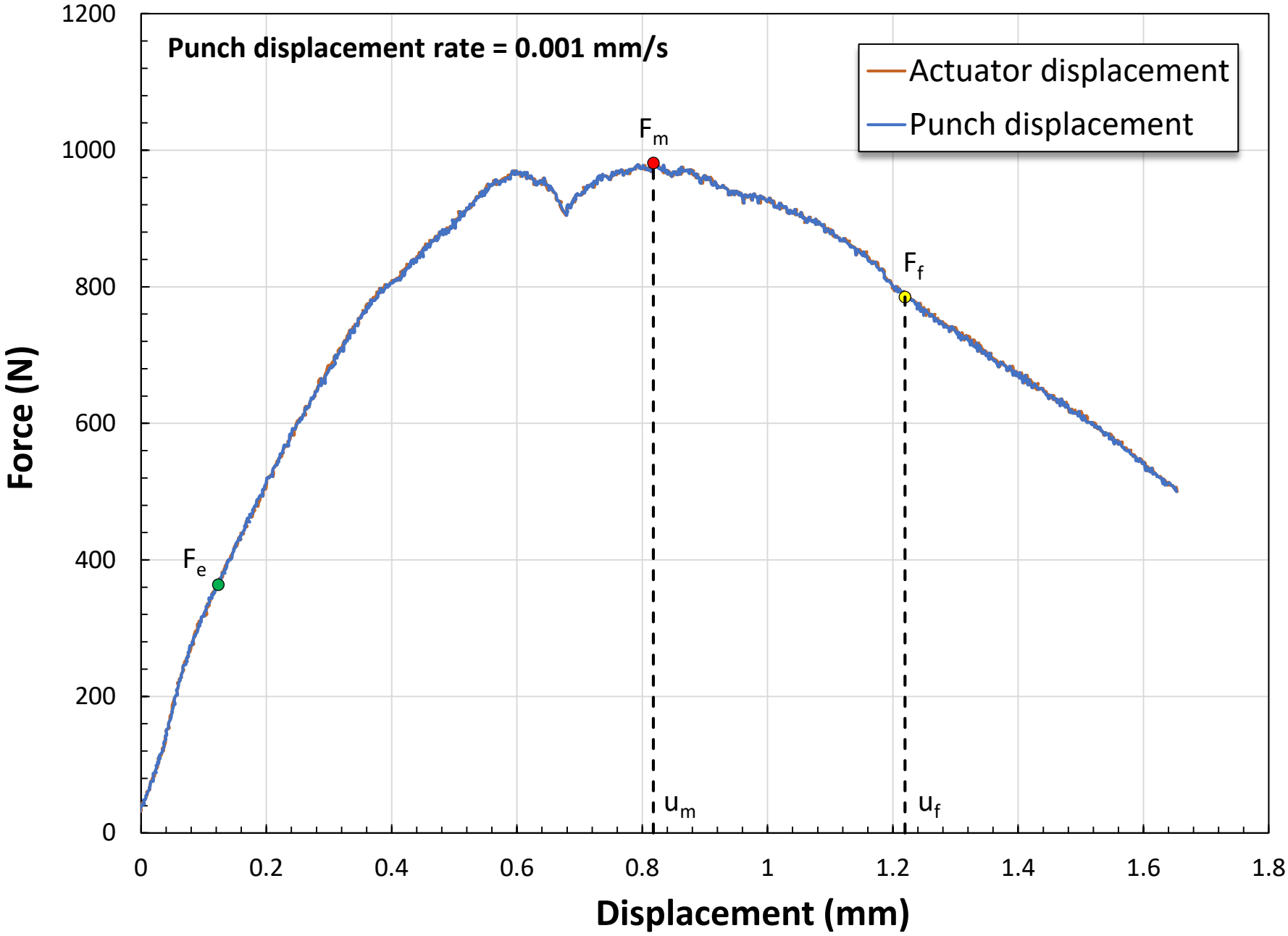

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

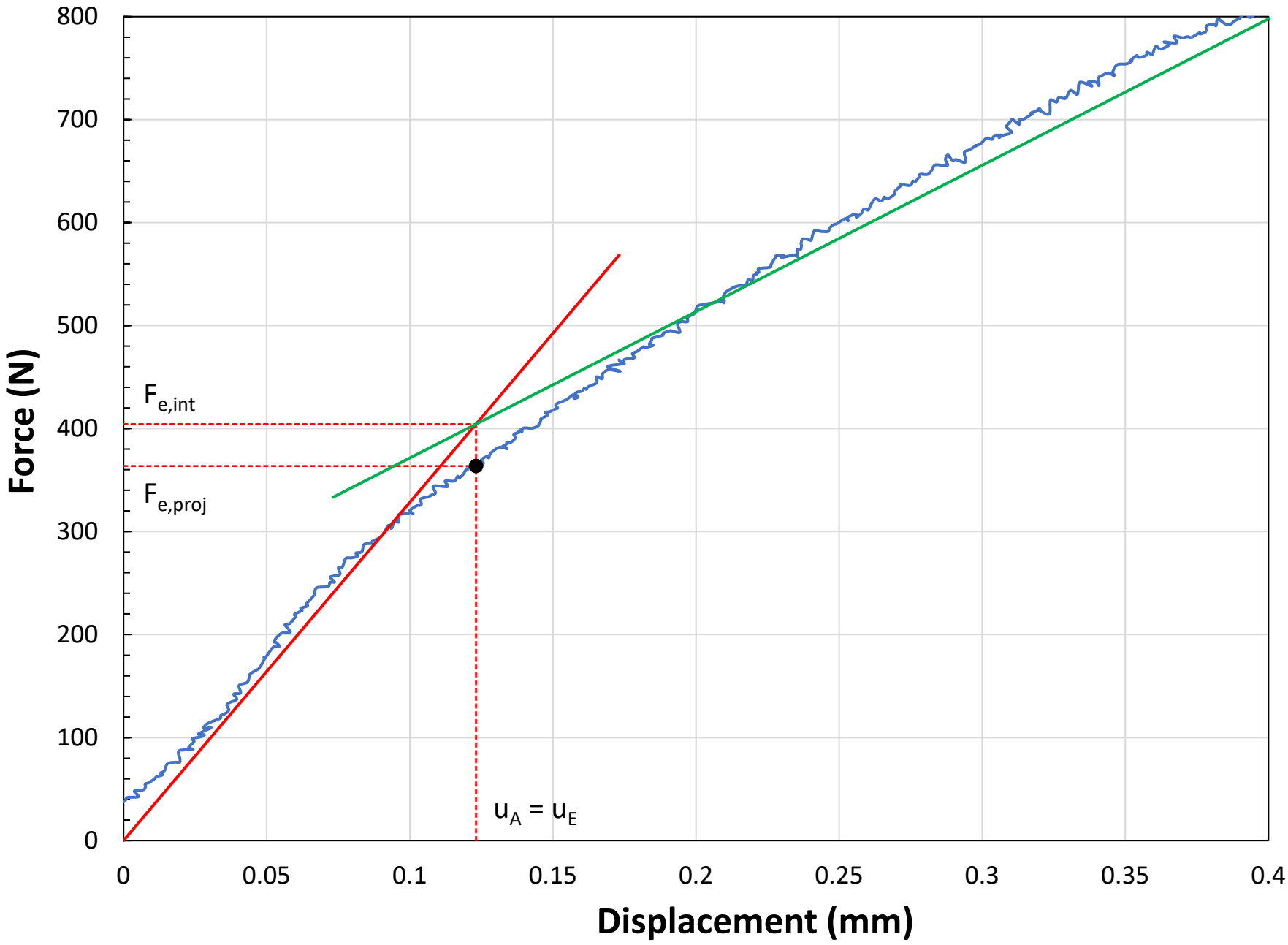

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: AB_3_N_a_SP10 (polis
Material: AM Ti-64
Test speed: 0.001449 mm/s
Max strain rate: 1.45E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	363.6	N
$F_{e,int}$ =	404.3	N
$F_{h0/10,off}$ =	522.6	N
$F_{0.1mm,off}$ =	688.9	N
$F_{0.1mm}$ =	317.7	N
$F_{0.48mm}$ =	880.6	N
$F_{0.5mm}$ =	898.1	N
$F_{0.65mm}$ =	949.1	N
$F_{0.9mm}$ =	962.4	N
F_{ept} =	430.5	N
$F_{e1.5}$ =	658.3	N
F_m =	981.3	N
F_{infl} =	76.1	N
F_f =	785.1	N
Displacement values		
u_e =	0.123	mm
$u_{h0/10,off}$ =	0.205	mm
$u_{0.1mm,off}$ =	0.310	mm
$u_{e1.5}$ =	0.294	mm
u_m =	0.818	mm
u_{infl} =	0.018	mm
u_f =	1.219	mm
Initial linear slope		
$Slope_{ini}$ =	3283.40	N/mm
Energy values		
E_{SP} =	0.94	J
E_m =	0.58	J
E_{PL} =	0.43	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

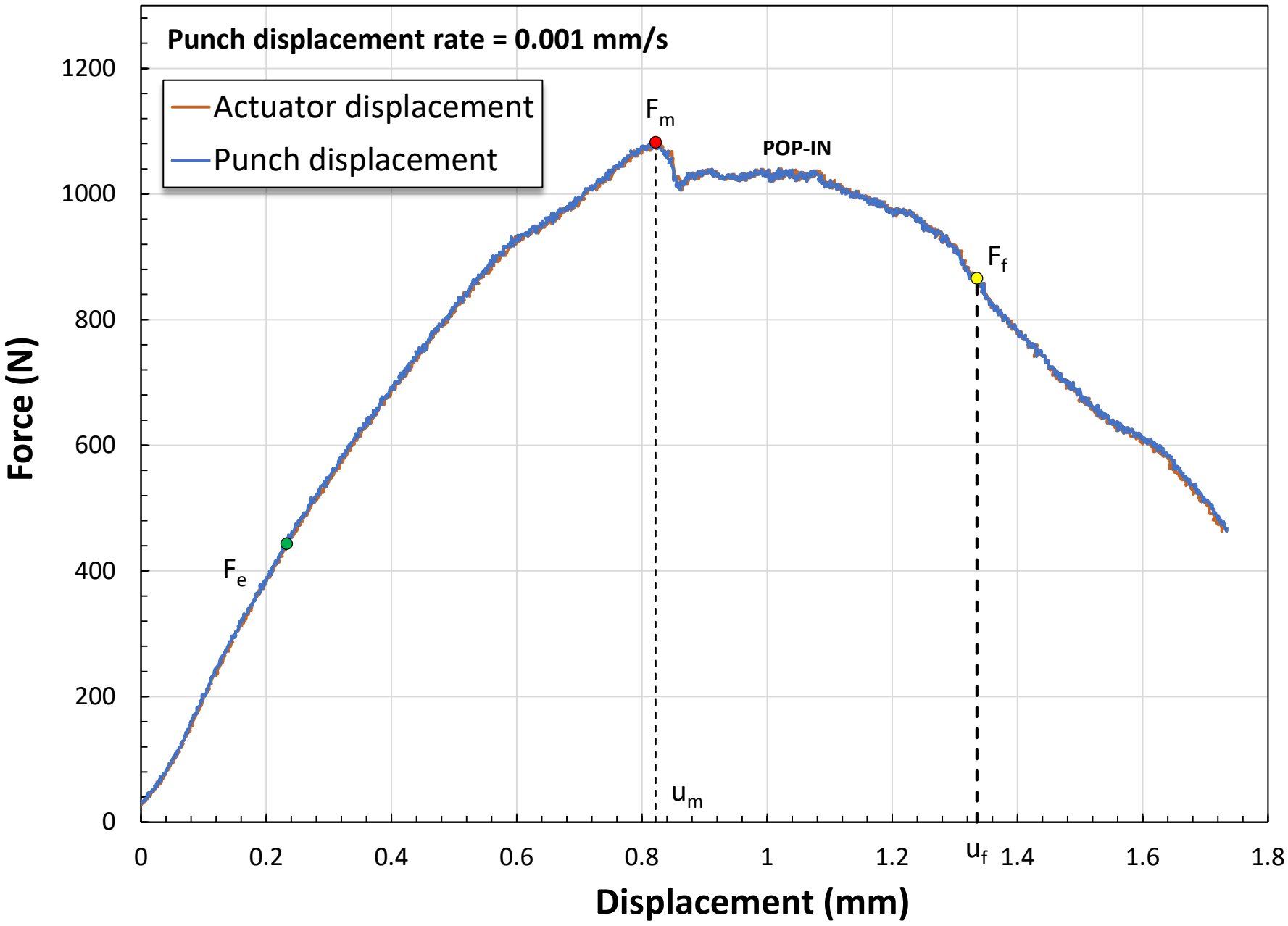
ANNEX 6

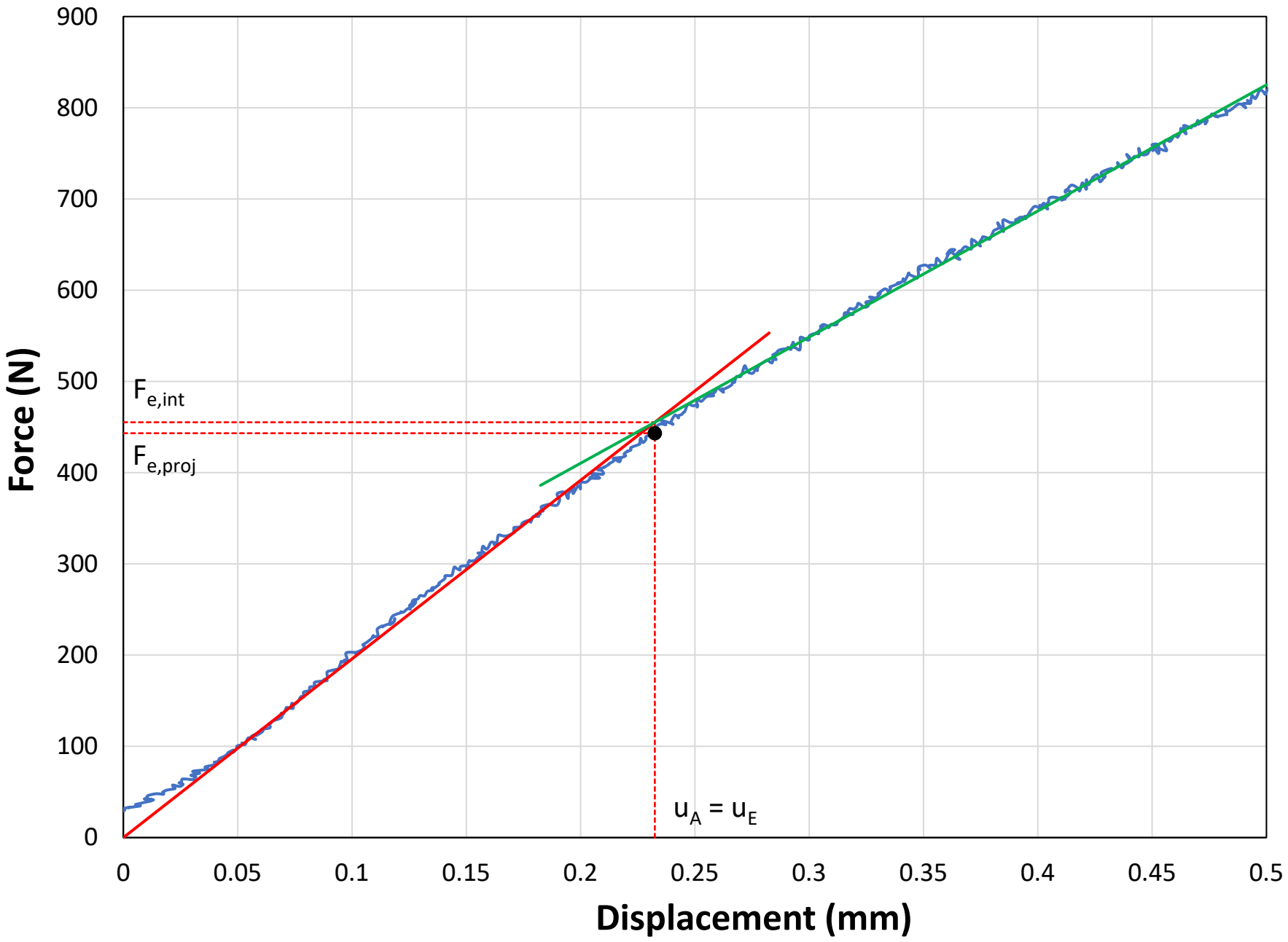
SP Test Results for
800 °C HIP, scan length = 78 mm, non-supported
(“rough” specimens)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP1
Material: AM Ti-64
Test speed: 0.001004 mm/s
Max strain rate: 1.00E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	443.2	N
$F_{e,int}$ =	455.3	N
$F_{h0/10,off}$ =	691.4	N
$F_{0.1mm,off}$ =	868.9	N
$F_{0.1mm}$ =	202.7	N
$F_{0.48mm}$ =	790.4	N
$F_{0.5mm}$ =	815.5	N
$F_{0.65mm}$ =	959.6	N
$F_{0.9mm}$ =	1032.8	N
F_{ept} =	572.9	N
$F_{e1.5}$ =	10.1	N
F_m =	1082.5	N
F_{infl} =	468.1	N
F_f =	866.0	N
Displacement values		
u_e =	0.232	mm
$u_{h0/10,off}$ =	0.404	mm
$u_{0.1mm,off}$ =	0.544	mm
$u_{e1.5}$ =	-0.025	mm
u_m =	0.822	mm
u_{infl} =	1.734	mm
u_f =	1.335	mm
Initial linear slope		
$Slope_{ini}$ =	1958.20	N/mm
Energy values		
E_{SP} =	1.05	J
E_m =	0.54	J
E_{PL} =	0.24	J

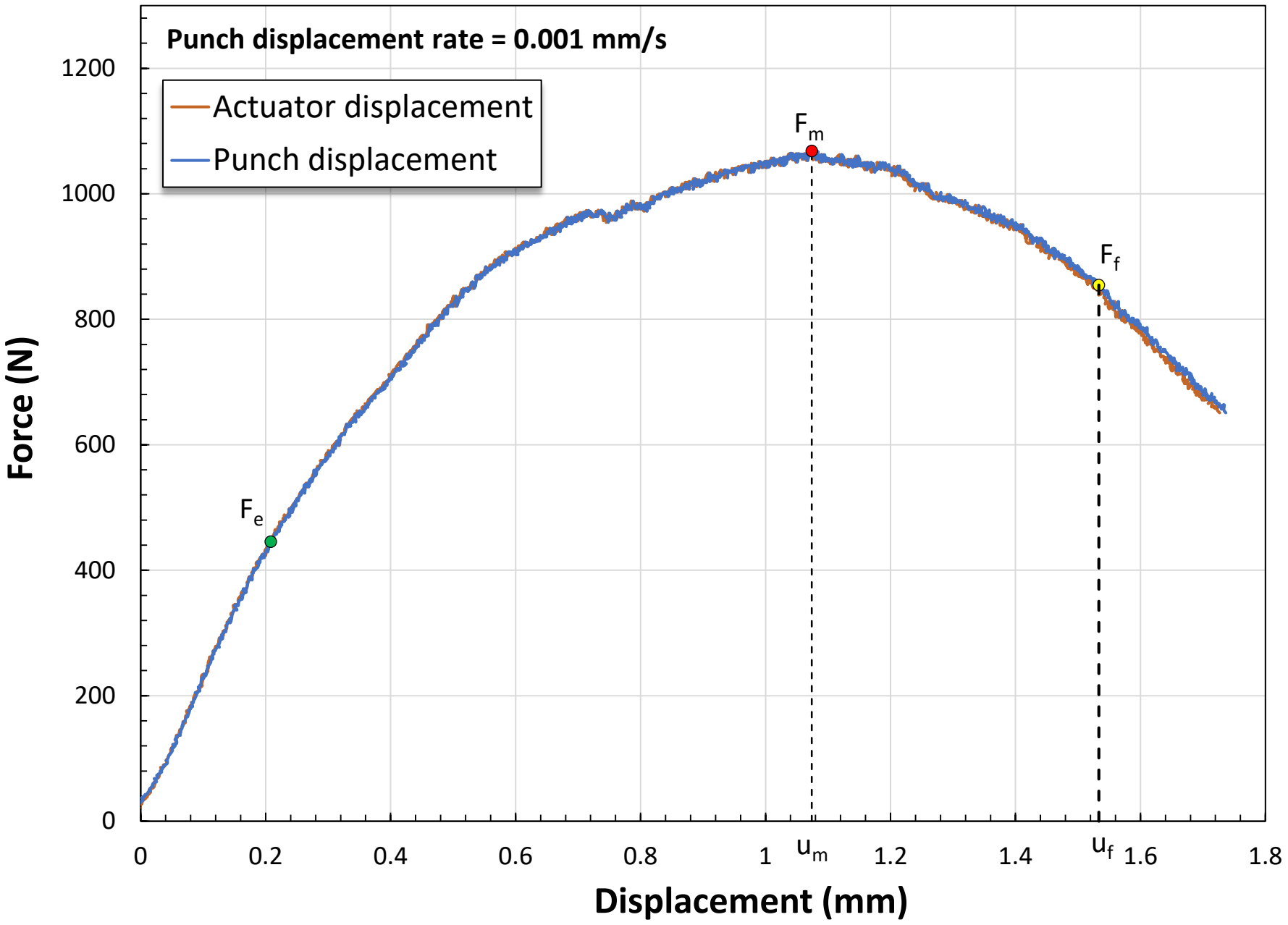

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
POP-IN
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

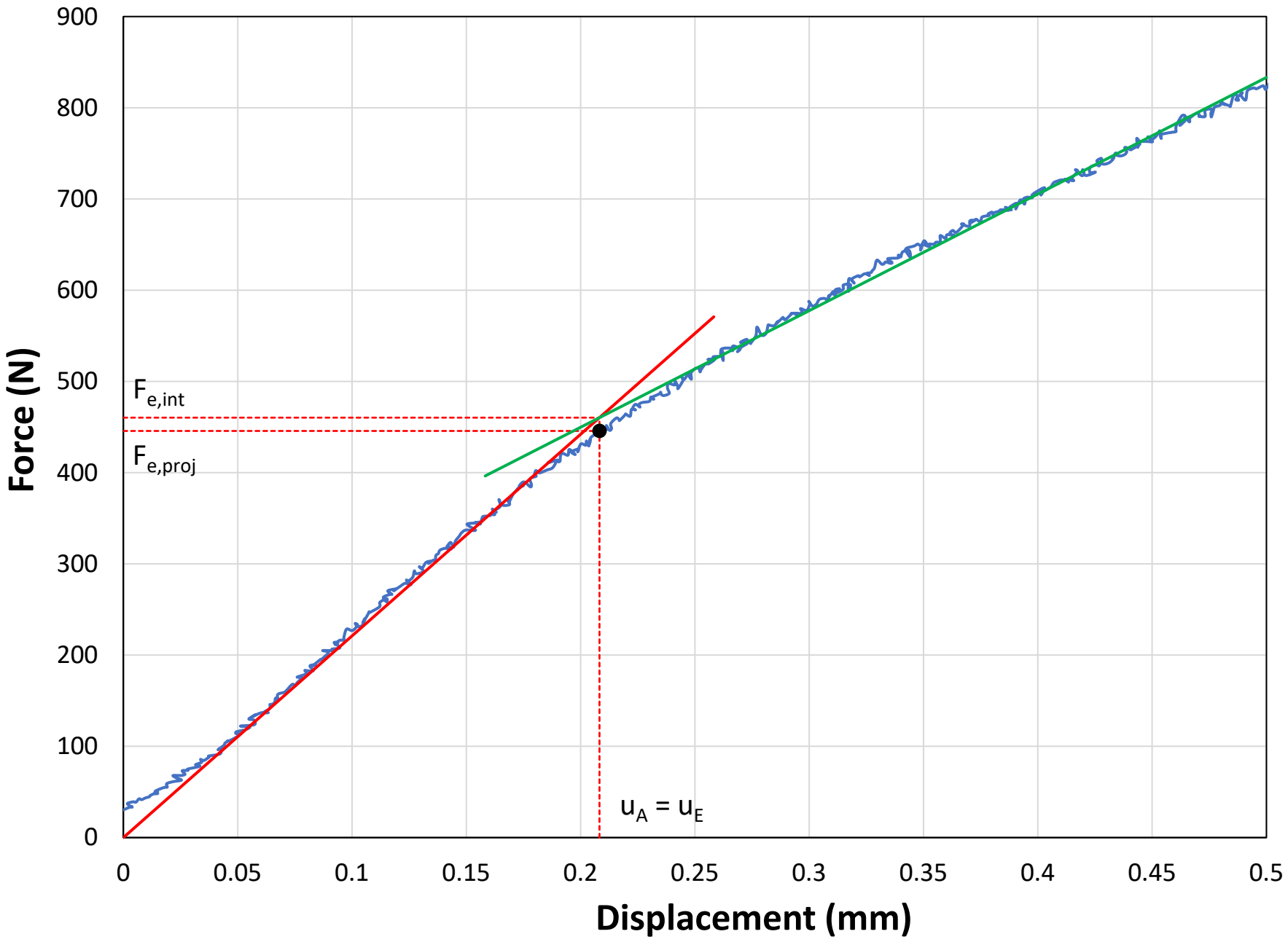

900
800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP2
Material: AM Ti-64
Test speed: 0.001005 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	445.7	N
$F_{e,int}$ =	460.3	N
$F_{h0/10,off}$ =	630.4	N
$F_{0.1mm,off}$ =	761.0	N
$F_{0.1mm}$ =	228.5	N
$F_{0.48mm}$ =	803.0	N
$F_{0.5mm}$ =	820.2	N
$F_{0.65mm}$ =	938.4	N
$F_{0.9mm}$ =	1020.1	N
F_{ept} =	966.0	N
$F_{e1.5}$ =	136.8	N
F_m =	1068.2	N
F_{infl} =	628.6	N
F_f =	854.6	N
Displacement values		
u_e =	0.208	mm
$u_{h0/10,off}$ =	0.336	mm
$u_{0.1mm,off}$ =	0.445	mm
$u_{e1.5}$ =	0.060	mm
u_m =	1.074	mm
u_{infl} =	0.332	mm
u_f =	1.533	mm
Initial linear slope		
$Slope_{ini}$ =	2210.27	N/mm
Energy values		
E_{SP} =	1.25	J
E_m =	0.80	J
E_{PL} =	0.54	J

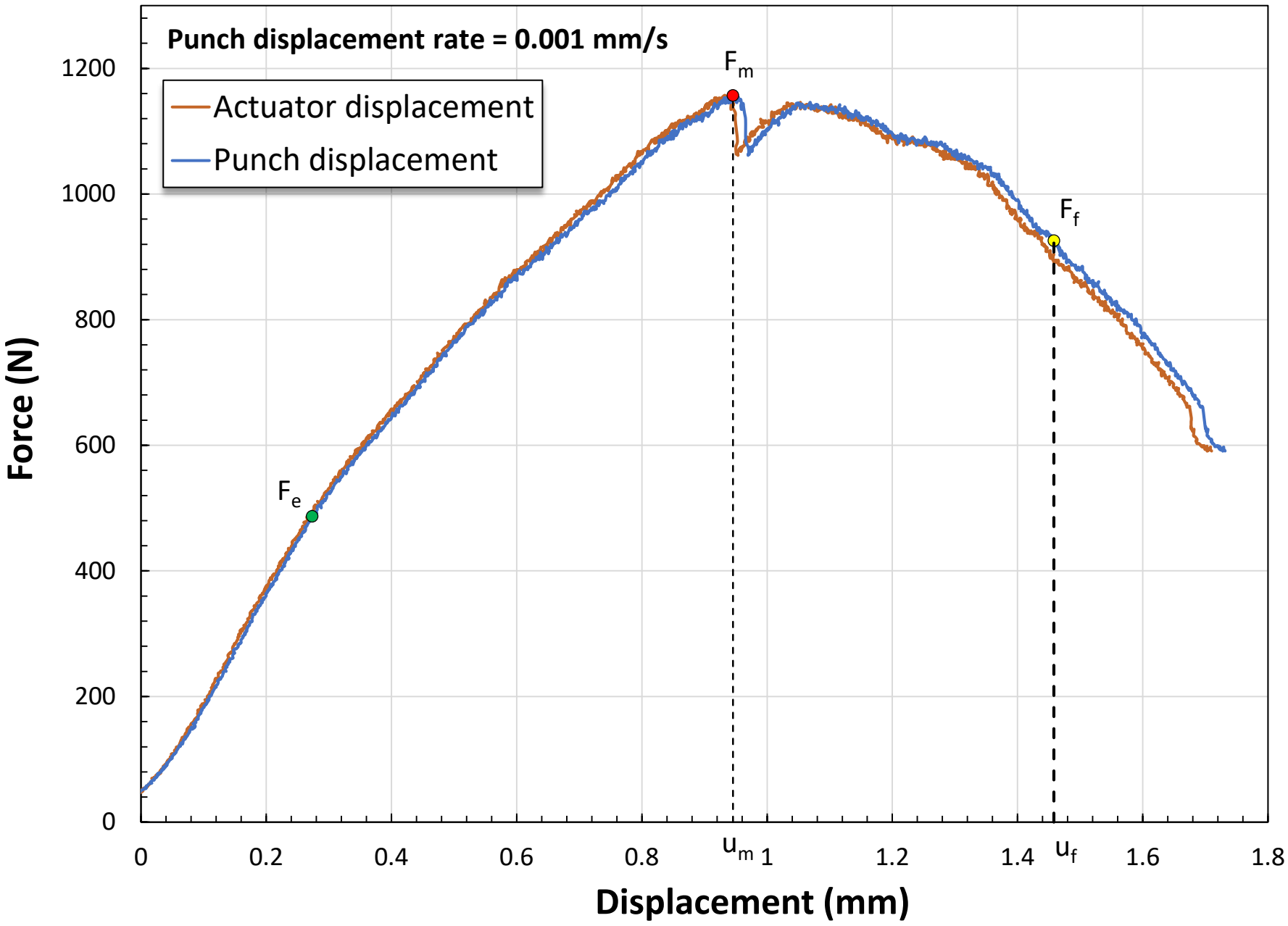

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

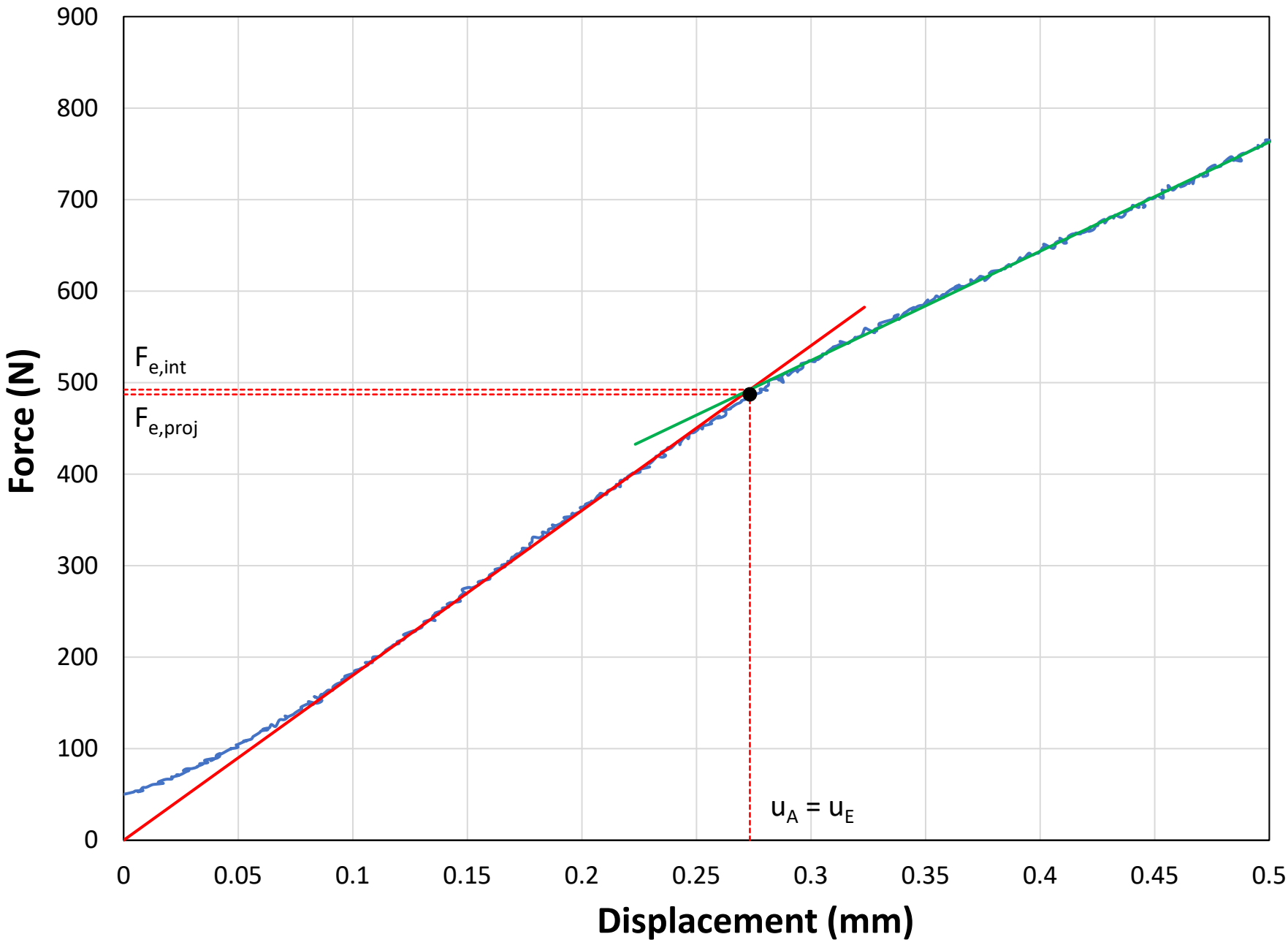

900
800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP3
Material: AM Ti-64
Test speed: 0.001012 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	487.1	N
$F_{e,int}$ =	492.4	N
$F_{h0/10,off}$ =	663.9	N
$F_{0.1mm,off}$ =	828.7	N
$F_{0.1mm}$ =	179.3	N
$F_{0.48mm}$ =	737.4	N
$F_{0.5mm}$ =	765.0	N
$F_{0.65mm}$ =	915.6	N
$F_{0.9mm}$ =	1126.4	N
F_{ept} =	708.1	N
$F_{e1.5}$ =	216.7	N
F_{m} =	1157.1	N
F_{infl} =	590.9	N
F_{f} =	925.7	N
Displacement values		
u_{e} =	0.273	mm
$u_{h0/10,off}$ =	0.419	mm
$u_{0.1mm,off}$ =	0.560	mm
$u_{e1.5}$ =	0.119	mm
u_{m} =	0.946	mm
u_{infl} =	1.731	mm
u_{f} =	1.458	mm
Initial linear slope		
$Slope_{ini}$ =	1801.57	N/mm
Energy values		
E_{SP} =	1.20	J
E_{m} =	0.65	J
E_{PL} =	0.28	J

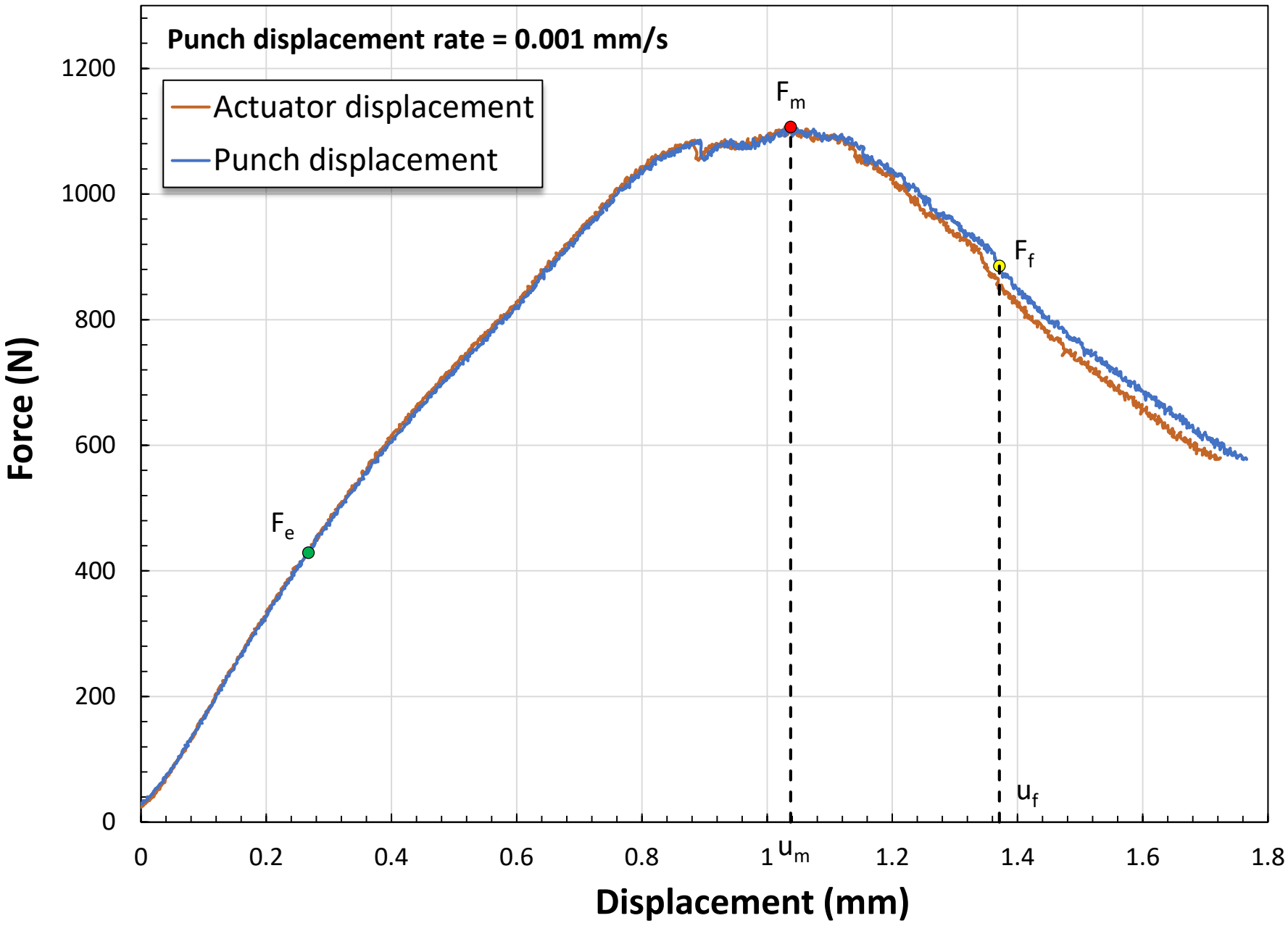

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

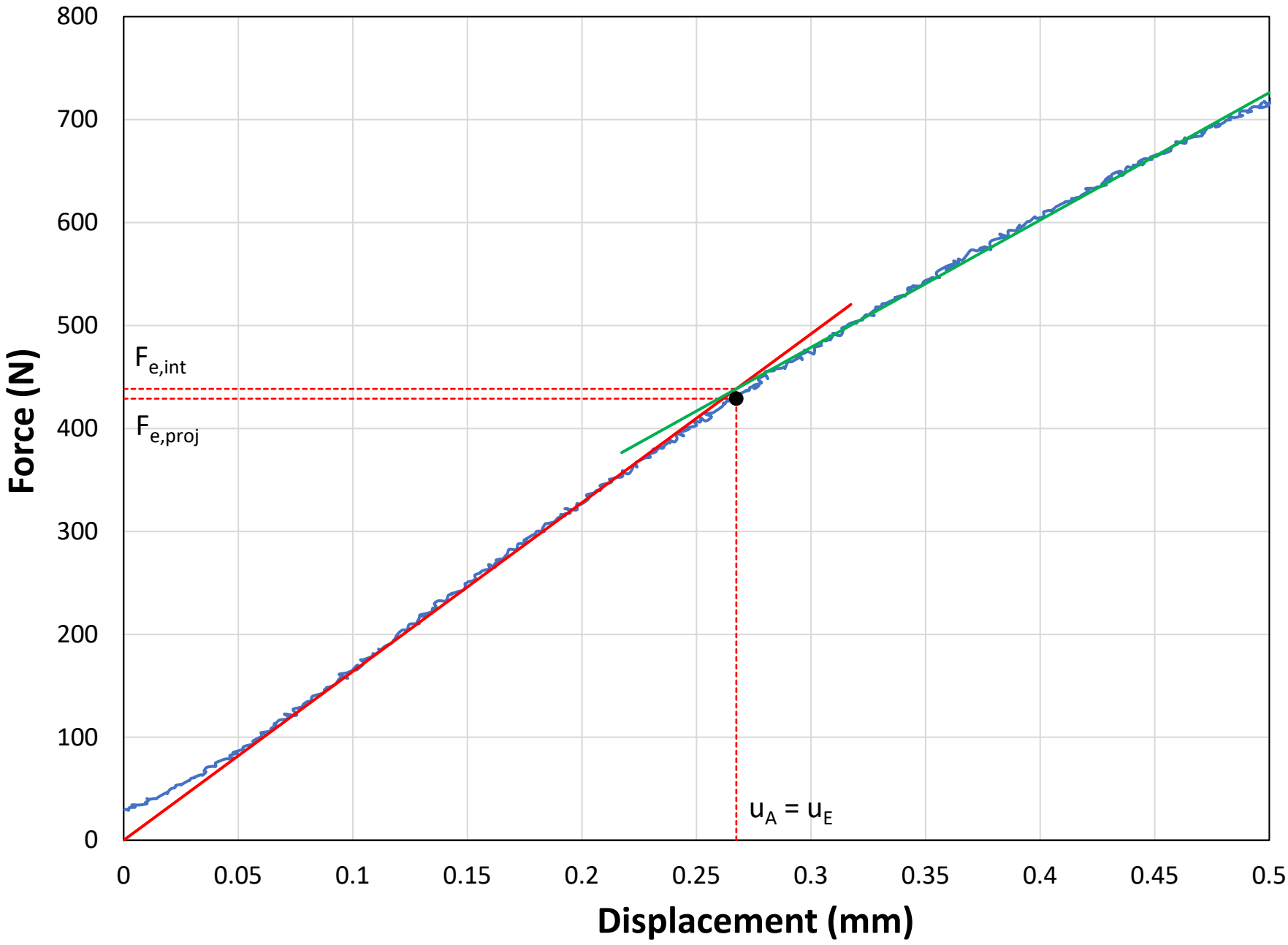

900
800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP4
Material: AM Ti-64
Test speed: 0.001023 mm/s
Max strain rate: 1.02E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	428.9	N
$F_{e,int}$ =	438.4	N
$F_{h0/10,off}$ =	677.5	N
$F_{0.1mm,off}$ =	817.2	N
$F_{0.1mm}$ =	164.1	N
$F_{0.48mm}$ =	692.9	N
$F_{0.5mm}$ =	714.6	N
$F_{0.65mm}$ =	879.5	N
$F_{0.9mm}$ =	1054.7	N
F_{ept} =	411.3	N
$F_{e1.5}$ =	142.5	N
F_m =	1106.8	N
F_{infl} =	577.5	N
F_f =	885.4	N
Displacement values		
u_e =	0.267	mm
$u_{h0/10,off}$ =	0.464	mm
$u_{0.1mm,off}$ =	0.598	mm
$u_{e1.5}$ =	0.086	mm
u_m =	1.038	mm
u_{infl} =	1.766	mm
u_f =	1.371	mm
Initial linear slope		
$Slope_{ini}$ =	1639.54	N/mm
Energy values		
E_{SP} =	1.05	J
E_m =	0.71	J
E_{PL} =	0.34	J

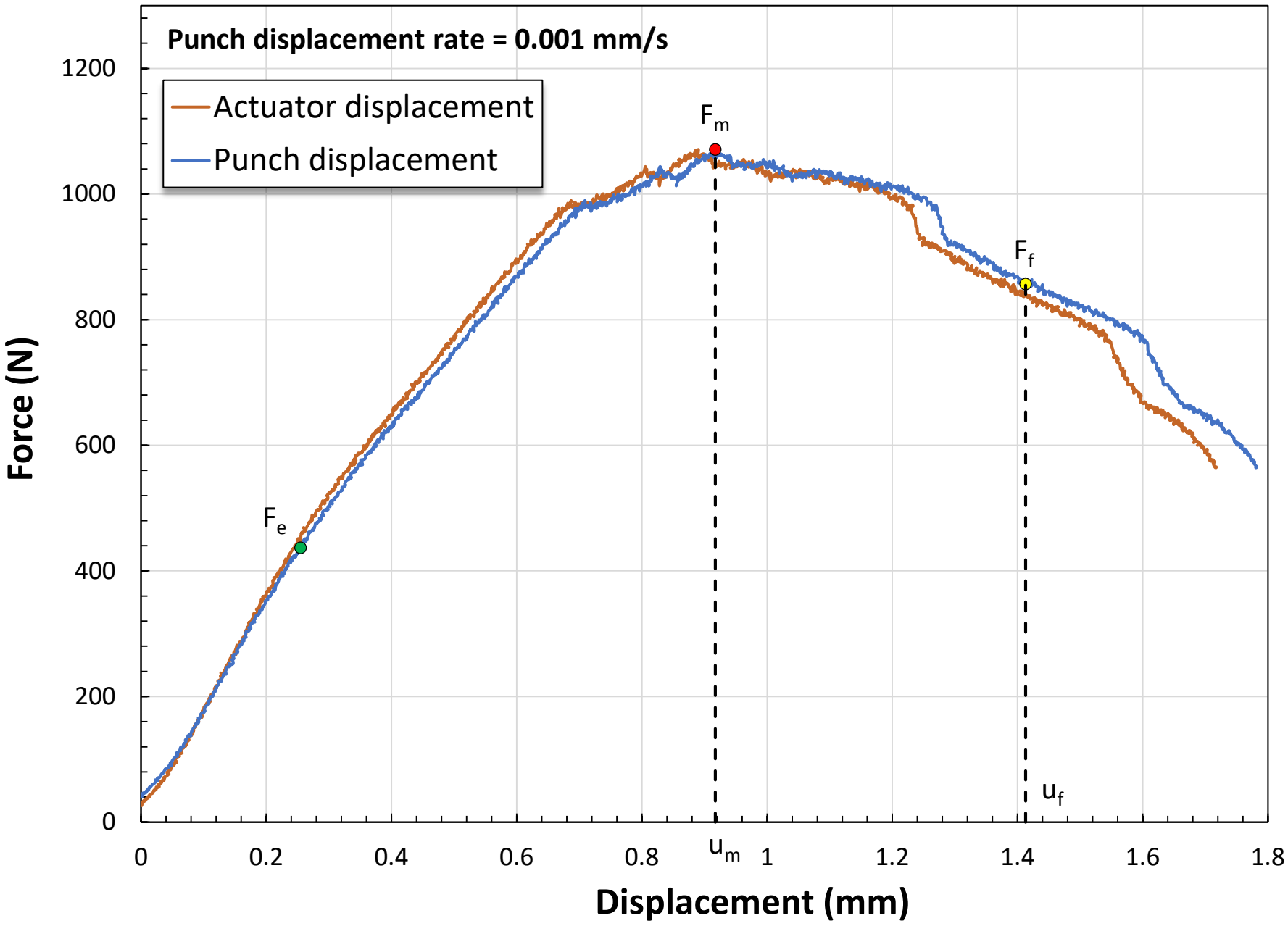

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

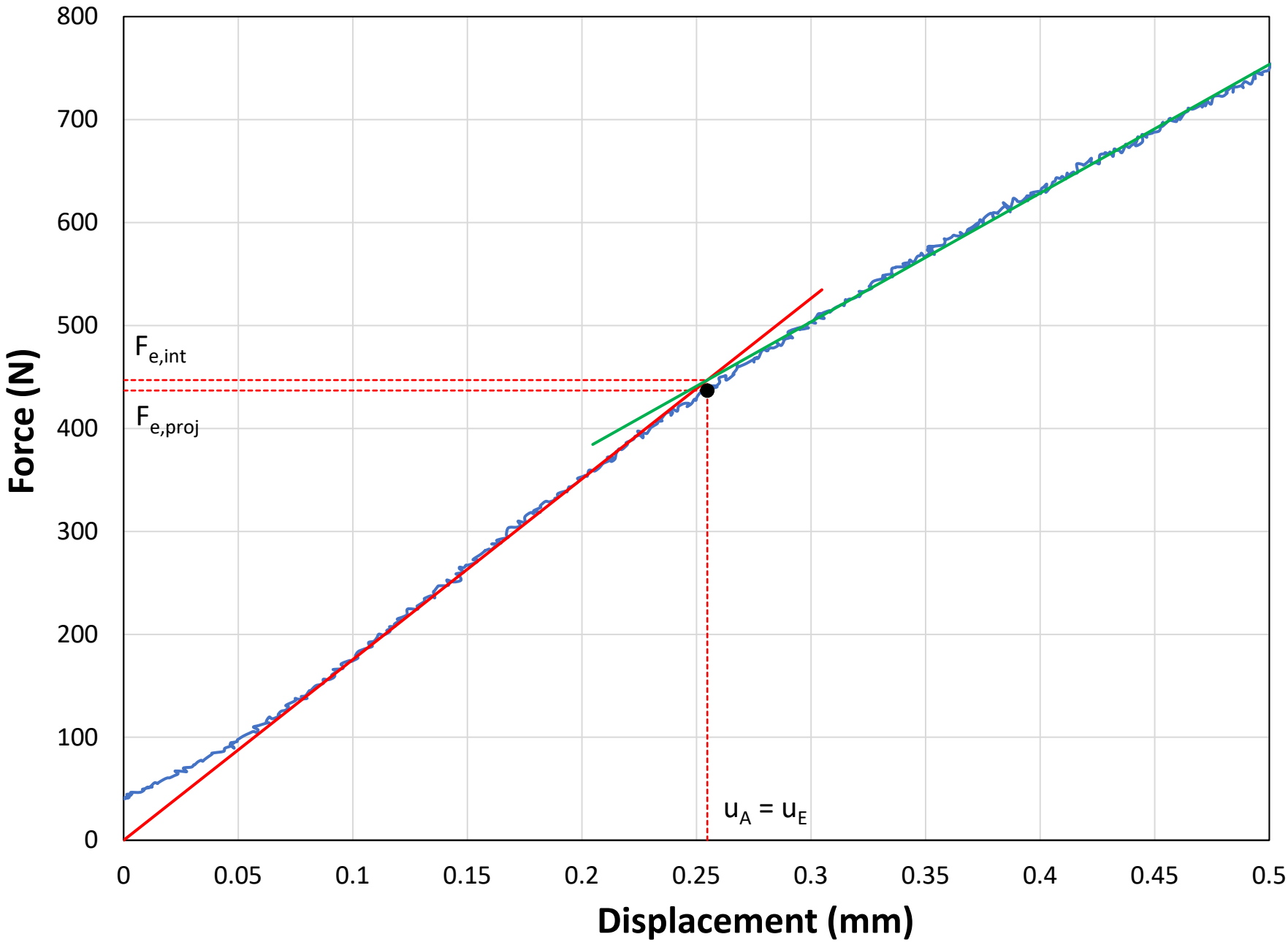

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP5
Material: AM Ti-64
Test speed: 0.001036 mm/s
Max strain rate: 1.04E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	436.8	N
$F_{e,int}$ =	447.0	N
$F_{h0/10,off}$ =	658.3	N
$F_{0.1mm,off}$ =	845.0	N
$F_{0.1mm}$ =	173.6	N
$F_{0.48mm}$ =	722.7	N
$F_{0.5mm}$ =	747.9	N
$F_{0.65mm}$ =	927.5	N
$F_{0.9mm}$ =	1056.0	N
F_{ept} =	115.1	N
$F_{e1.5}$ =	190.3	N
F_m =	1070.9	N
F_{infl} =	565.7	N
F_f =	856.7	N
Displacement values		
u_e =	0.255	mm
$u_{h0/10,off}$ =	0.426	mm
$u_{0.1mm,off}$ =	0.582	mm
$u_{e1.5}$ =	0.108	mm
u_m =	0.917	mm
u_{infl} =	1.782	mm
u_f =	1.413	mm
Initial linear slope		
$Slope_{ini}$ =	1754.55	N/mm
Energy values		
E_{SP} =	1.09	J
E_m =	0.60	J
E_{PL} =	0.27	J

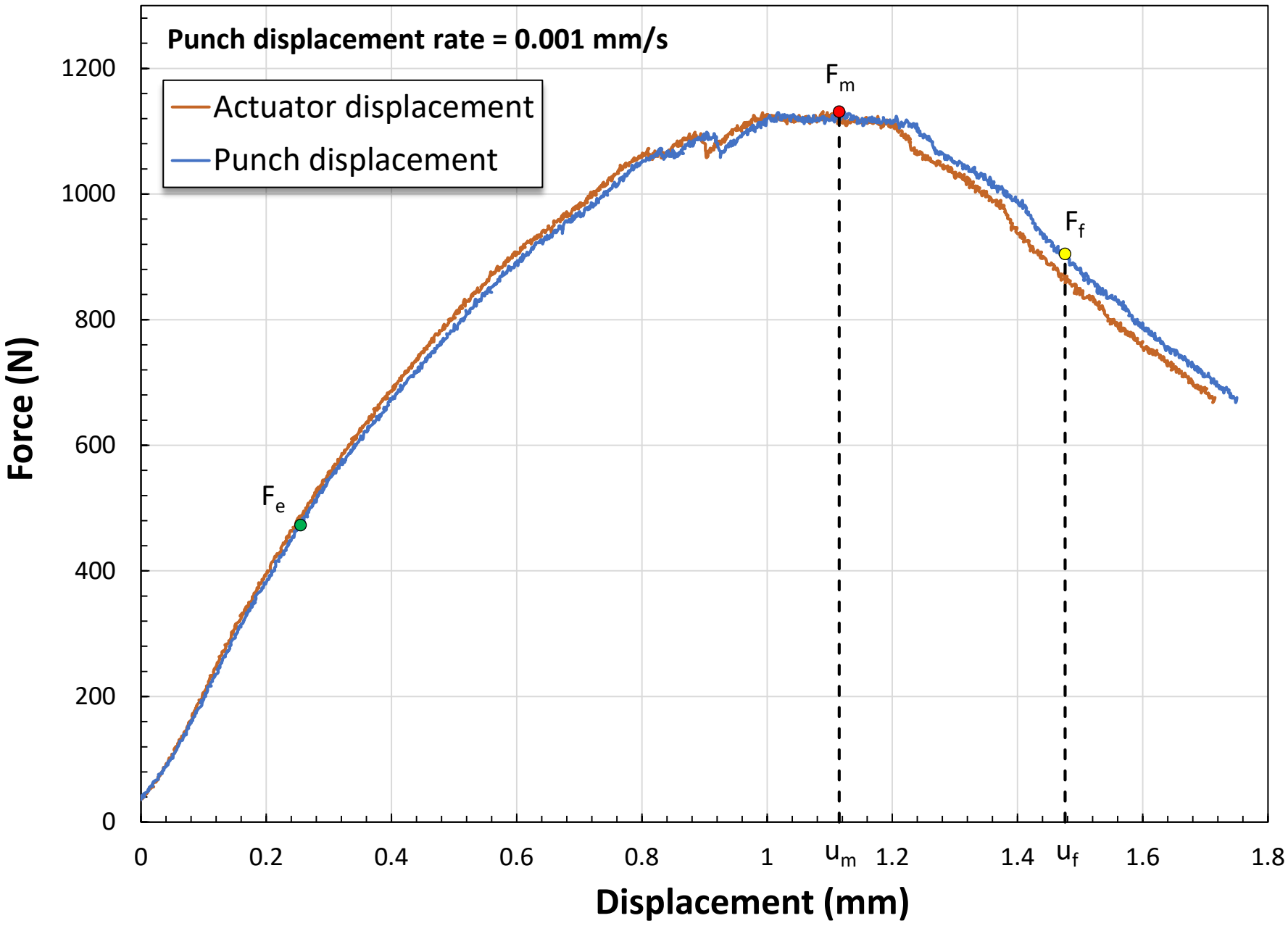

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

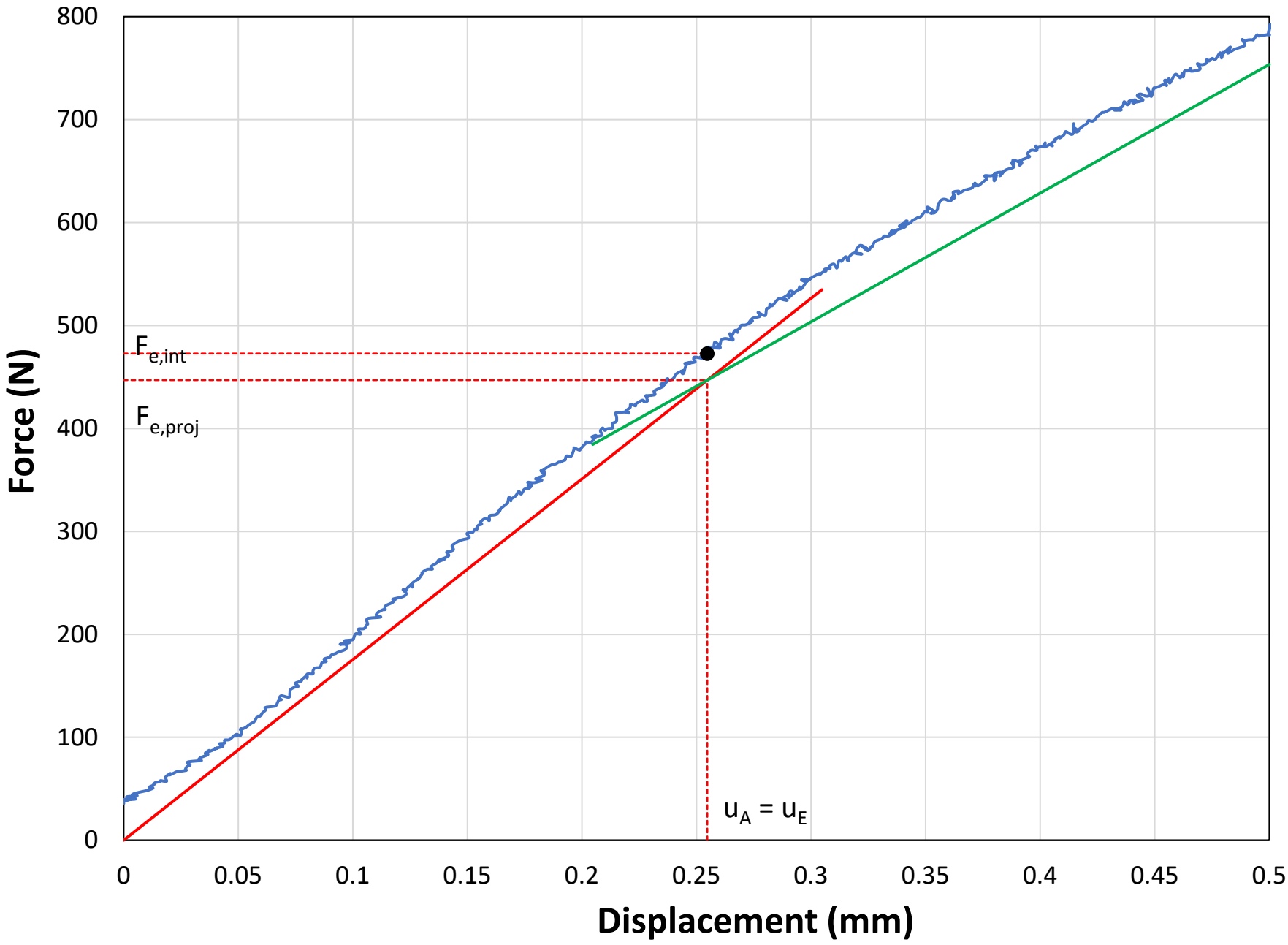

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP6
Material: AM Ti-64
Test speed: 0.001022 mm/s
Max strain rate: 1.02E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	472.8	N
$F_{e,int}$ =	447.0	N
$F_{h0/10,off}$ =	781.3	N
$F_{0.1mm,off}$ =	904.7	N
$F_{0.1mm}$ =	194.5	N
$F_{0.48mm}$ =	763.6	N
$F_{0.5mm}$ =	786.6	N
$F_{0.65mm}$ =	930.1	N
$F_{0.9mm}$ =	1093.5	N
F_{ept} =	1122.7	N
$F_{e1.5}$ =	180.0	N
F_{m} =	1131.1	N
F_{infl} =	960.9	N
F_{f} =	904.9	N
Displacement values		
u_{e} =	0.255	mm
$u_{h0/10,off}$ =	0.495	mm
$u_{0.1mm,off}$ =	0.616	mm
$u_{e1.5}$ =	0.091	mm
u_{m} =	1.115	mm
u_{infl} =	1.422	mm
u_{f} =	1.476	mm
Initial linear slope		
$Slope_{ini}$ =	1754.55	N/mm
Energy values		
E_{SP} =	1.22	J
E_{m} =	0.84	J
E_{PL} =	0.48	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

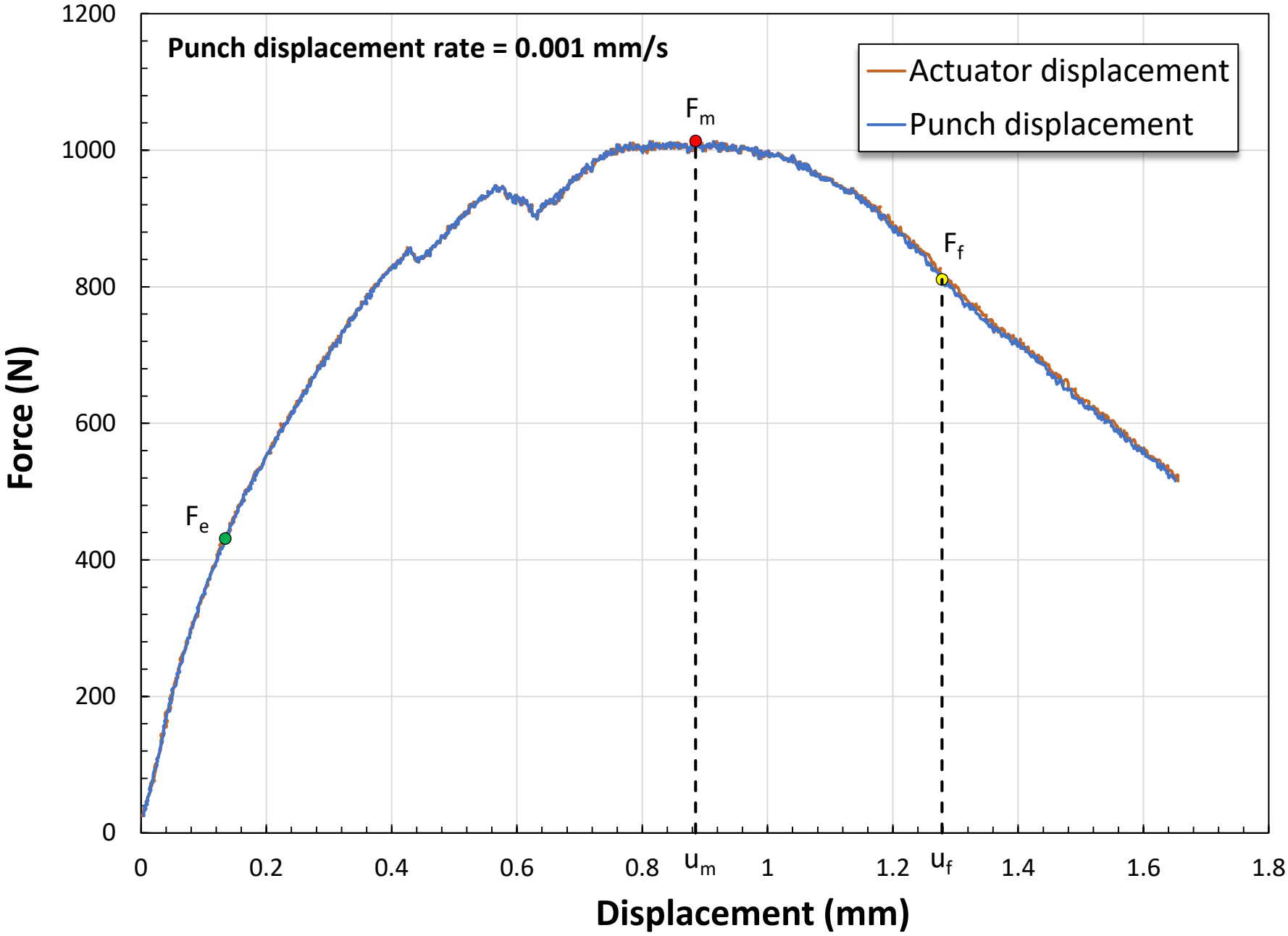
ANNEX 7

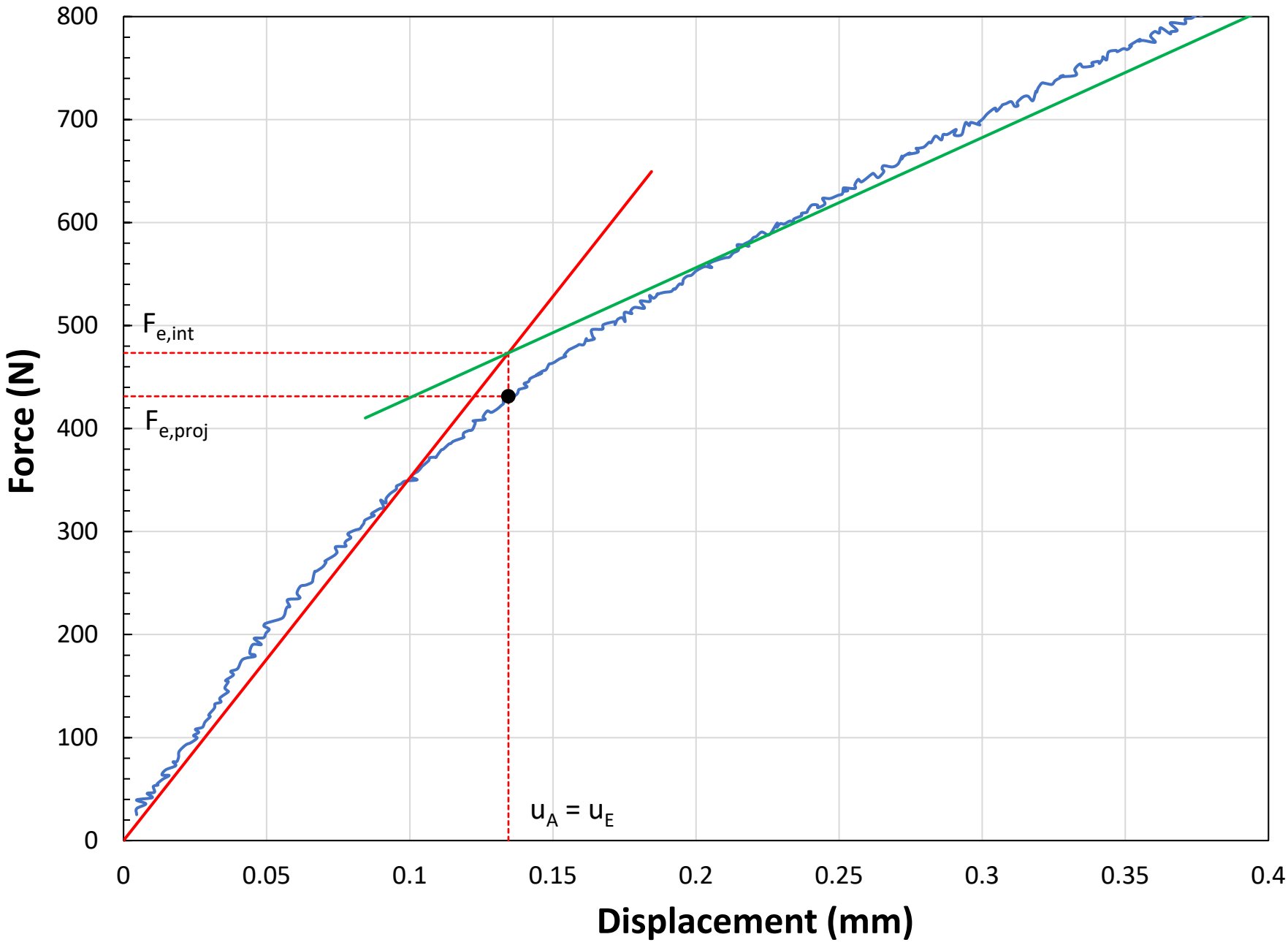
SP Test Results for
800 °C HIP, scan length = 78 mm, non-supported
(polished specimens)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP7 (p
Material: AM Ti-64
Test speed: 0.001441 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	431.3	N
$F_{e,int}$ =	473.5	N
$F_{h0/10,off}$ =	559.8	N
$F_{0.1mm,off}$ =	698.0	N
$F_{0.1mm}$ =	348.9	N
$F_{0.48mm}$ =	874.7	N
$F_{0.5mm}$ =	890.4	N
$F_{0.65mm}$ =	922.1	N
$F_{0.9mm}$ =	1005.9	N
F_{ept} =	652.4	N
$F_{e1.5}$ =	577.2	N
F_m =	1013.5	N
F_{infl} =	988.7	N
F_f =	810.8	N
Displacement values		
u_e =	0.134	mm
$u_{h0/10,off}$ =	0.205	mm
$u_{0.1mm,off}$ =	0.299	mm
$u_{e1.5}$ =	0.219	mm
u_m =	0.885	mm
u_{infl} =	1.026	mm
u_f =	1.278	mm
Initial linear slope		
$Slope_{ini}$ =	3521.07	N/mm
Energy values		
E_{SP} =	1.03	J
E_m =	0.66	J
E_{PL} =	0.51	J

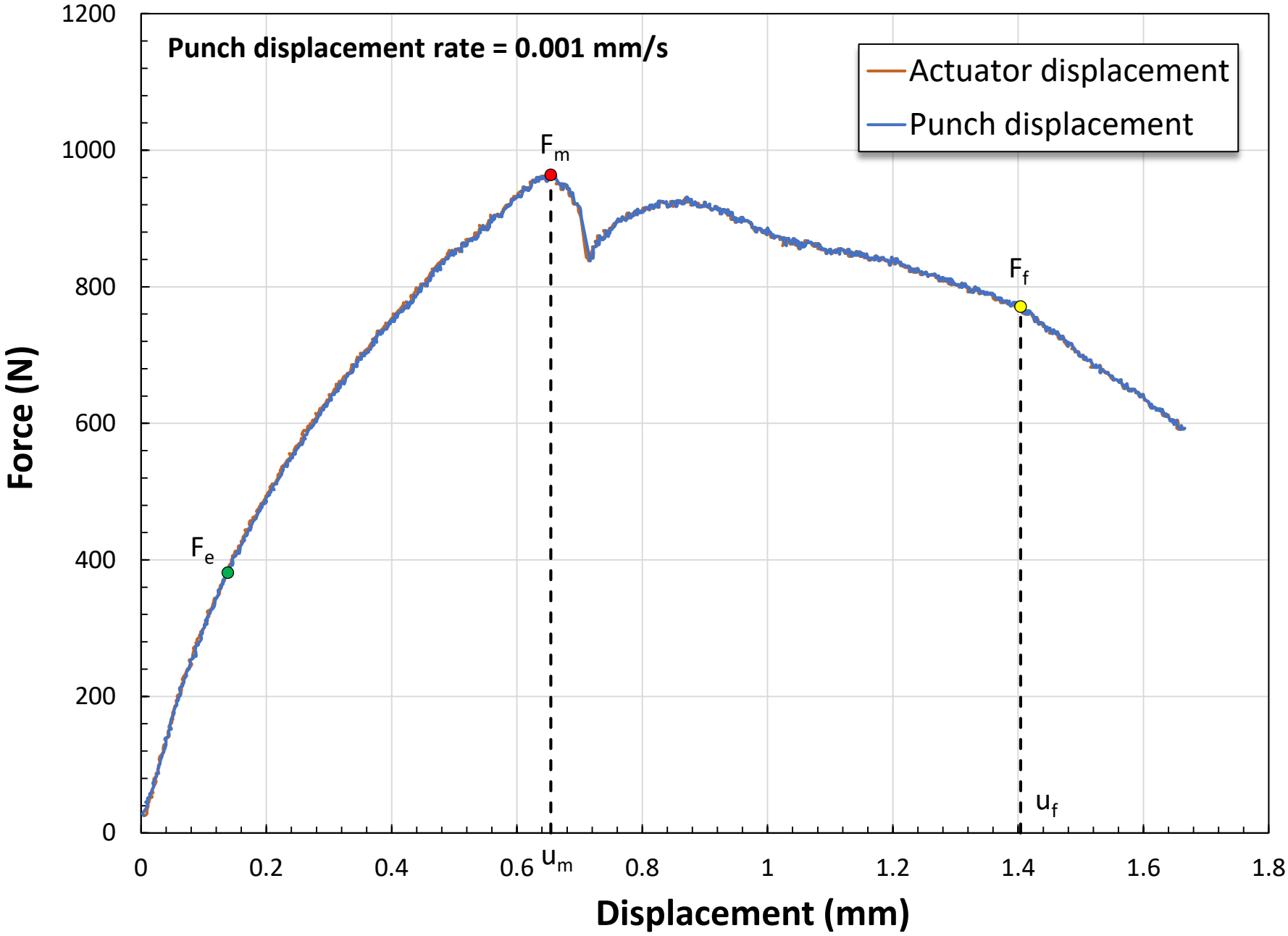

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

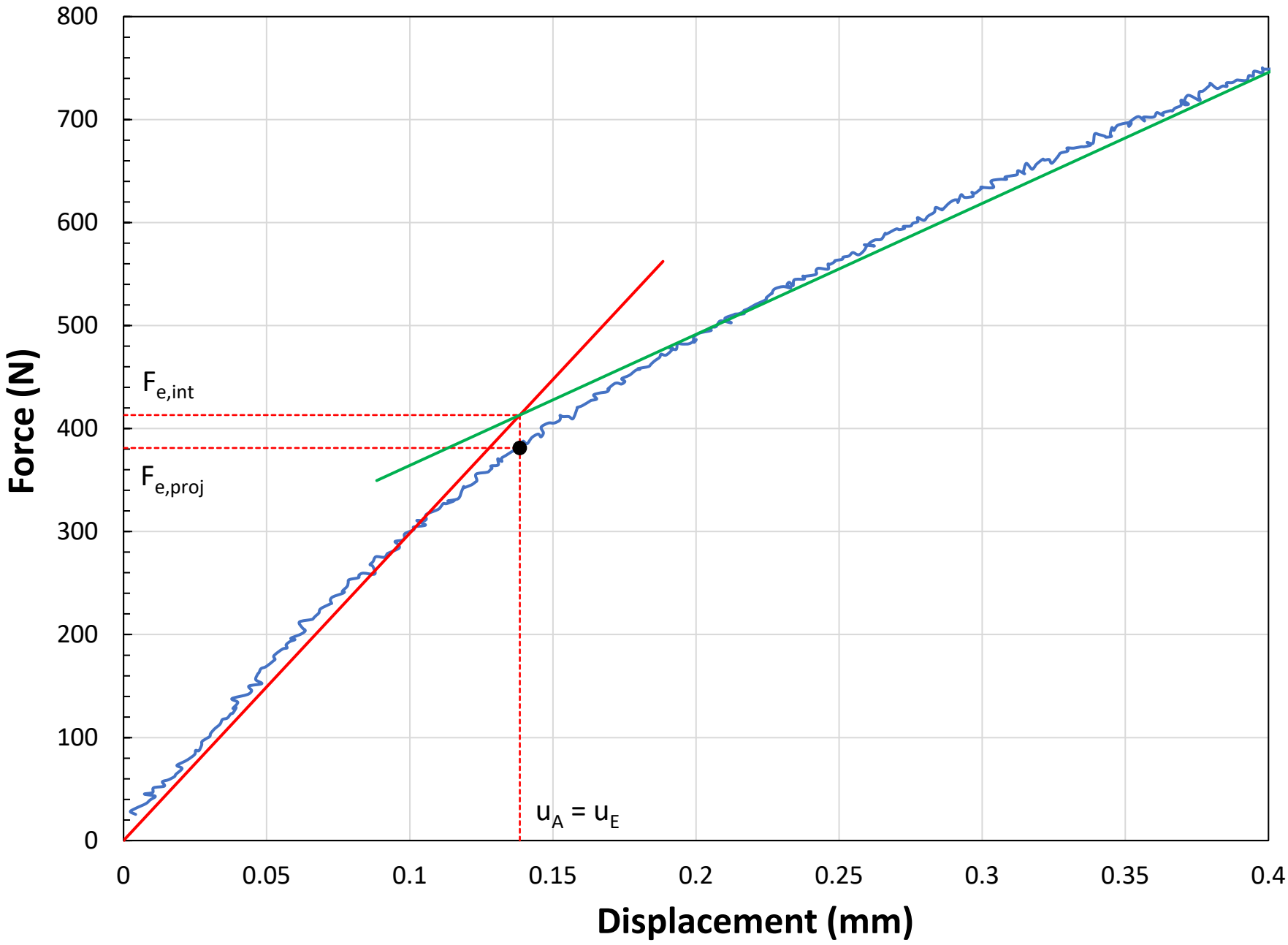

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP8 (p
Material: AM Ti-64
Test speed: 0.001443 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	381.2	N
$F_{e,int}$ =	413.1	N
$F_{h0/10,off}$ =	513.8	N
$F_{0.1mm,off}$ =	661.1	N
$F_{0.1mm}$ =	298.0	N
$F_{0.48mm}$ =	832.4	N
$F_{0.5mm}$ =	850.4	N
$F_{0.65mm}$ =	961.4	N
$F_{0.9mm}$ =	918.9	N
F_{ept} =	722.6	N
$F_{e1.5}$ =	673.6	N
F_m =	963.9	N
F_{infl} =	592.8	N
F_f =	771.1	N
Displacement values		
u_e =	0.138	mm
$u_{h0/10,off}$ =	0.217	mm
$u_{0.1mm,off}$ =	0.322	mm
$u_{e1.5}$ =	0.334	mm
u_m =	0.654	mm
u_{infl} =	1.666	mm
u_f =	1.404	mm
Initial linear slope		
$Slope_{ini}$ =	2983.80	N/mm
Energy values		
E_{SP} =	1.05	J
E_m =	0.40	J
E_{PL} =	0.25	J

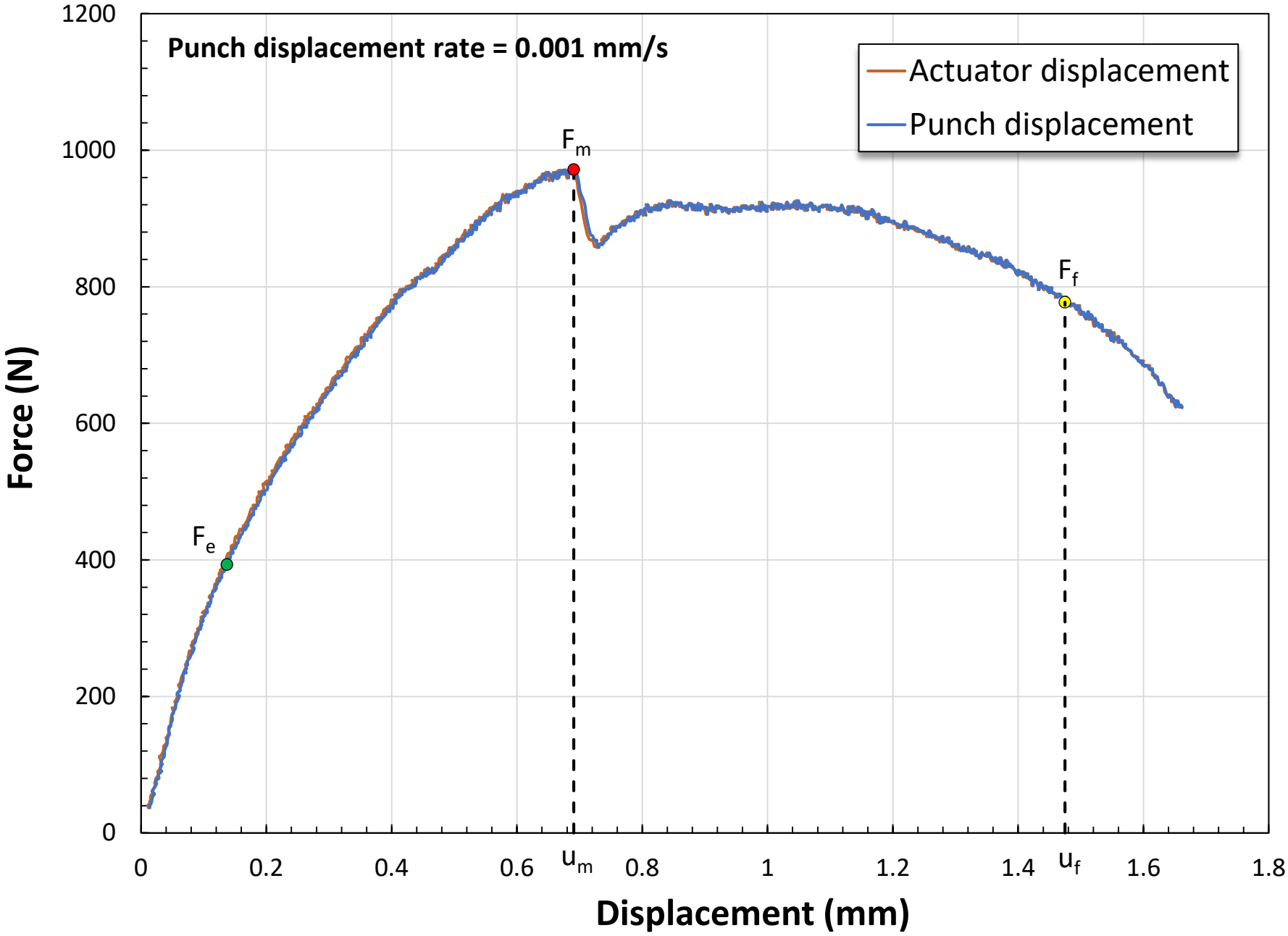

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

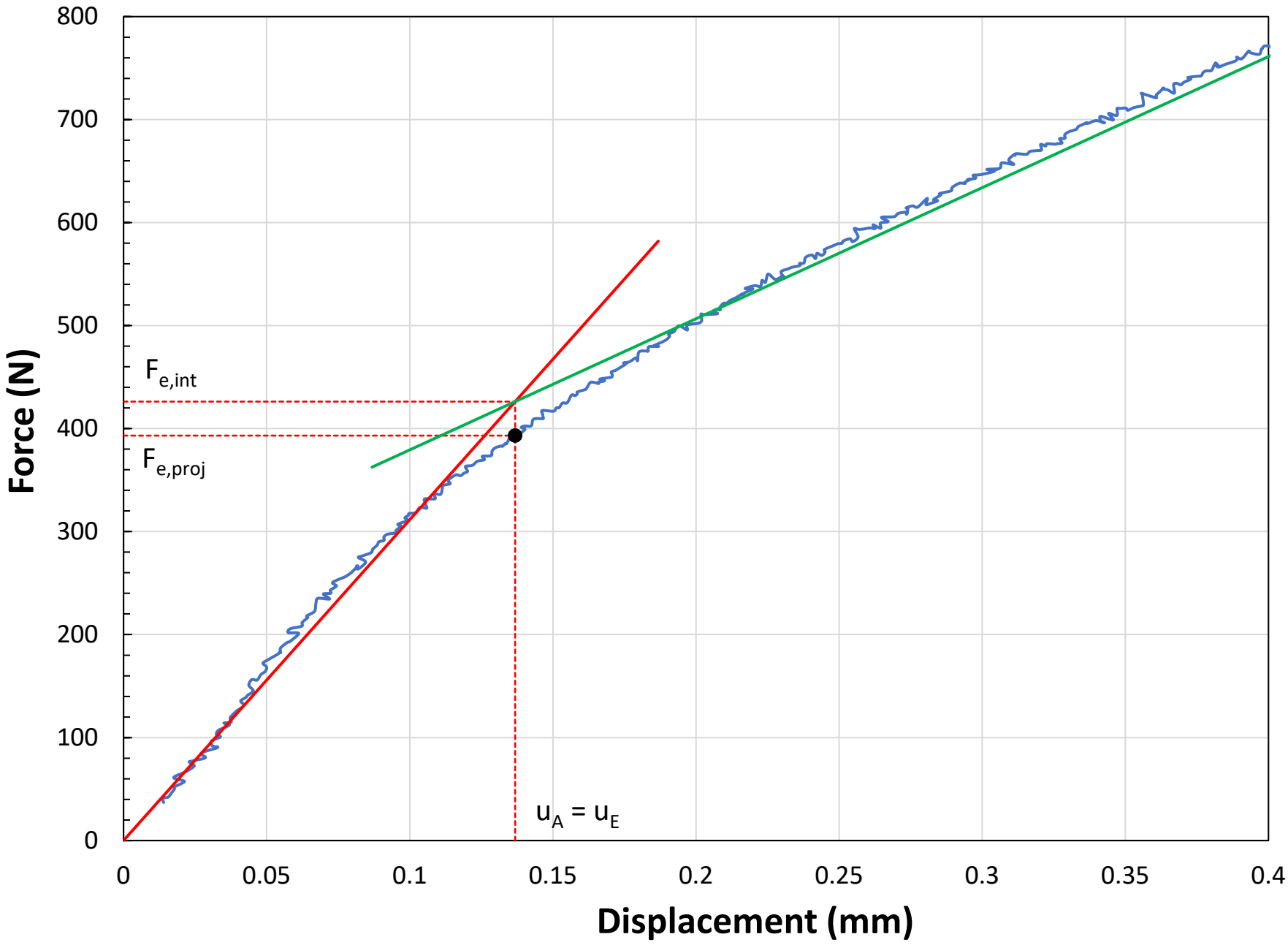

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP9 (p
Material: AM Ti-64
Test speed: 0.001434 mm/s
Max strain rate: 1.43E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	393.2	N
$F_{e,int}$ =	426.2	N
$F_{h0/10,off}$ =	528.3	N
$F_{0.1mm,off}$ =	656.9	N
$F_{0.1mm}$ =	317.5	N
$F_{0.48mm}$ =	833.0	N
$F_{0.5mm}$ =	853.6	N
$F_{0.65mm}$ =	967.8	N
$F_{0.9mm}$ =	916.7	N
F_{ept} =	613.3	N
$F_{e1.5}$ =	753.9	N
F_m =	971.8	N
F_{infl} =	623.1	N
F_f =	777.4	N
Displacement values		
u_e =	0.137	mm
$u_{h0/10,off}$ =	0.214	mm
$u_{0.1mm,off}$ =	0.311	mm
$u_{e1.5}$ =	0.381	mm
u_m =	0.691	mm
u_{infl} =	1.662	mm
u_f =	1.475	mm
Initial linear slope		
$Slope_{ini}$ =	3115.09	N/mm
Energy values		
E_{SP} =	1.14	J
E_m =	0.44	J
E_{PL} =	0.29	J

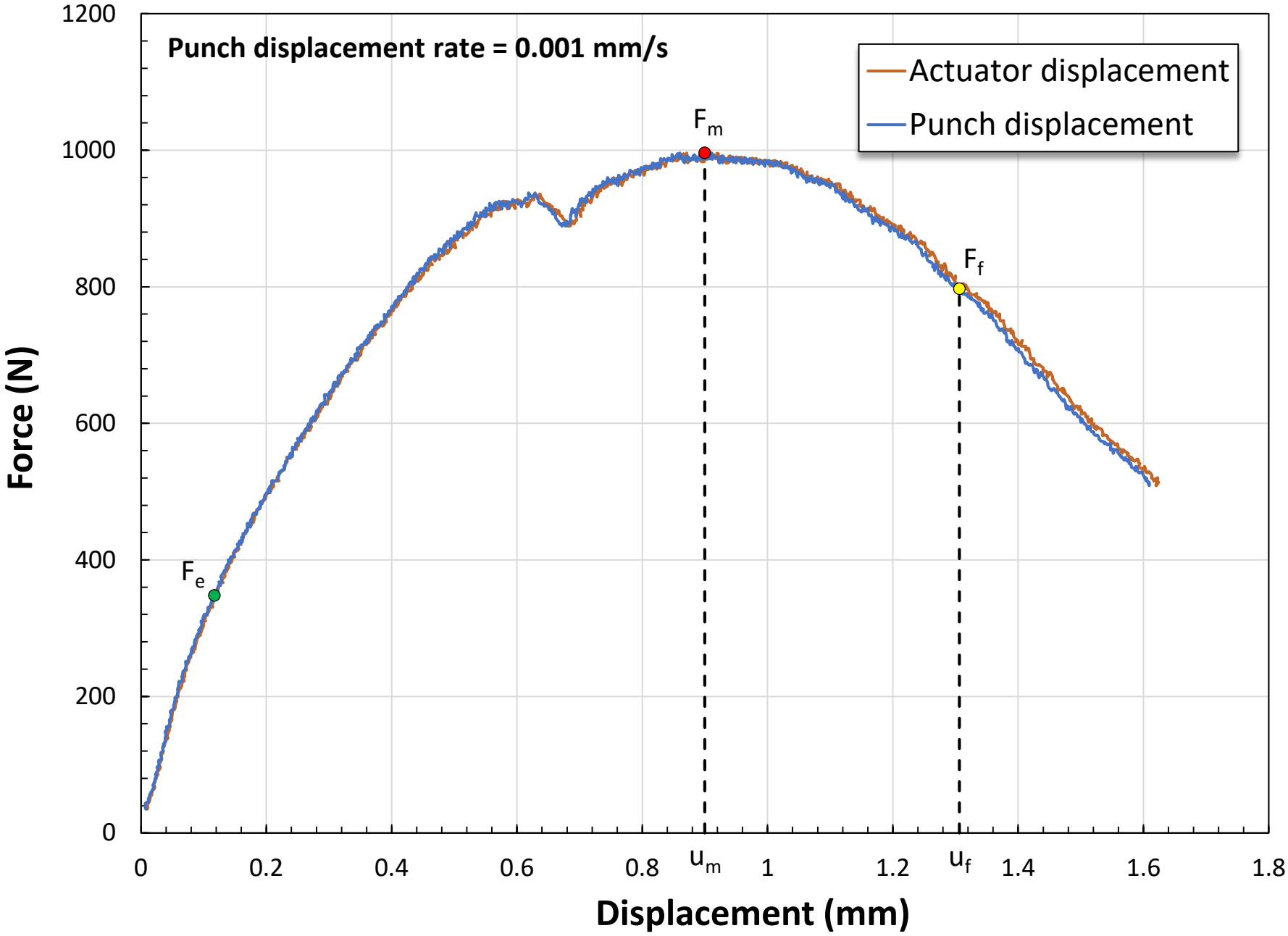

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

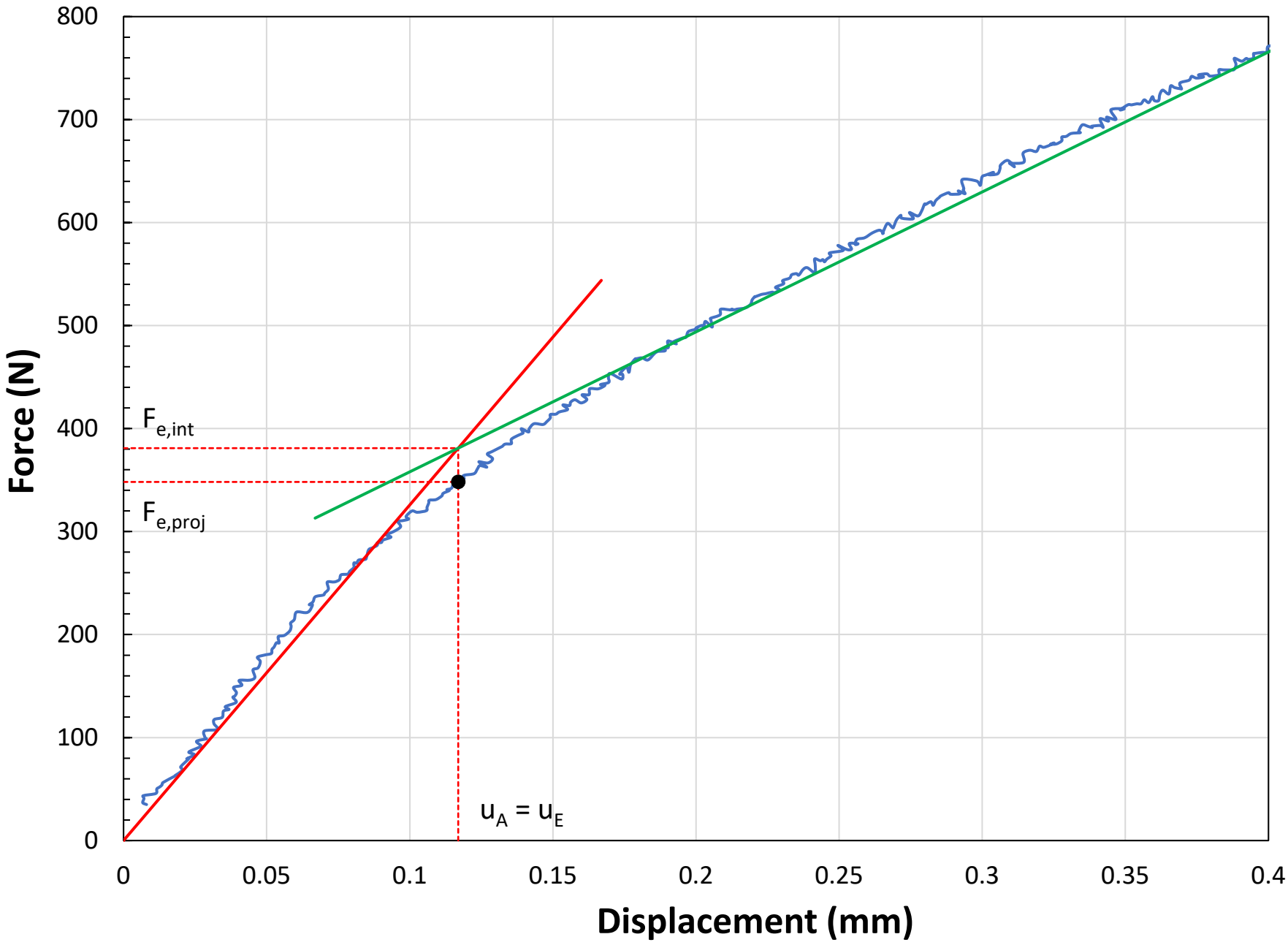

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 800HIP_1_N_a_SP10 (
Material: AM Ti-64
Test speed: 0.001428 mm/s
Max strain rate: 1.43E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	348.2	N
$F_{e,int}$ =	381.0	N
$F_{h0/10,off}$ =	484.1	N
$F_{0.1mm,off}$ =	630.0	N
$F_{0.1mm}$ =	314.7	N
$F_{0.48mm}$ =	854.8	N
$F_{0.5mm}$ =	874.9	N
$F_{0.65mm}$ =	917.2	N
$F_{0.9mm}$ =	989.1	N
F_{ept} =	558.4	N
$F_{e1.5}$ =	589.4	N
F_{m} =	996.4	N
F_{infl} =	686.5	N
F_{f} =	797.1	N
Displacement values		
u_{e} =	0.117	mm
$u_{h0/10,off}$ =	0.193	mm
$u_{0.1mm,off}$ =	0.294	mm
$u_{e1.5}$ =	0.265	mm
u_{m} =	0.900	mm
u_{infl} =	1.416	mm
u_{f} =	1.306	mm
Initial linear slope		
$Slope_{ini}$ =	3258.38	N/mm
Energy values		
E_{SP} =	1.02	J
E_{m} =	0.64	J
E_{PL} =	0.49	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

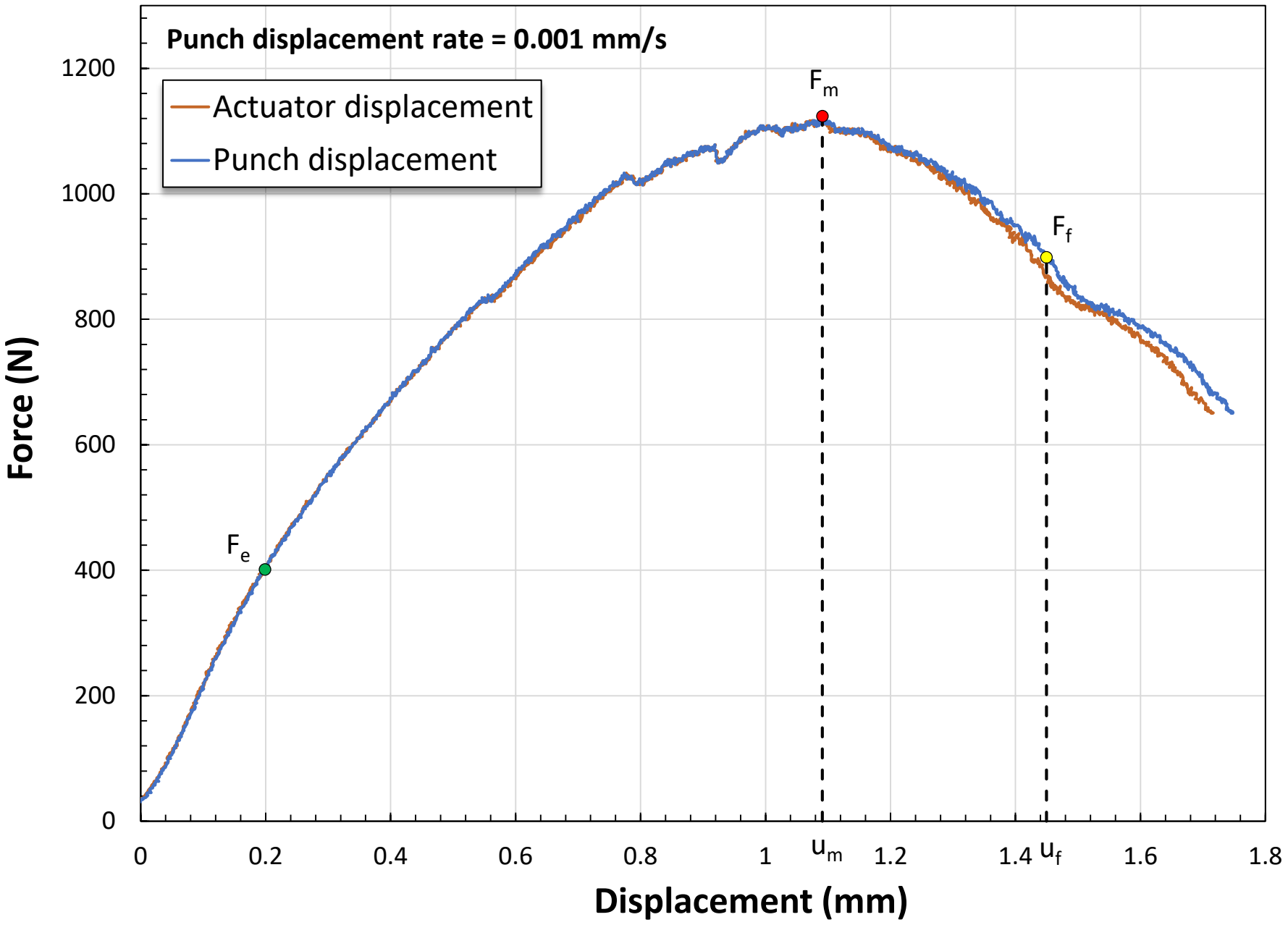
ANNEX 8

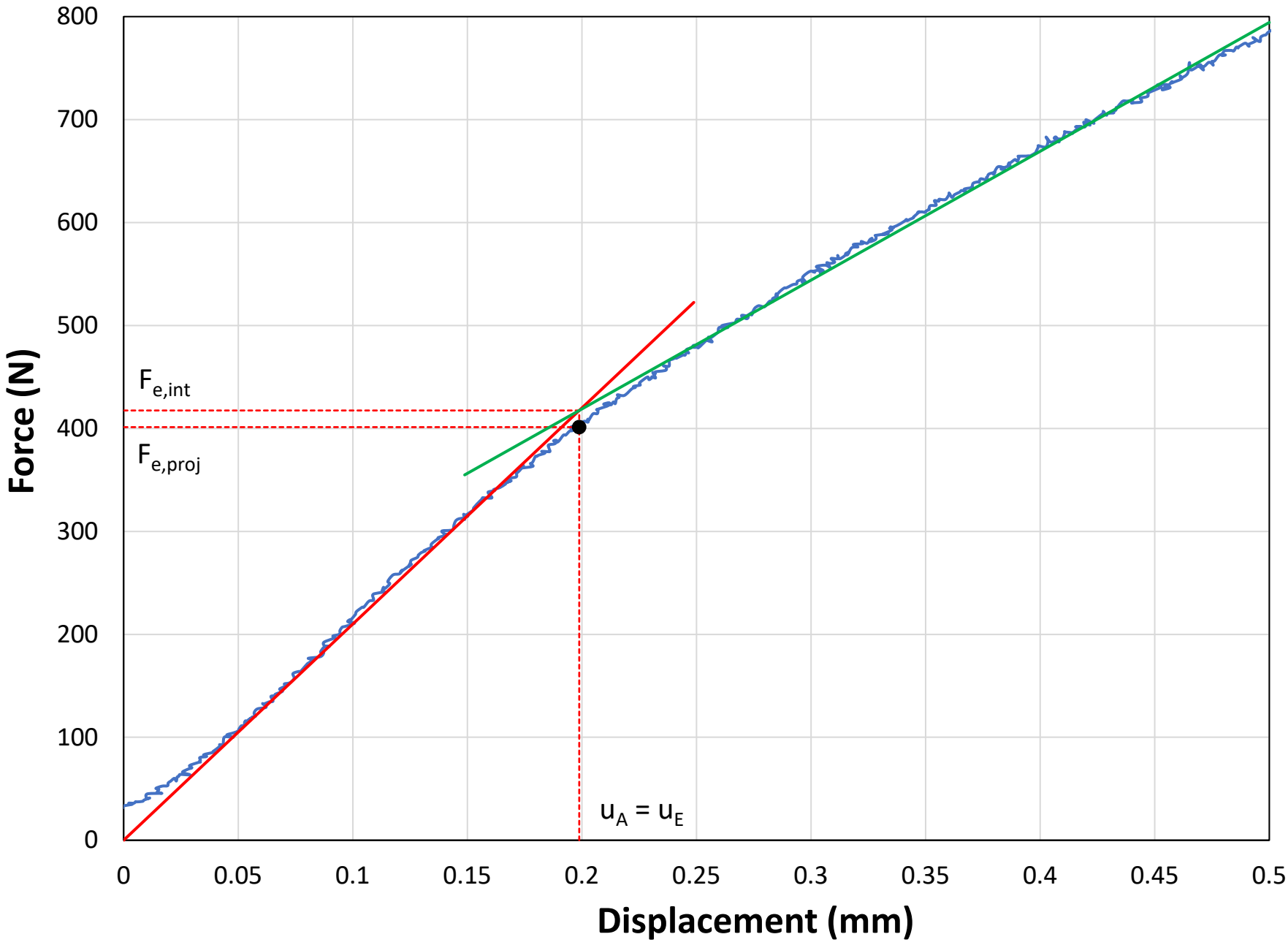
SP Test Results for
900 °C HIP, scan length = 78 mm, non-supported
(“rough” specimens)

Small Punch Test Results

Specimen ID: 900HIP_1_N_a_SP2
Material: AM Ti-64
Test speed: 0.001017 mm/s
Max strain rate: 1.02E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	401.3	N
$F_{e,int}$ =	417.4	N
$F_{h0/10,off}$ =	583.9	N
$F_{0.1mm,off}$ =	720.0	N
$F_{0.1mm}$ =	207.5	N
$F_{0.48mm}$ =	762.7	N
$F_{0.5mm}$ =	784.5	N
$F_{0.65mm}$ =	918.6	N
$F_{0.9mm}$ =	1071.1	N
F_{ept} =	1038.6	N
$F_{e1.5}$ =	139.7	N
F_m =	1123.6	N
F_{infl} =	650.9	N
F_f =	898.9	N
Displacement values		
u_e =	0.199	mm
$u_{h0/10,off}$ =	0.328	mm
$u_{0.1mm,off}$ =	0.444	mm
$u_{e1.5}$ =	0.064	mm
u_m =	1.091	mm
u_{infl} =	1.748	mm
u_f =	1.450	mm
Initial linear slope		
$Slope_{ini}$ =	2099.36	N/mm
Energy values		
E_{SP} =	1.18	J
E_m =	0.81	J
E_{PL} =	0.51	J

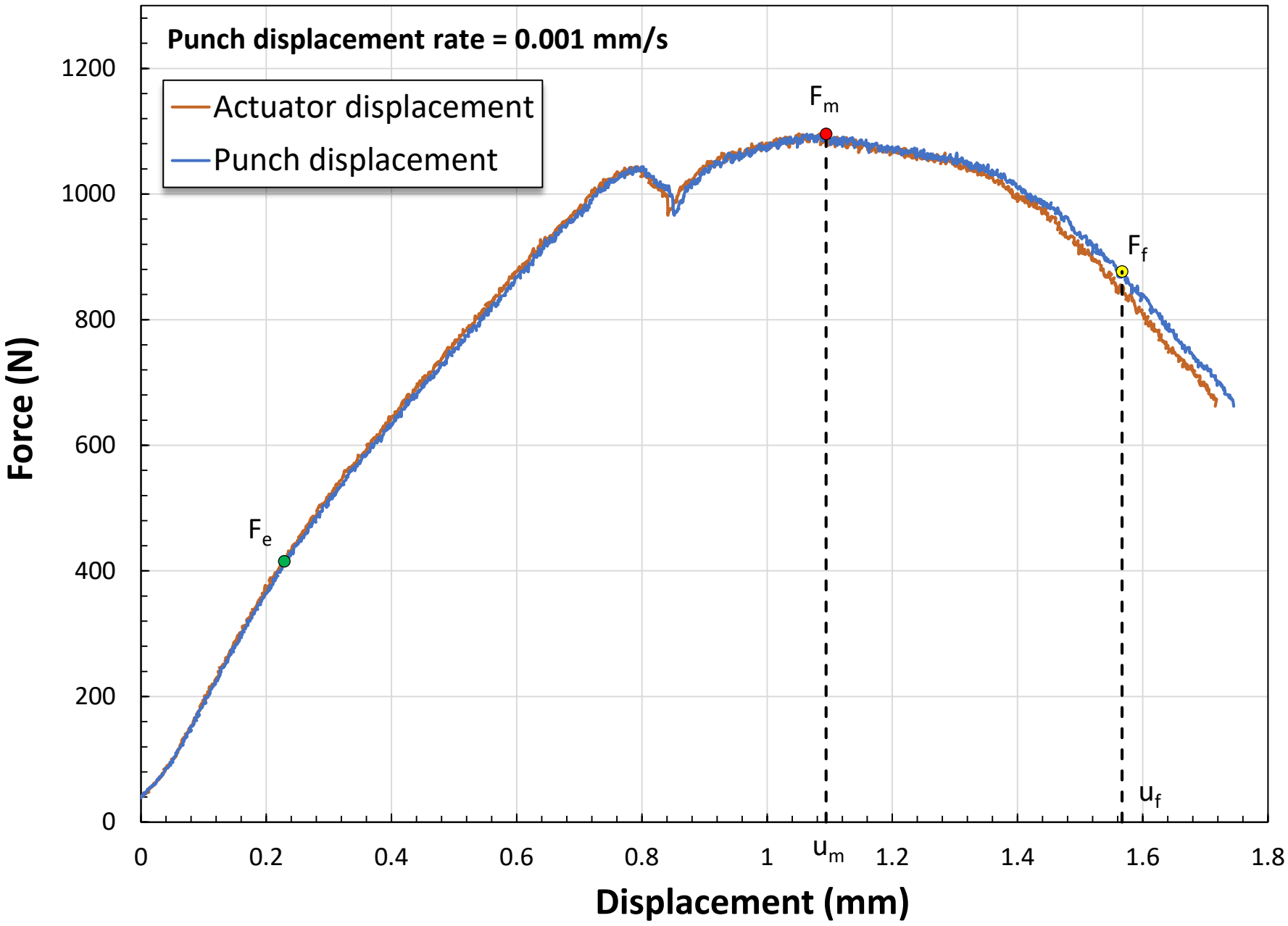

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
u_m
1.2
1.4
u_f
1.6
1.8

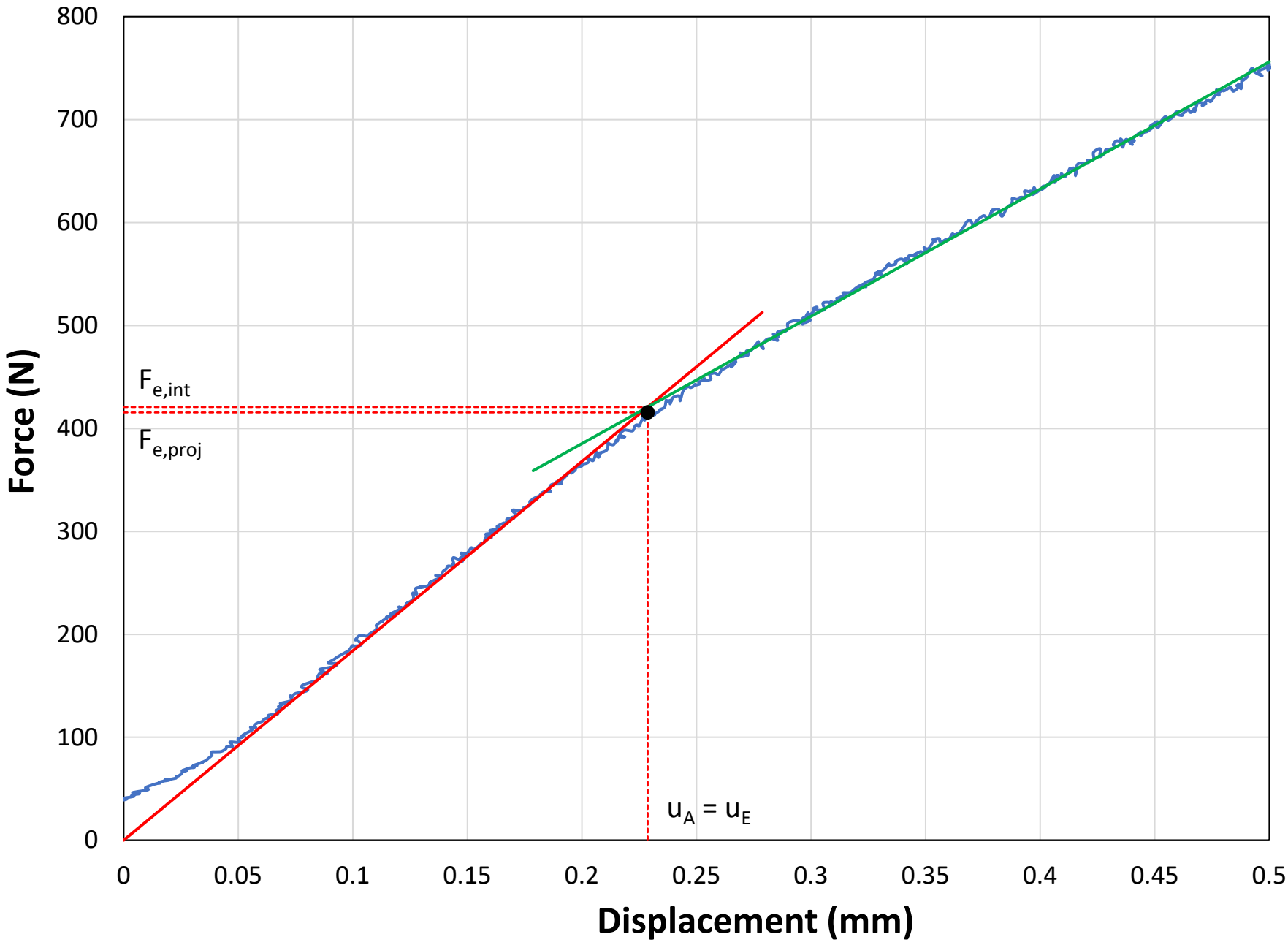

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_1_N_a_SP3
Material: AM Ti-64
Test speed: 0.001014 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	415.5	N
$F_{e,int}$ =	420.7	N
$F_{h0/10,off}$ =	609.6	N
$F_{0.1mm,off}$ =	766.2	N
$F_{0.1mm}$ =	189.0	N
$F_{0.48mm}$ =	729.5	N
$F_{0.5mm}$ =	748.0	N
$F_{0.65mm}$ =	917.2	N
$F_{0.9mm}$ =	1037.6	N
F_{ept} =	979.7	N
$F_{e1.5}$ =	152.6	N
F_m =	1095.6	N
F_{infl} =	731.2	N
F_f =	876.5	N
Displacement values		
u_e =	0.229	mm
$u_{h0/10,off}$ =	0.383	mm
$u_{0.1mm,off}$ =	0.517	mm
$u_{e1.5}$ =	0.082	mm
u_m =	1.094	mm
u_{infl} =	0.483	mm
u_f =	1.567	mm
Initial linear slope		
$Slope_{ini}$ =	1839.49	N/mm
Energy values		
E_{SP} =	1.28	J
E_m =	0.79	J
E_{PL} =	0.47	J

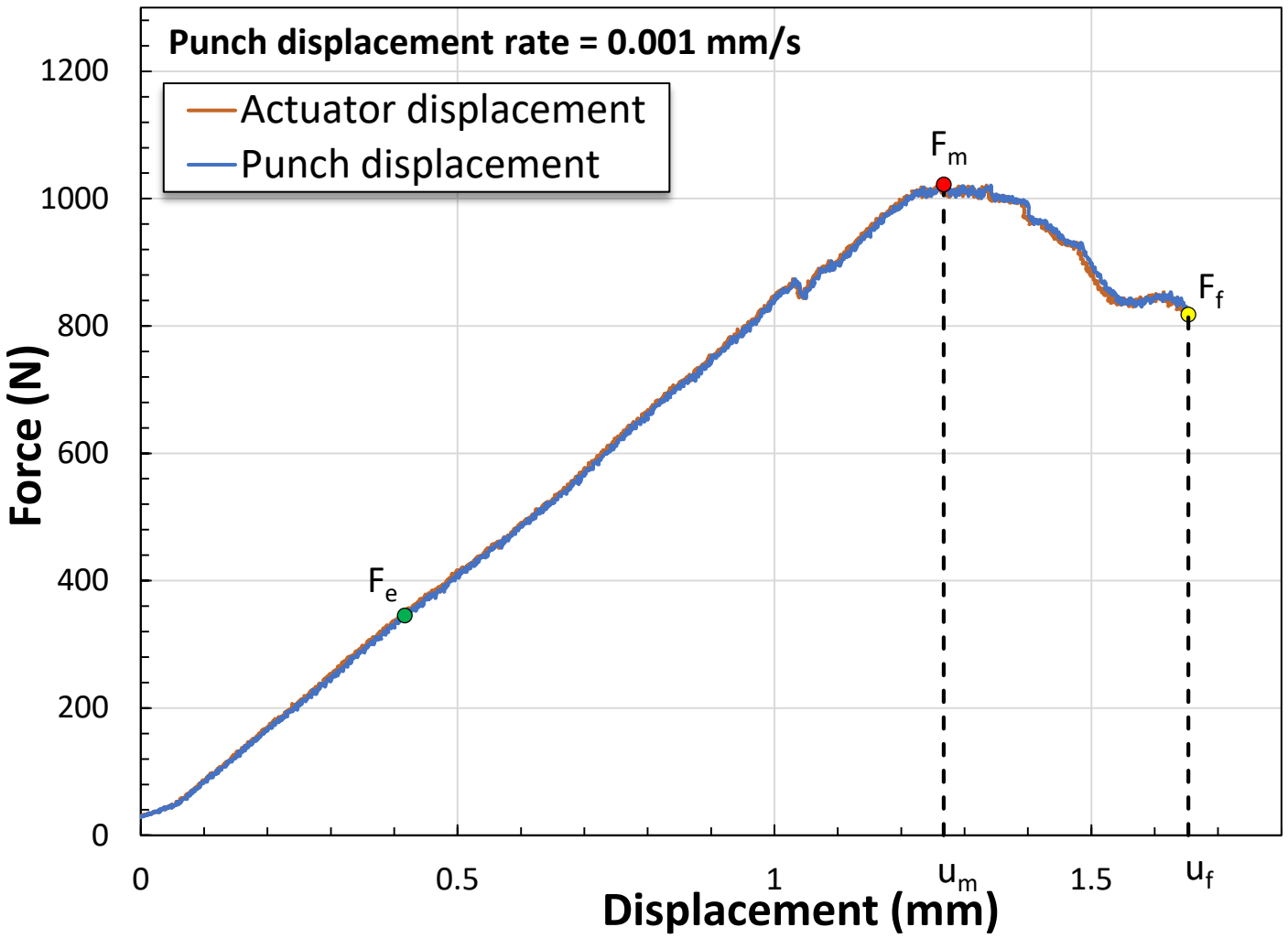

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

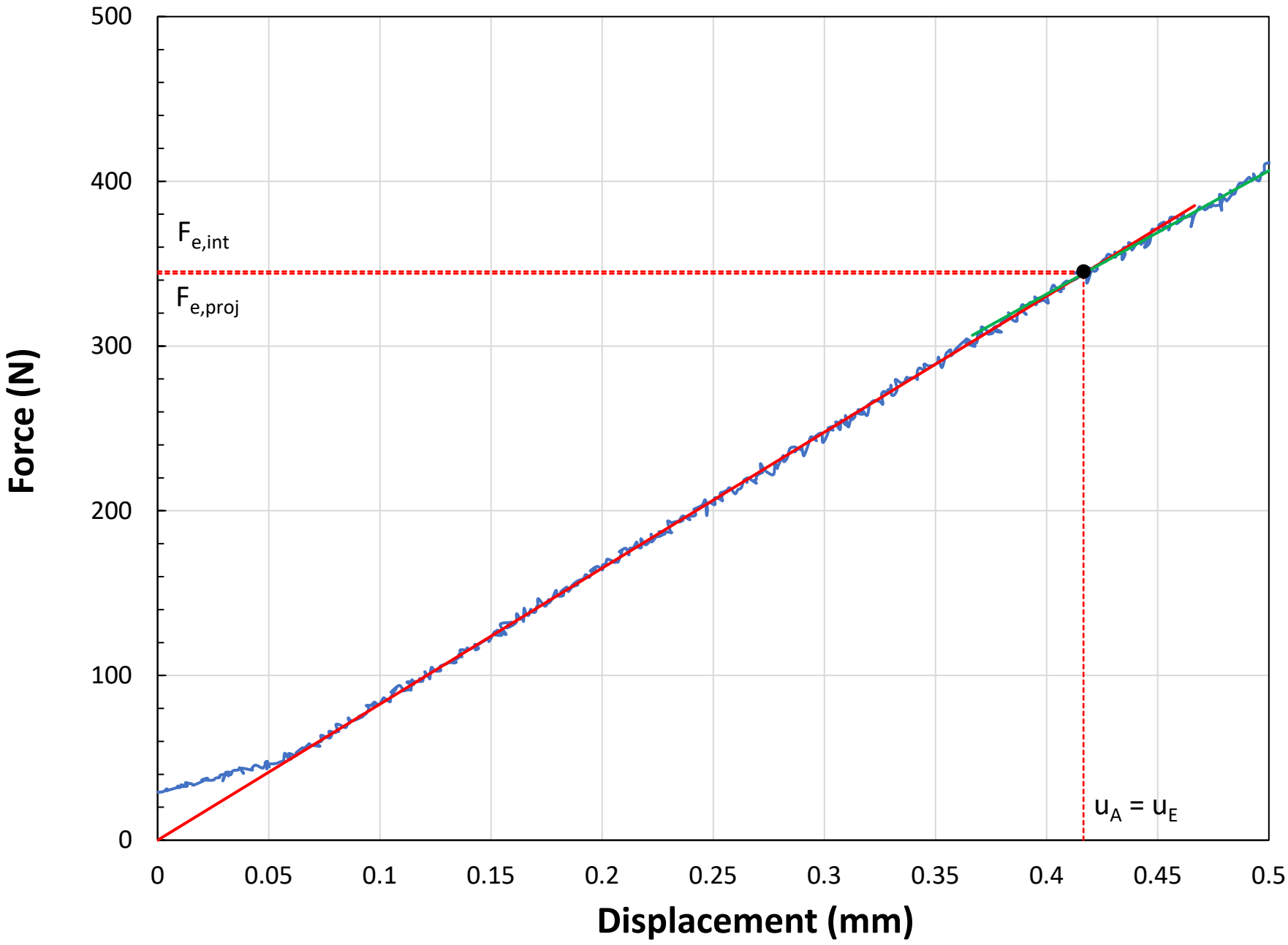

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_1_N_a_SP4
Material: AM Ti-64
Test speed: 0.001005 mm/s
Max strain rate: 1.00E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	345.3	N
$F_{e,int}$ =	344.0	N
$F_{h0/10,off}$ =	1011.2	N
$F_{0.1mm,off}$ =	1004.9	N
$F_{0.1mm}$ =	82.4	N
$F_{0.48mm}$ =	391.9	N
$F_{0.5mm}$ =	410.4	N
$F_{0.65mm}$ =	521.4	N
$F_{0.9mm}$ =	743.9	N
F_{ept} =	193.3	N
$F_{e1.5}$ =	144.1	N
F_m =	1022.4	N
F_{infl} =	5.0	N
F_f =	817.9	N
Displacement values		
u_e =	0.417	mm
$u_{h0/10,off}$ =	1.276	mm
$u_{0.1mm,off}$ =	1.320	mm
$u_{e1.5}$ =	0.176	mm
u_m =	1.267	mm
u_{infl} =	-0.107	mm
u_f =	1.653	mm
Initial linear slope		
$Slope_{ini}$ =	825.63	N/mm
Energy values		
E_{SP} =	1.02	J
E_m =	0.66	J
E_{PL} =	0.03	J

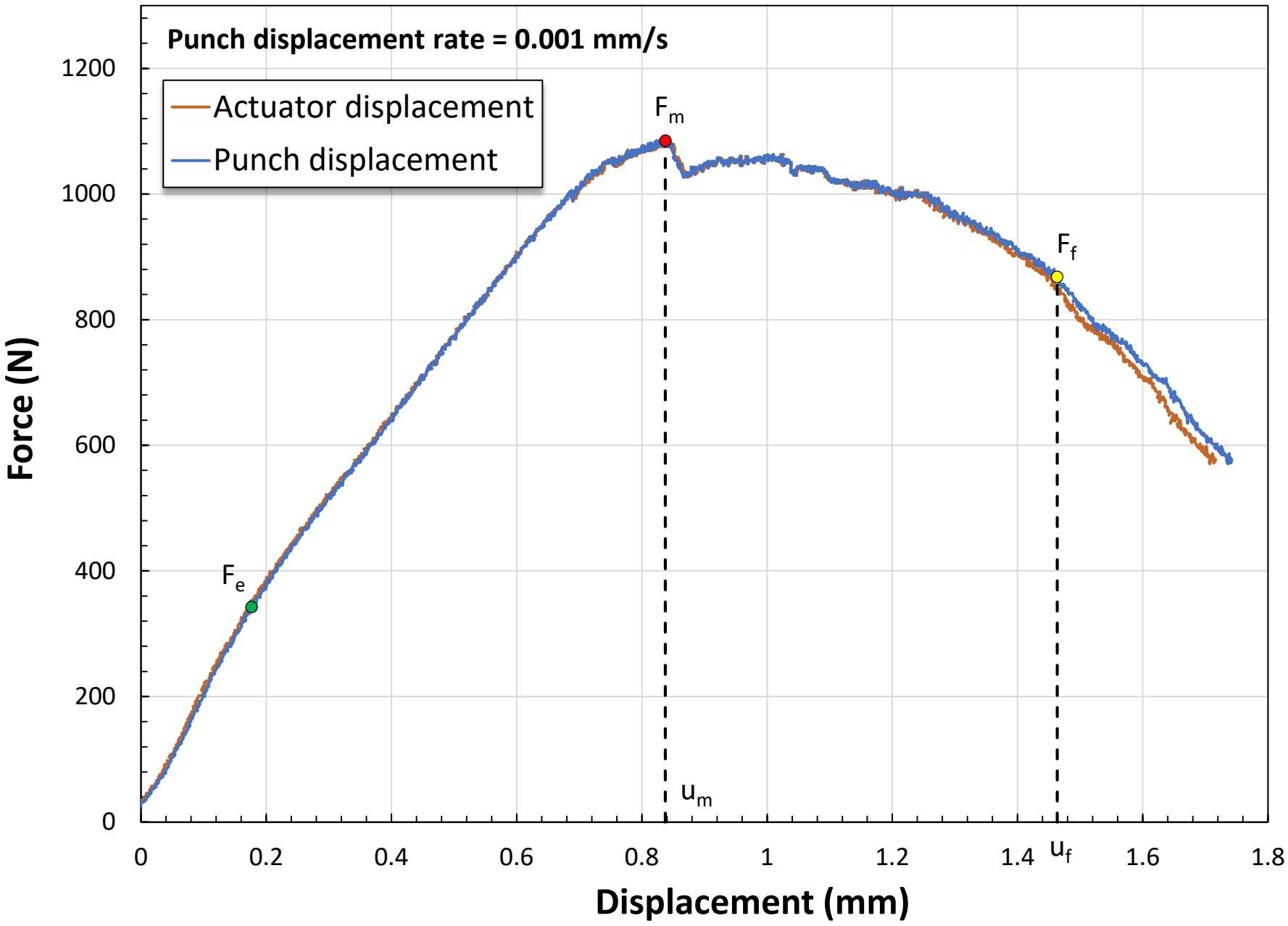

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
Force (N)
1200
1000
800
600
400
200
0
0
0.5
1
u_m
1.5
u_f
Displacement (mm)

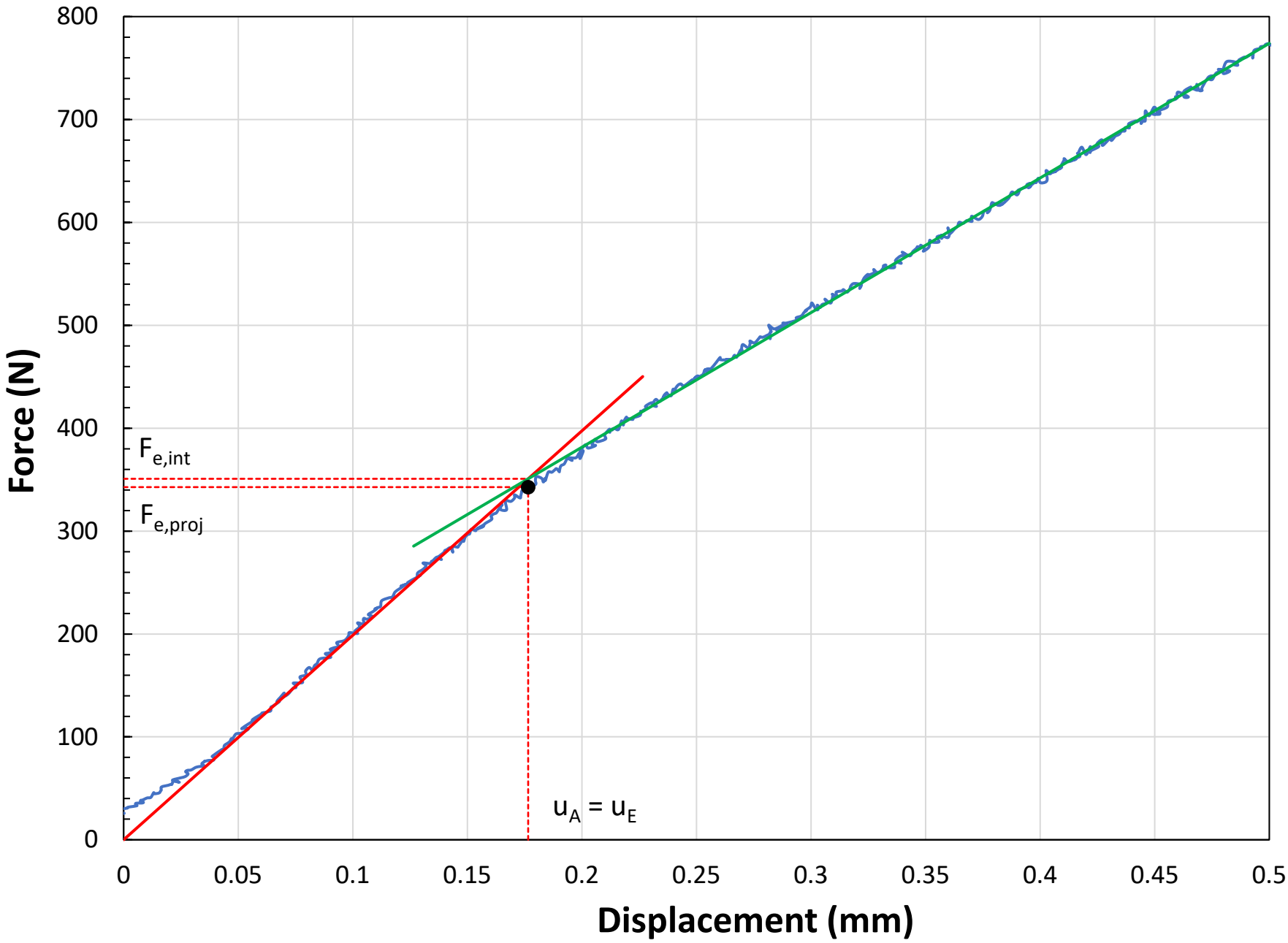

500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_1_N_a_SP5
Material: AM Ti-64
Test speed: 0.00101 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	342.7	N
$F_{e,int}$ =	350.8	N
$F_{h0/10,off}$ =	539.8	N
$F_{0.1mm,off}$ =	723.3	N
$F_{0.1mm}$ =	201.3	N
$F_{0.48mm}$ =	748.8	N
$F_{0.5mm}$ =	773.6	N
$F_{0.65mm}$ =	958.5	N
$F_{0.9mm}$ =	1047.8	N
F_{ept} =	97.4	N
$F_{e1.5}$ =	128.8	N
F_m =	1085.0	N
F_{infl} =	577.3	N
F_f =	868.0	N
Displacement values		
u_e =	0.177	mm
$u_{h0/10,off}$ =	0.322	mm
$u_{0.1mm,off}$ =	0.465	mm
$u_{e1.5}$ =	0.064	mm
u_m =	0.837	mm
u_{infl} =	1.742	mm
u_f =	1.463	mm
Initial linear slope		
$Slope_{ini}$ =	1987.01	N/mm
Energy values		
E_{SP} =	1.17	J
E_m =	0.54	J
E_{PL} =	0.24	J

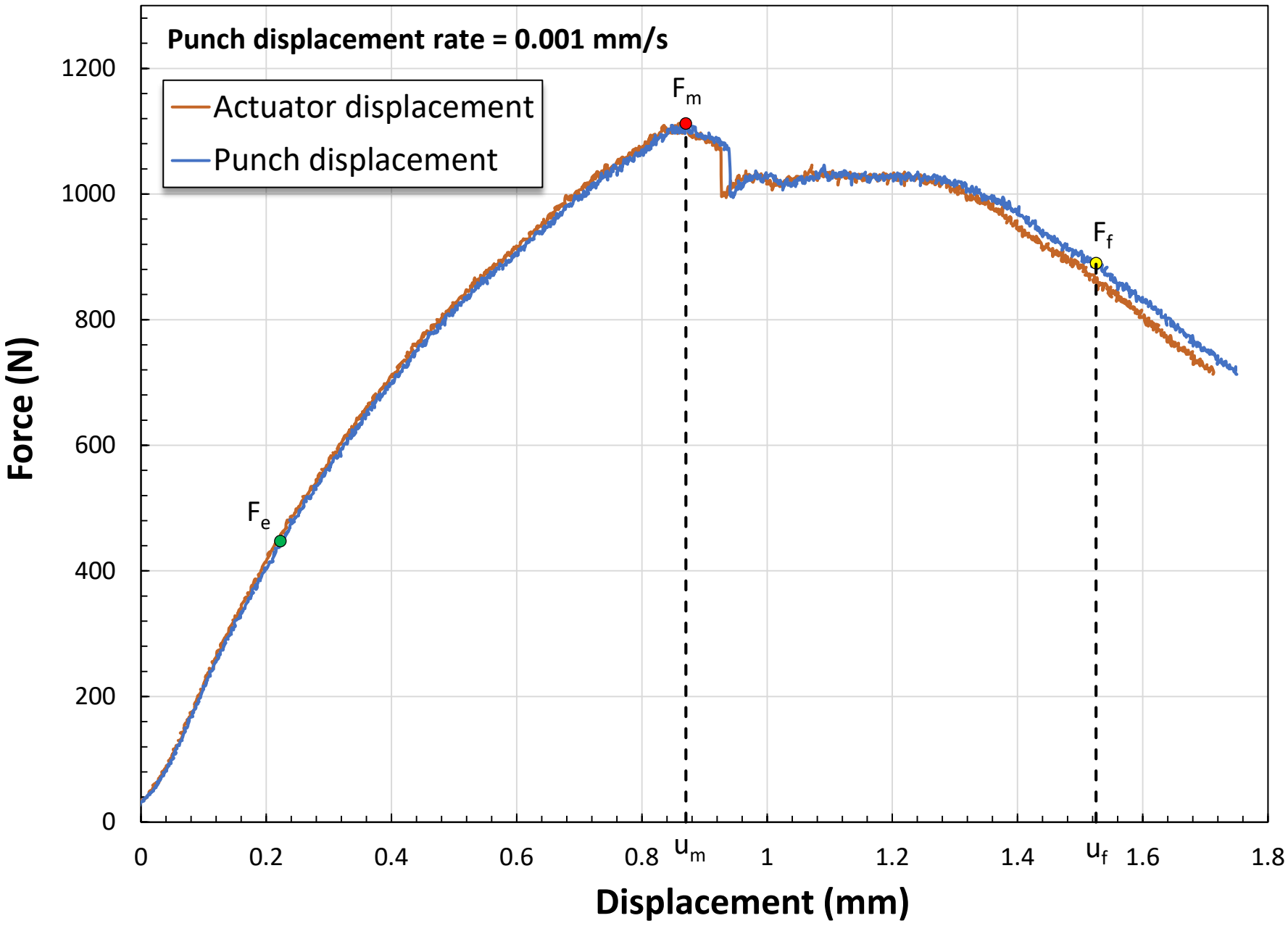

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

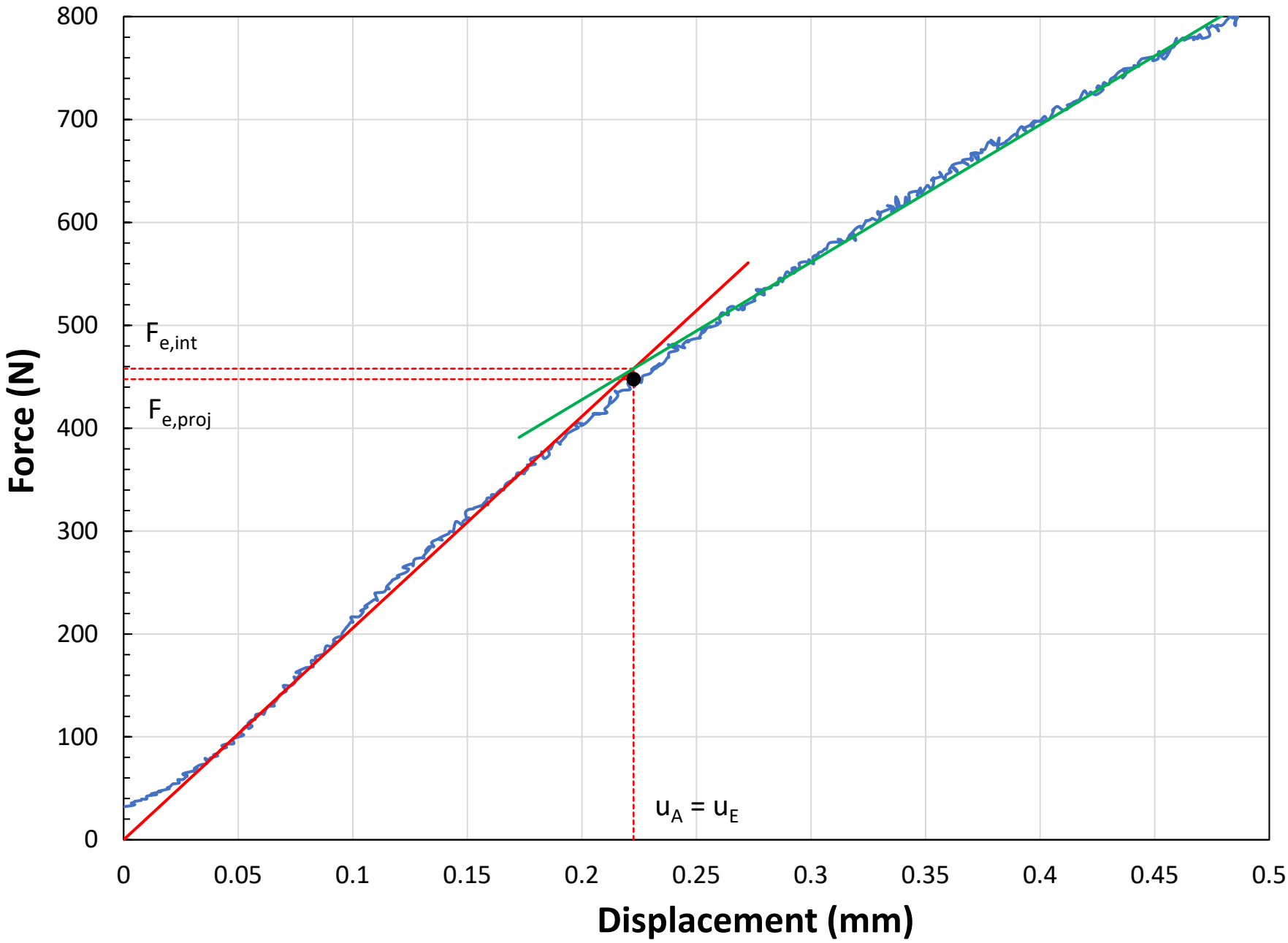

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_1_N_a_SP7
Material: AM Ti-64
Test speed: 0.00102 mm/s
Max strain rate: 1.02E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	447.6	N
$F_{e,int}$ =	457.9	N
$F_{h0/10,off}$ =	662.2	N
$F_{0.1mm,off}$ =	792.1	N
$F_{0.1mm}$ =	211.6	N
$F_{0.48mm}$ =	791.3	N
$F_{0.5mm}$ =	810.9	N
$F_{0.65mm}$ =	946.7	N
$F_{0.9mm}$ =	1090.2	N
F_{ept} =	1017.1	N
$F_{e1.5}$ =	134.1	N
F_m =	1112.3	N
F_{infl} =	515.1	N
F_f =	889.9	N
Displacement values		
u_e =	0.223	mm
$u_{h0/10,off}$ =	0.373	mm
$u_{0.1mm,off}$ =	0.485	mm
$u_{e1.5}$ =	0.066	mm
u_m =	0.870	mm
u_{infl} =	0.268	mm
u_f =	1.525	mm
Initial linear slope		
$Slope_{ini}$ =	2057.23	N/mm
Energy values		
E_{SP} =	1.25	J
E_m =	0.59	J
E_{PL} =	0.29	J

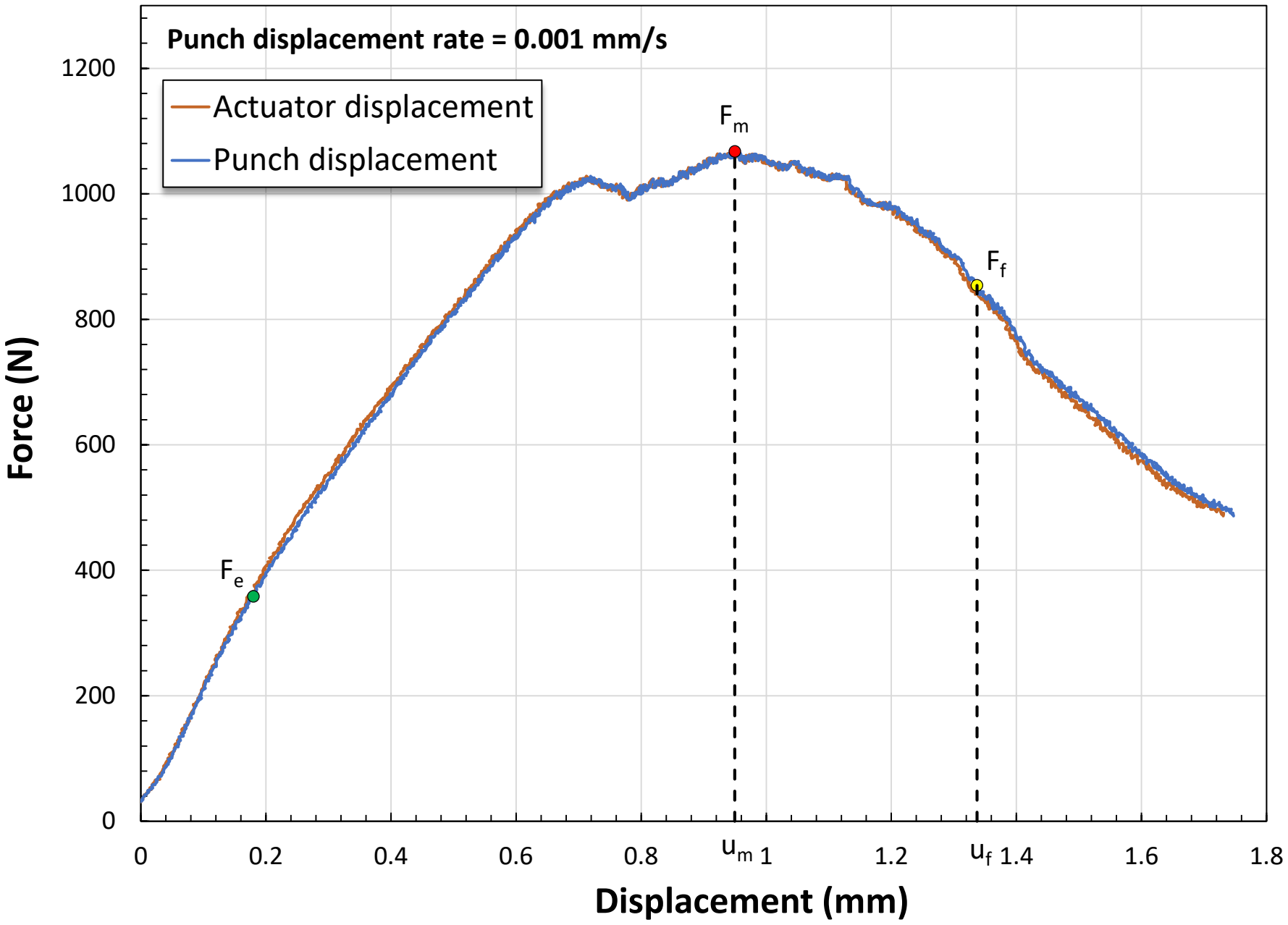

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

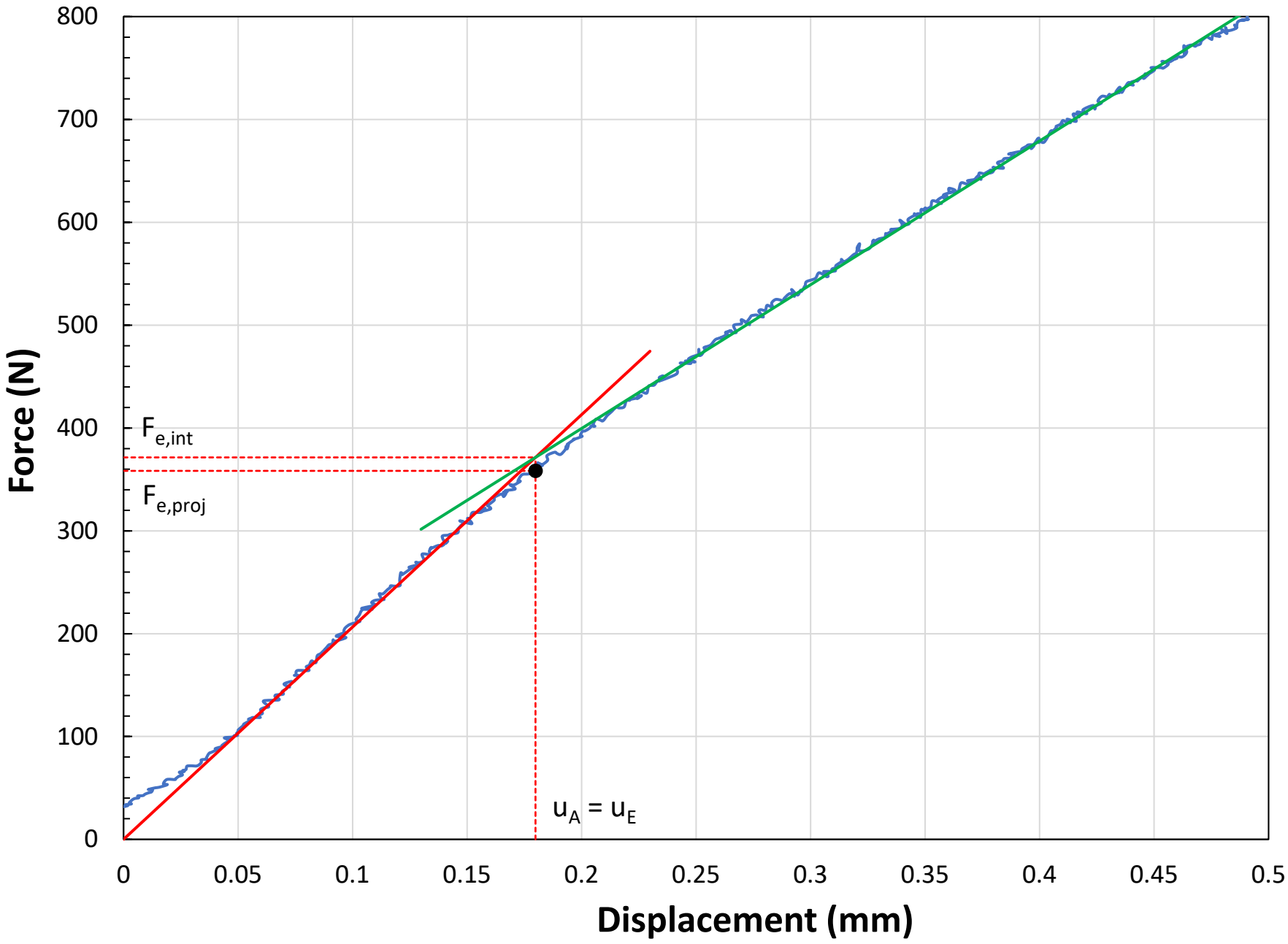

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_1_N_a_SP8
Material: AM Ti-64
Test speed: 0.001006 mm/s
Max strain rate: 1.01E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	358.3	N
$F_{e,int}$ =	371.4	N
$F_{h0/10,off}$ =	595.4	N
$F_{0.1mm,off}$ =	781.4	N
$F_{0.1mm}$ =	209.2	N
$F_{0.48mm}$ =	787.7	N
$F_{0.5mm}$ =	809.0	N
$F_{0.65mm}$ =	983.9	N
$F_{0.9mm}$ =	1042.8	N
F_{ept} =	1032.2	N
$F_{e1.5}$ =	138.9	N
F_m =	1067.5	N
F_{infl} =	486.6	N
F_f =	854.0	N
Displacement values		
u_e =	0.180	mm
$u_{h0/10,off}$ =	0.339	mm
$u_{0.1mm,off}$ =	0.479	mm
$u_{e1.5}$ =	0.066	mm
u_m =	0.950	mm
u_{infl} =	1.747	mm
u_f =	1.337	mm
Initial linear slope		
$Slope_{ini}$ =	2064.56	N/mm
Energy values		
E_{SP} =	1.05	J
E_m =	0.67	J
E_{PL} =	0.39	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
u_m 1
1.2
u_f 1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

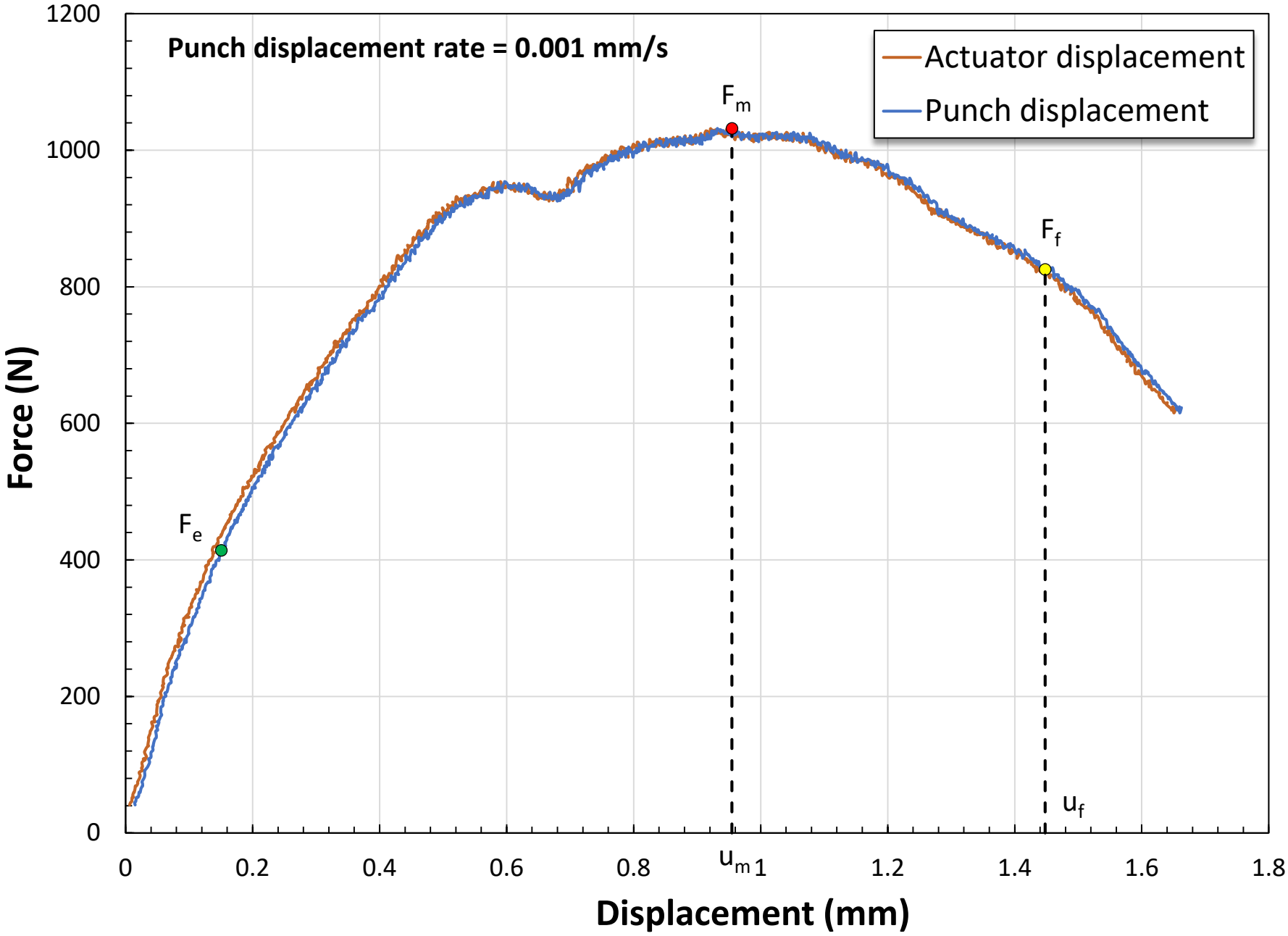
ANNEX 9

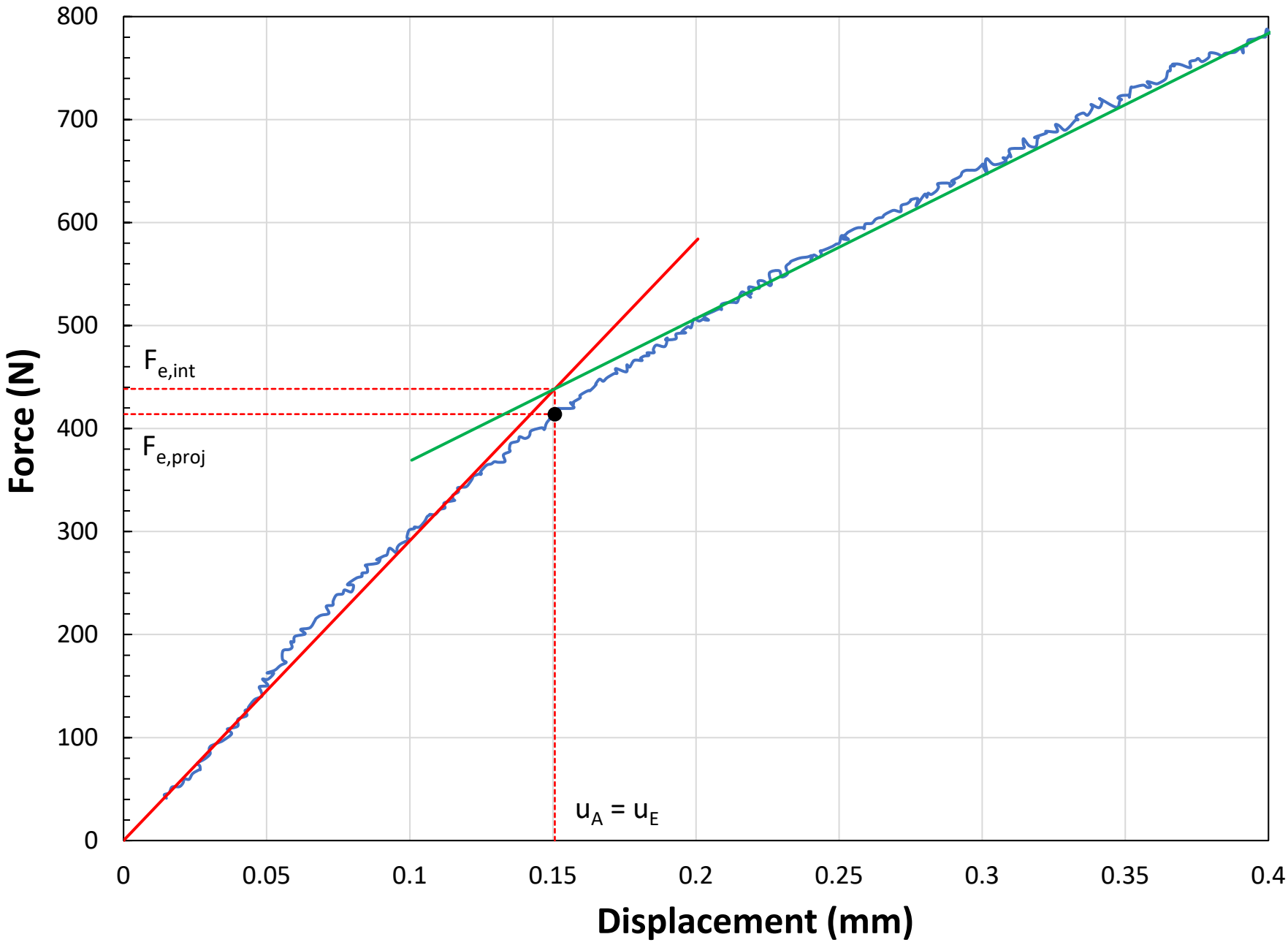
SP Test Results for
900 °C HIP, scan length = 78 mm, non-supported
(polished specimens)

Small Punch Test Results

Specimen ID: 900HIP_1_N_a_SP9 (p
Material: AM Ti-64
Test speed: 0.001428 mm/s
Max strain rate: 1.43E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	414.0	N
$F_{e,int}$ =	438.5	N
$F_{h0/10,off}$ =	568.5	N
$F_{0.1mm,off}$ =	715.2	N
$F_{0.1mm}$ =	301.3	N
$F_{0.48mm}$ =	877.3	N
$F_{0.5mm}$ =	898.4	N
$F_{0.65mm}$ =	938.6	N
$F_{0.9mm}$ =	1015.8	N
F_{ept} =	156.7	N
$F_{e1.5}$ =	764.7	N
F_m =	1031.9	N
F_{infl} =	622.9	N
F_f =	825.5	N
Displacement values		
u_e =	0.151	mm
$u_{h0/10,off}$ =	0.241	mm
$u_{0.1mm,off}$ =	0.347	mm
$u_{e1.5}$ =	0.391	mm
u_m =	0.955	mm
u_{infl} =	1.663	mm
u_f =	1.448	mm
Initial linear slope		
$Slope_{ini}$ =	2910.50	N/mm
Energy values		
E_{SP} =	1.18	J
E_m =	0.71	J
E_{PL} =	0.53	J

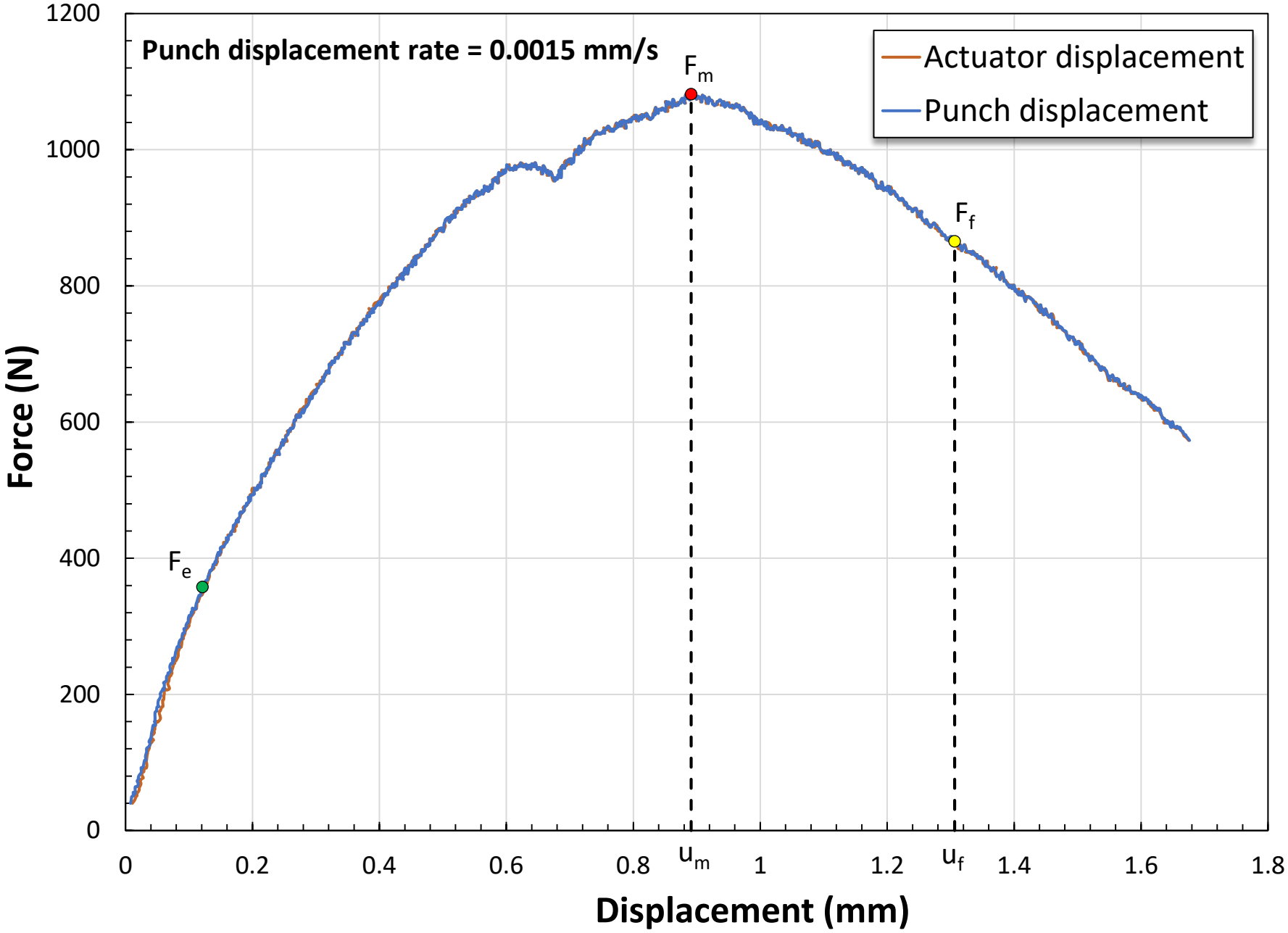

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

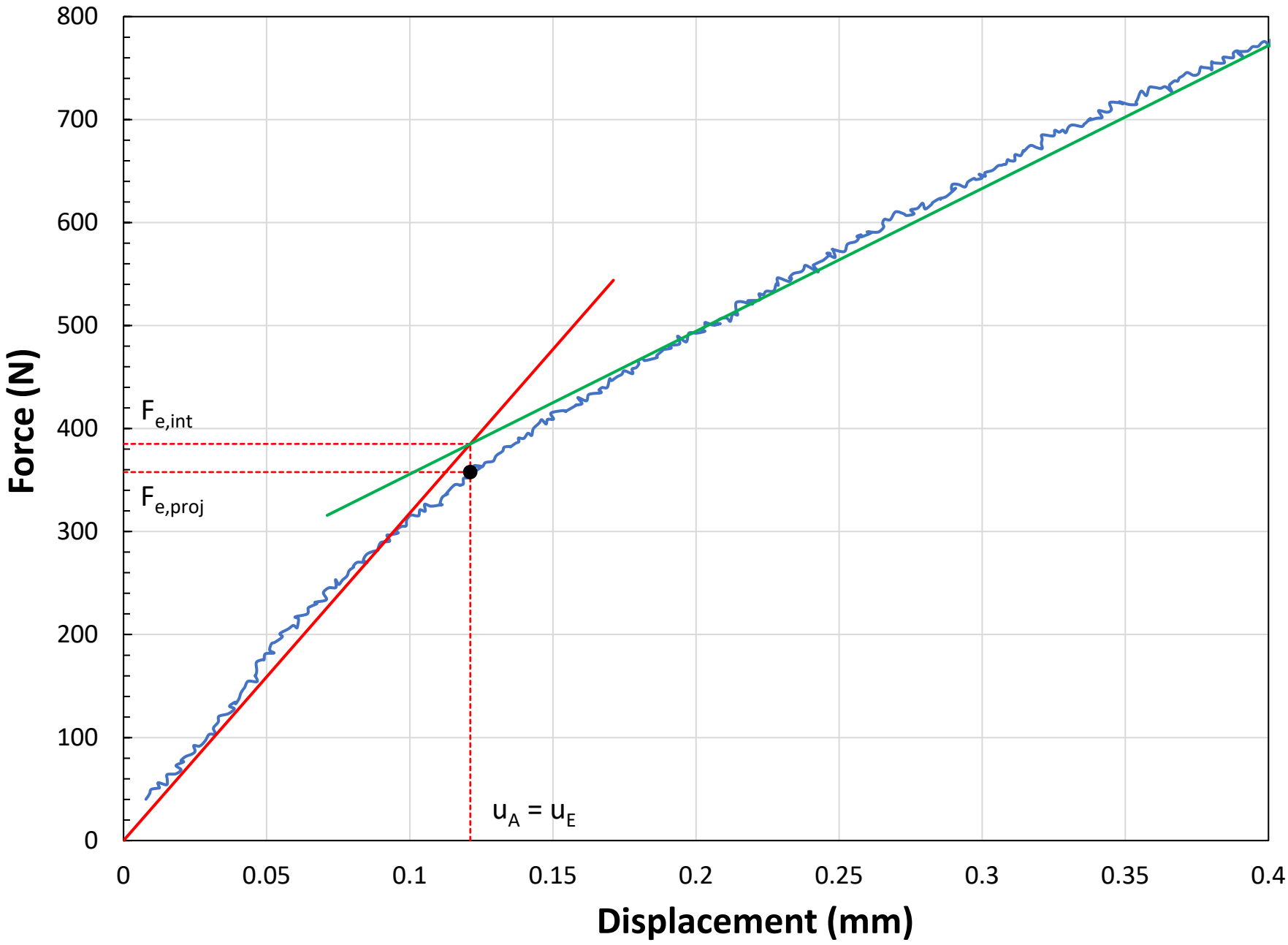

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_1_N_a_SP10 (
Material: AM Ti-64
Test speed: 0.001438 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	357.8	N
$F_{e,int}$ =	385.1	N
$F_{h0/10,off}$ =	496.9	N
$F_{0.1mm,off}$ =	656.5	N
$F_{0.1mm}$ =	311.3	N
$F_{0.48mm}$ =	869.2	N
$F_{0.5mm}$ =	881.3	N
$F_{0.65mm}$ =	971.0	N
$F_{0.9mm}$ =	1074.2	N
F_{ept} =	676.9	N
$F_{e1.5}$ =	714.7	N
F_m =	1081.8	N
F_{infl} =	573.1	N
F_f =	865.4	N
Displacement values		
u_e =	0.121	mm
$u_{h0/10,off}$ =	0.203	mm
$u_{0.1mm,off}$ =	0.307	mm
$u_{e1.5}$ =	0.354	mm
u_m =	0.891	mm
u_{infl} =	1.676	mm
u_f =	1.306	mm
Initial linear slope		
$Slope_{ini}$ =	3178.87	N/mm
Energy values		
E_{SP} =	1.07	J
E_m =	0.66	J
E_{PL} =	0.47	J


Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

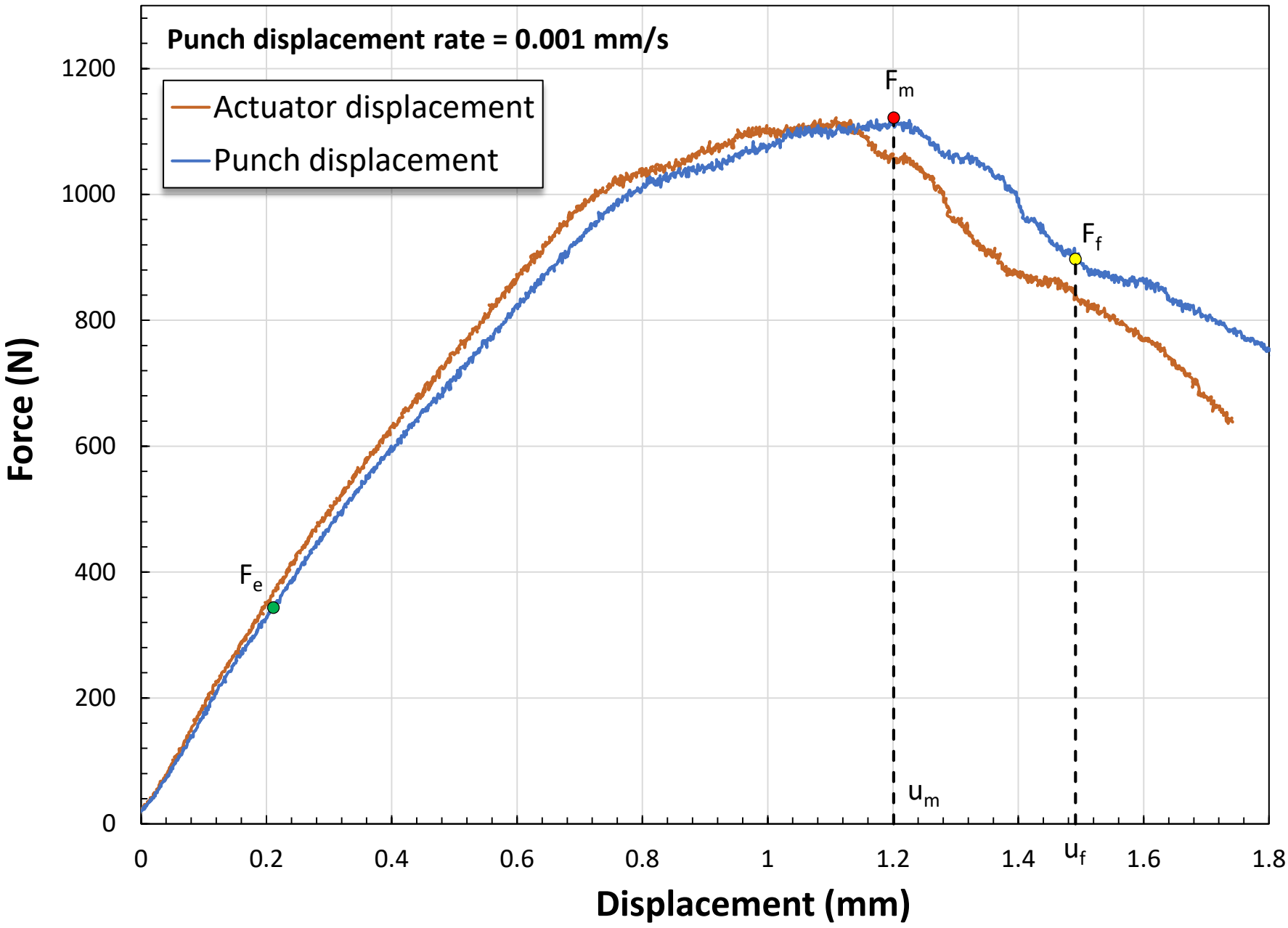
ANNEX 10

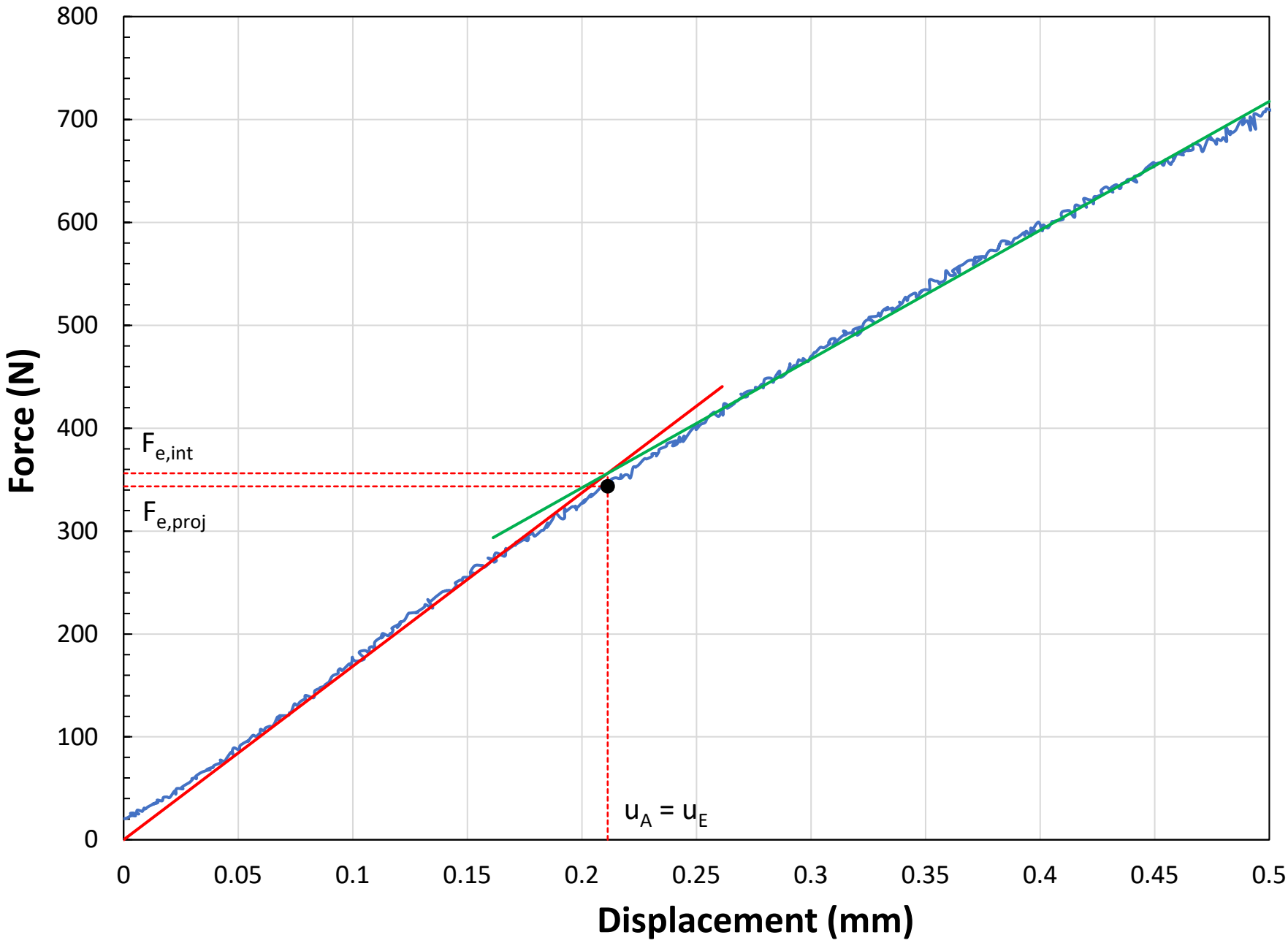
SP Test Results for
900 °C HIP, scan length = 26 mm, non-supported
(“rough” specimens)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP1
Material: AM Ti-64
Test speed: 0.001105 mm/s
Max strain rate: 1.10E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	343.4	N
$F_{e,int}$ =	356.2	N
$F_{h0/10,off}$ =	595.2	N
$F_{0.1mm,off}$ =	759.3	N
$F_{0.1mm}$ =	176.4	N
$F_{0.48mm}$ =	682.5	N
$F_{0.5mm}$ =	710.3	N
$F_{0.65mm}$ =	880.1	N
$F_{0.9mm}$ =	1035.2	N
F_{ept} =	1102.4	N
$F_{e1.5}$ =	77.5	N
F_m =	1121.8	N
F_{infl} =	584.1	N
F_f =	897.5	N
Displacement values		
u_e =	0.211	mm
$u_{h0/10,off}$ =	0.403	mm
$u_{0.1mm,off}$ =	0.552	mm
$u_{e1.5}$ =	0.042	mm
u_m =	1.201	mm
u_{infl} =	0.389	mm
u_f =	1.491	mm
Initial linear slope		
$Slope_{ini}$ =	1685.89	N/mm
Energy values		
E_{SP} =	1.18	J
E_m =	0.89	J
E_{PL} =	0.51	J

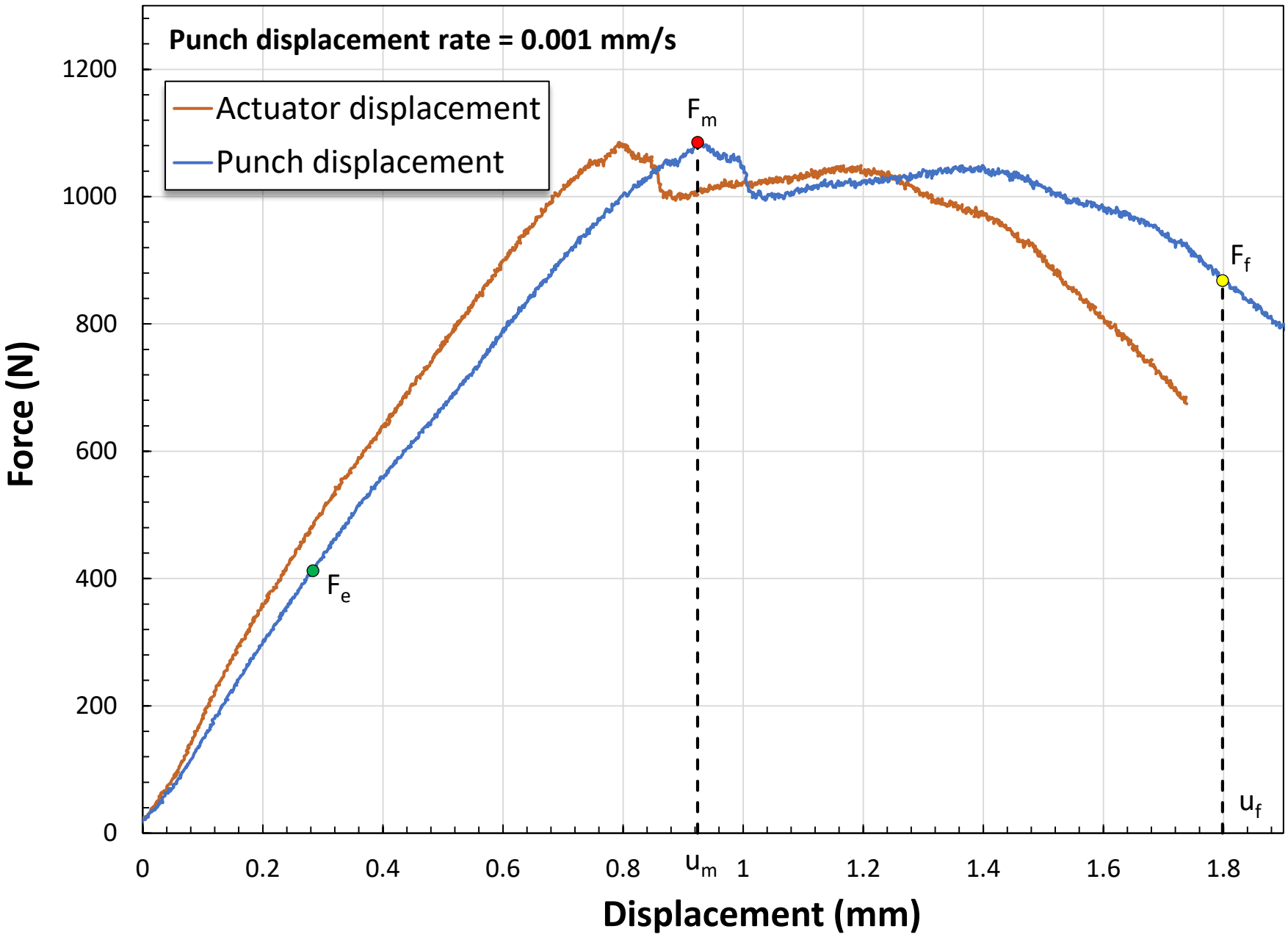

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

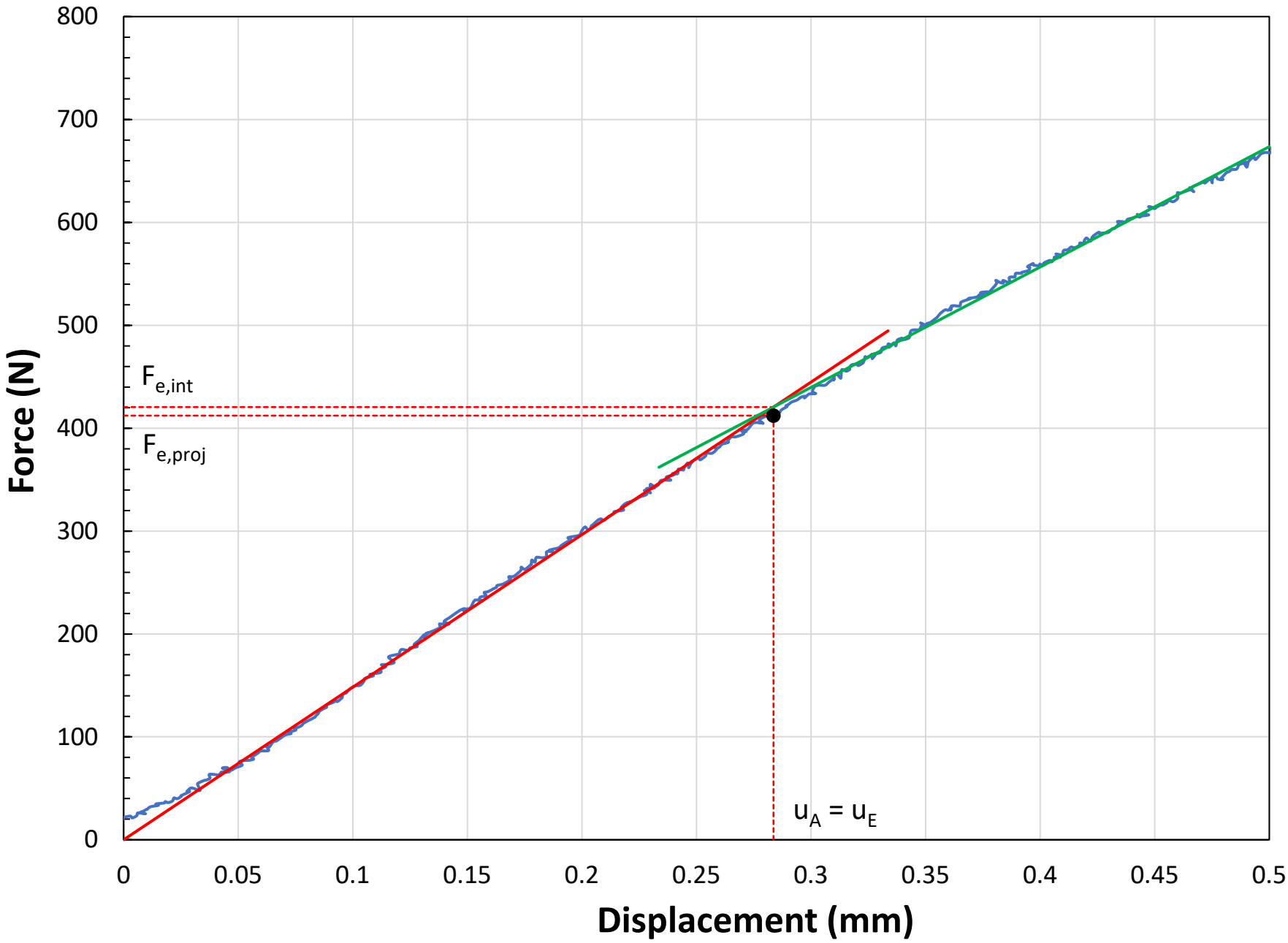

800
700
600
500
400
300
200
100
0
Force (N)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)
F e,int
F e,proj
u A = u E

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP2
Material: AM Ti-64
Test speed: 0.001171 mm/s
Max strain rate: 1.17E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	412.2	N
$F_{e,int}$ =	420.5	N
$F_{h0/10,off}$ =	668.2	N
$F_{0.1mm,off}$ =	920.9	N
$F_{0.1mm}$ =	146.5	N
$F_{0.48mm}$ =	641.9	N
$F_{0.5mm}$ =	668.0	N
$F_{0.65mm}$ =	844.5	N
$F_{0.9mm}$ =	1062.3	N
F_{ept} =	#DIV/0!	N
$F_{e1.5}$ =	82.3	N
F_m =	1085.3	N
F_{infl} =	#DIV/0!	N
F_f =	868.2	N
Displacement values		
u_e =	0.284	mm
$u_{h0/10,off}$ =	0.501	mm
$u_{0.1mm,off}$ =	0.721	mm
$u_{e1.5}$ =	0.057	mm
u_m =	0.924	mm
u_{infl} =	#DIV/0!	mm
u_f =	1.799	mm
Initial linear slope		
$Slope_{ini}$ =	1482.61	N/mm
Energy values		
E_{SP} =	1.44	J
E_m =	0.56	J
E_{PL} =	0.16	J

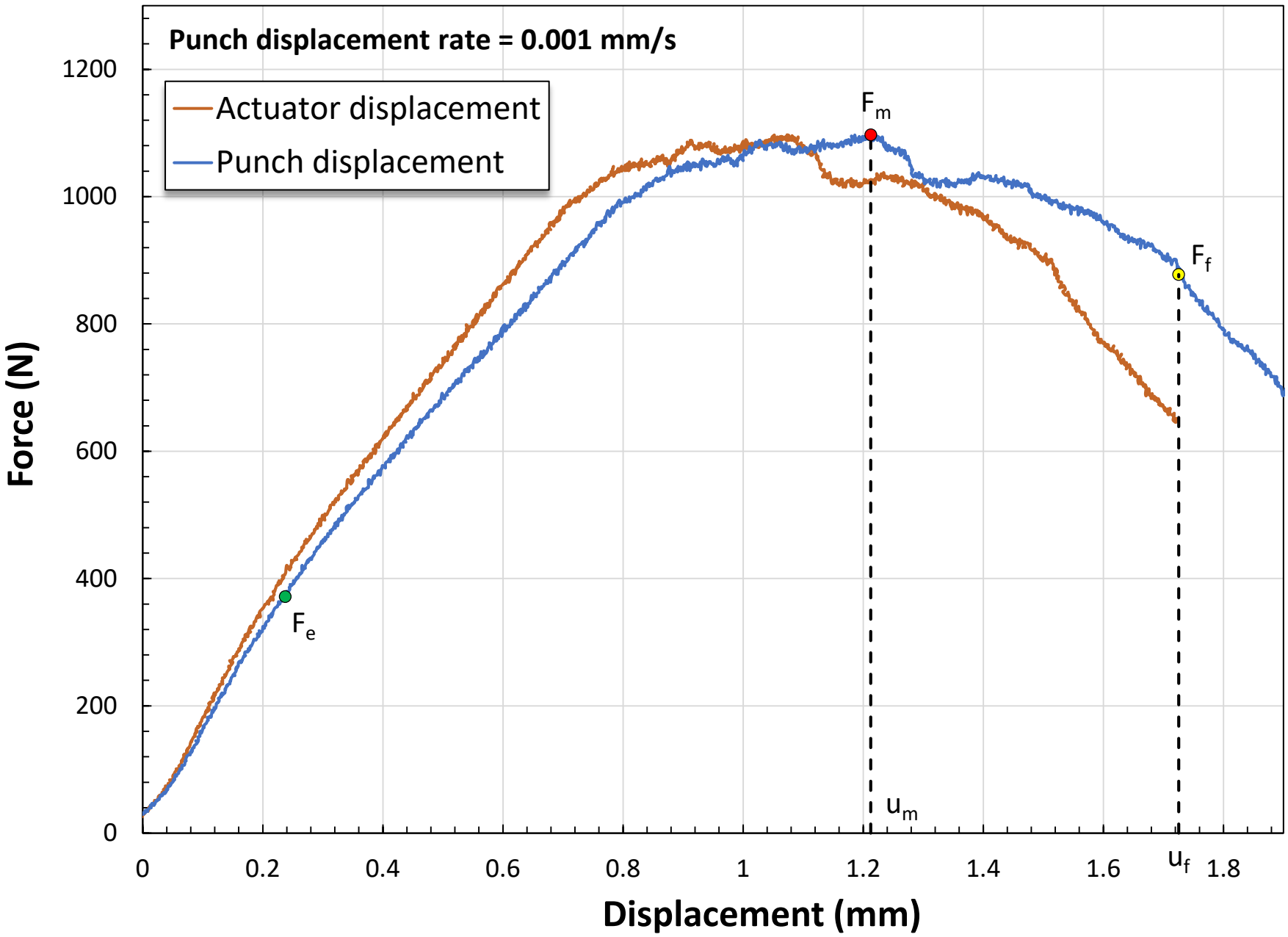

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

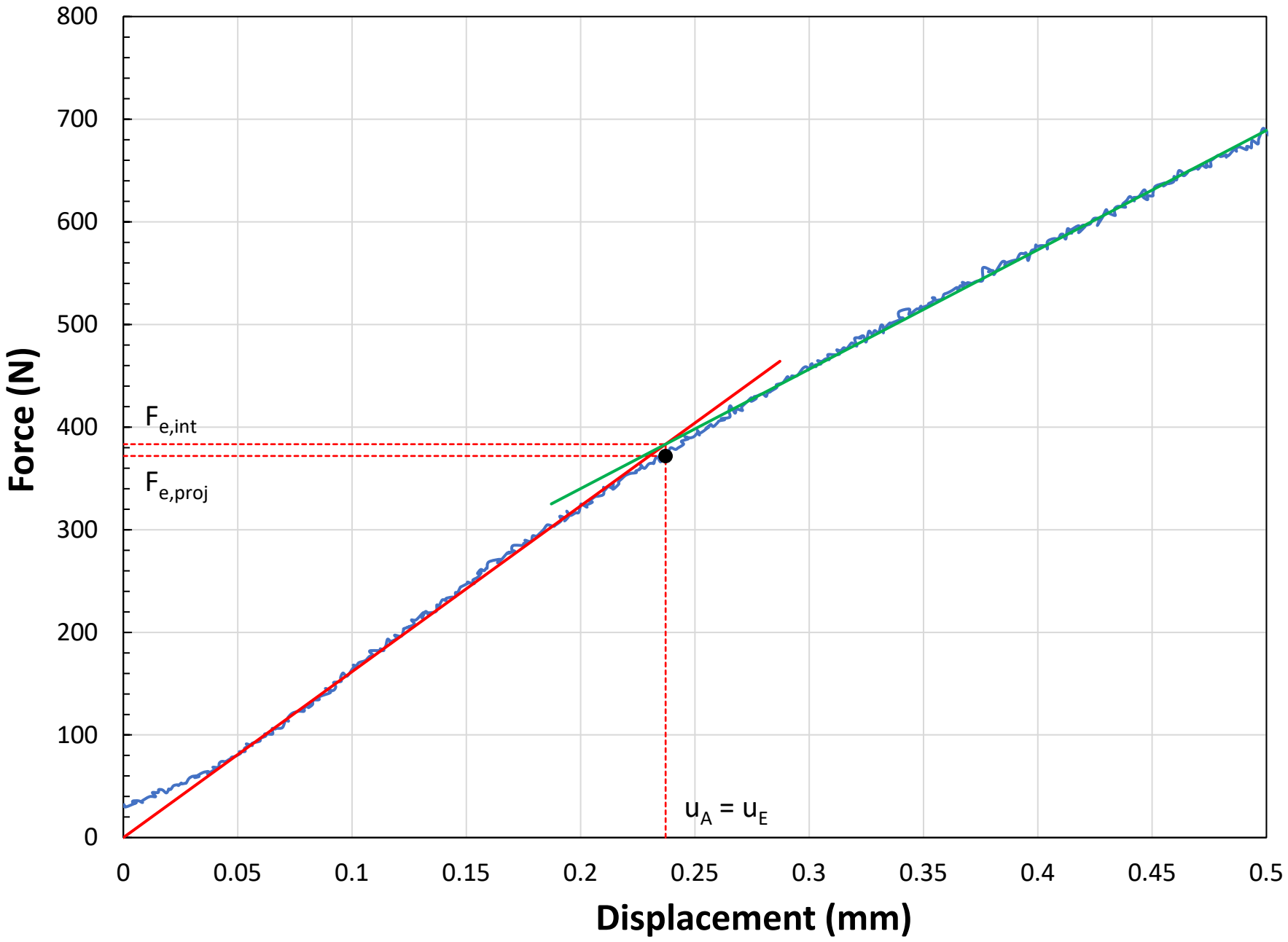

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP3
Material: AM Ti-64
Test speed: 0.001142 mm/s
Max strain rate: 1.14E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	371.8	N
$F_{e,int}$ =	383.3	N
$F_{h0/10,off}$ =	584.3	N
$F_{0.1mm,off}$ =	743.4	N
$F_{0.1mm}$ =	157.2	N
$F_{0.48mm}$ =	663.6	N
$F_{0.5mm}$ =	691.1	N
$F_{0.65mm}$ =	838.0	N
$F_{0.9mm}$ =	1046.7	N
F_{ept} =	392.2	N
$F_{e1.5}$ =	131.6	N
F_m =	1097.0	N
F_{infl} =	1083.1	N
F_f =	877.6	N
Displacement values		
u_e =	0.237	mm
$u_{h0/10,off}$ =	0.412	mm
$u_{0.1mm,off}$ =	0.561	mm
$u_{e1.5}$ =	0.082	mm
u_m =	1.213	mm
u_{infl} =	1.131	mm
u_f =	1.726	mm
Initial linear slope		
$Slope_{ini}$ =	1615.91	N/mm
Energy values		
E_{SP} =	1.39	J
E_m =	0.88	J
E_{PL} =	0.50	J

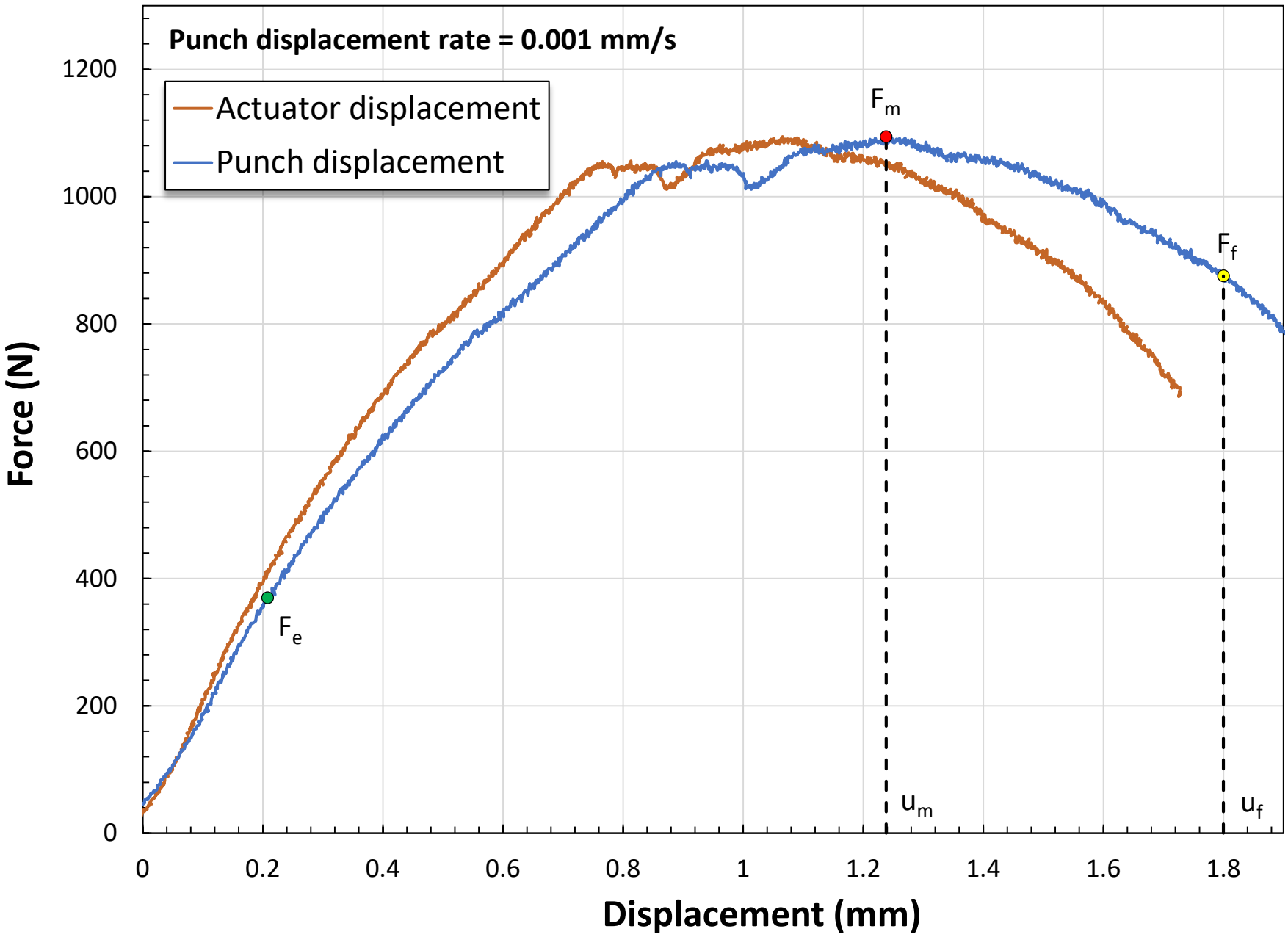

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

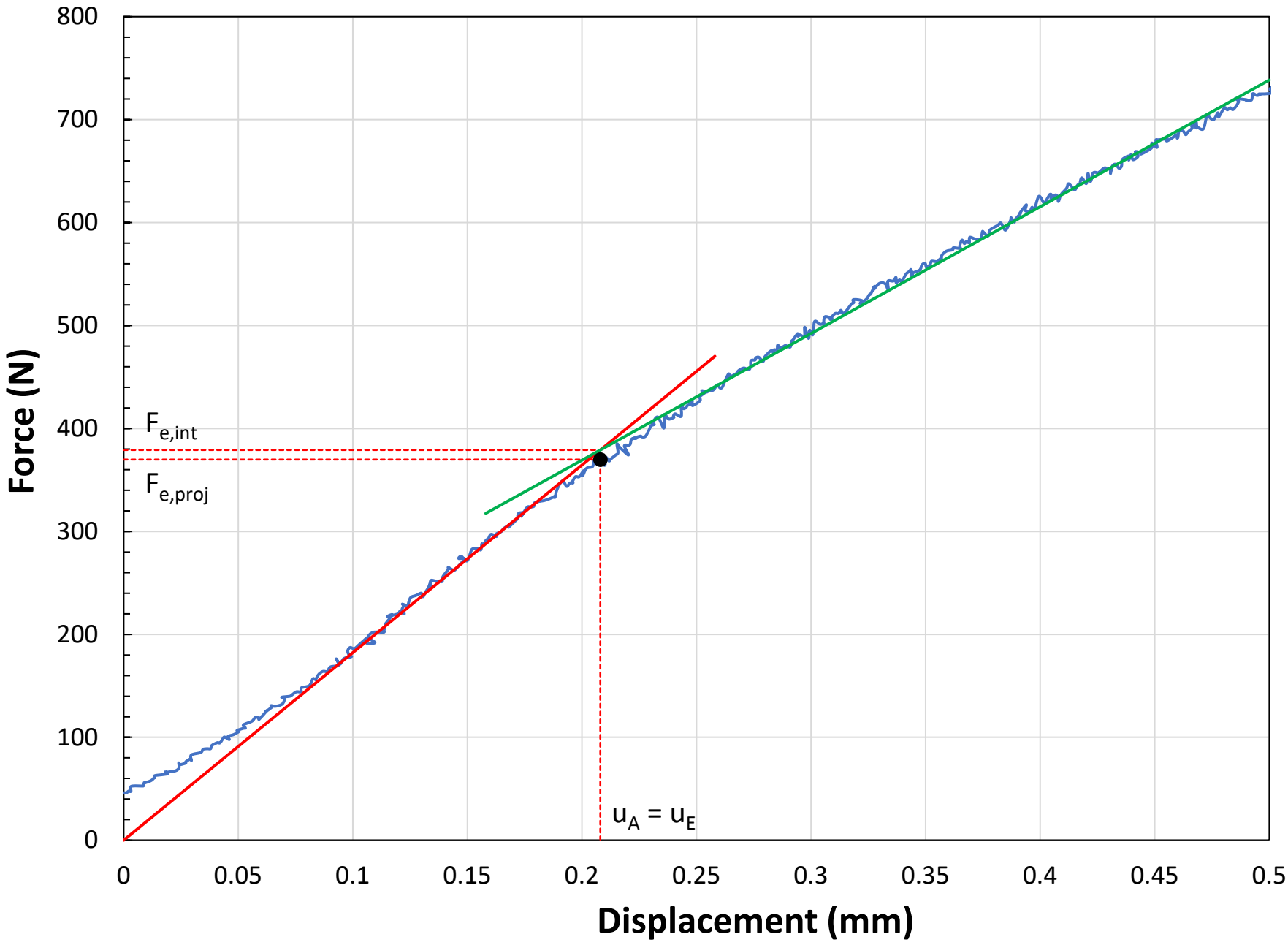

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP4
Material: AM Ti-64
Test speed: 0.001164 mm/s
Max strain rate: 1.16E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	369.8	N
$F_{e,int}$ =	379.0	N
$F_{h0/10,off}$ =	580.9	N
$F_{0.1mm,off}$ =	724.9	N
$F_{0.1mm}$ =	187.2	N
$F_{0.48mm}$ =	704.5	N
$F_{0.5mm}$ =	724.9	N
$F_{0.65mm}$ =	860.5	N
$F_{0.9mm}$ =	1049.7	N
F_{ept} =	60.7	N
$F_{e1.5}$ =	210.0	N
F_m =	1094.2	N
F_{infl} =	688.8	N
F_f =	875.4	N
Displacement values		
u_e =	0.208	mm
$u_{h0/10,off}$ =	0.369	mm
$u_{0.1mm,off}$ =	0.498	mm
$u_{e1.5}$ =	0.114	mm
u_m =	1.238	mm
u_{infl} =	2.005	mm
u_f =	1.800	mm
Initial linear slope		
$Slope_{ini}$ =	1821.89	N/mm
Energy values		
E_{SP} =	1.49	J
E_m =	0.92	J
E_{PL} =	0.60	J

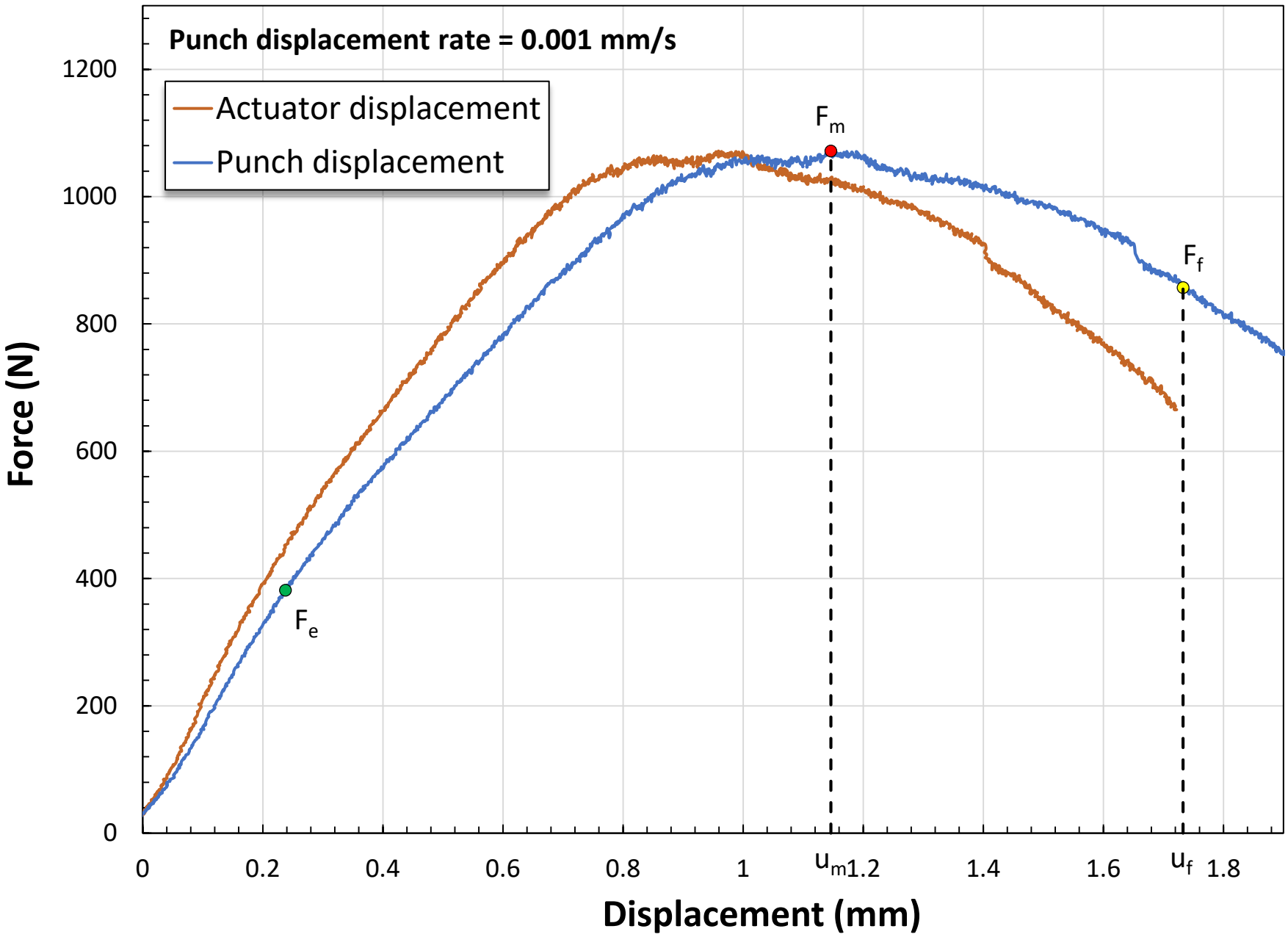

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

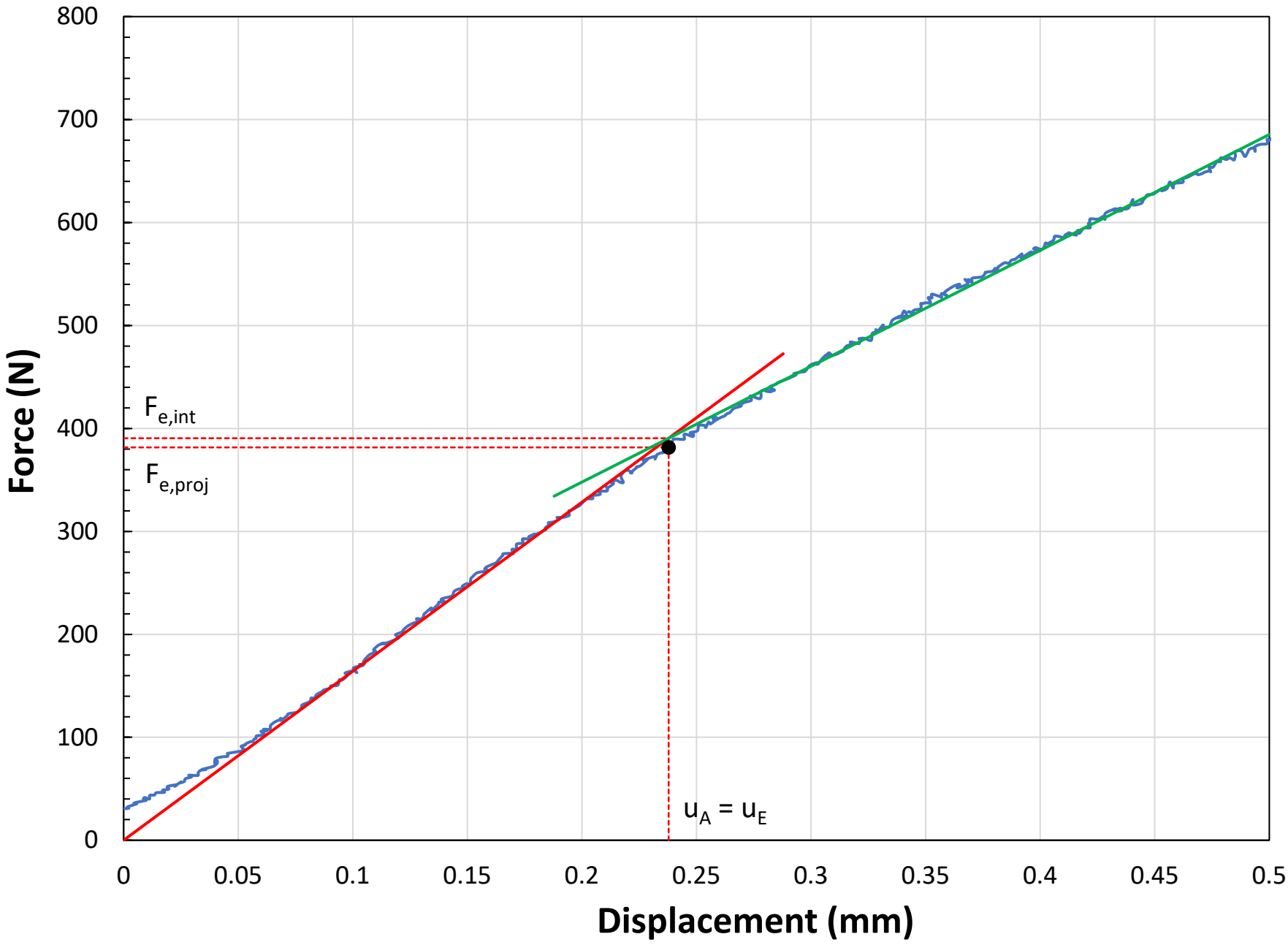

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP5
Material: AM Ti-64
Test speed: 0.001171 mm/s
Max strain rate: 1.17E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	381.6	N
$F_{e,int}$ =	390.5	N
$F_{h0/10,off}$ =	573.8	N
$F_{0.1mm,off}$ =	715.8	N
$F_{0.1mm}$ =	162.4	N
$F_{0.48mm}$ =	662.9	N
$F_{0.5mm}$ =	679.5	N
$F_{0.65mm}$ =	828.5	N
$F_{0.9mm}$ =	1026.5	N
F_{ept} =	1027.3	N
$F_{e1.5}$ =	131.3	N
F_m =	1071.5	N
F_{infl} =	46.1	N
F_f =	857.2	N
Displacement values		
u_e =	0.238	mm
$u_{h0/10,off}$ =	0.400	mm
$u_{0.1mm,off}$ =	0.536	mm
$u_{e1.5}$ =	0.078	mm
u_m =	1.146	mm
u_{infl} =	0.014	mm
u_f =	1.733	mm
Initial linear slope		
$Slope_{ini}$ =	1641.54	N/mm
Energy values		
E_{SP} =	1.38	J
E_m =	0.80	J
E_{PL} =	0.45	J

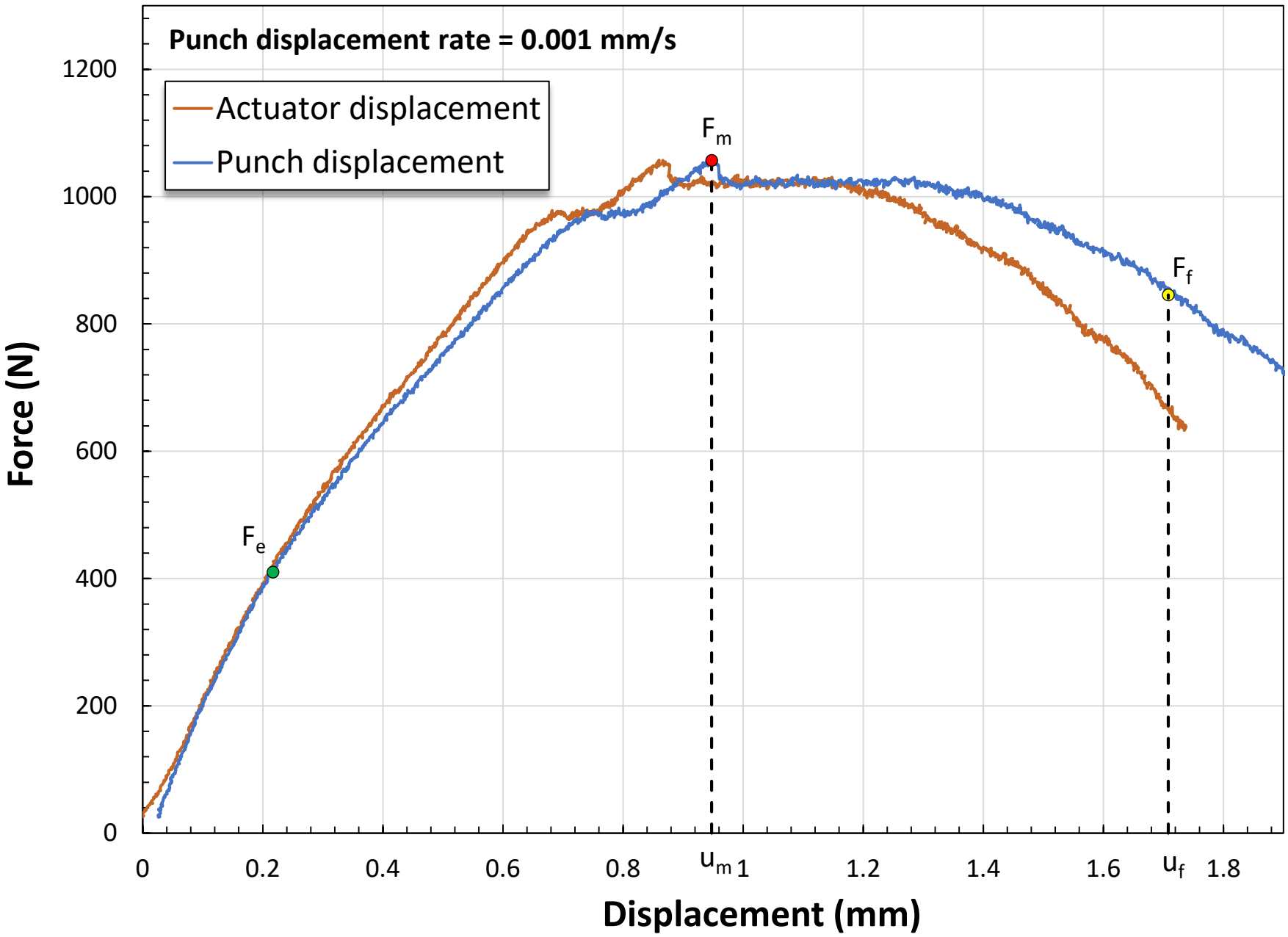

Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
u_m
1.2
1.4
1.6
u_f
1.8

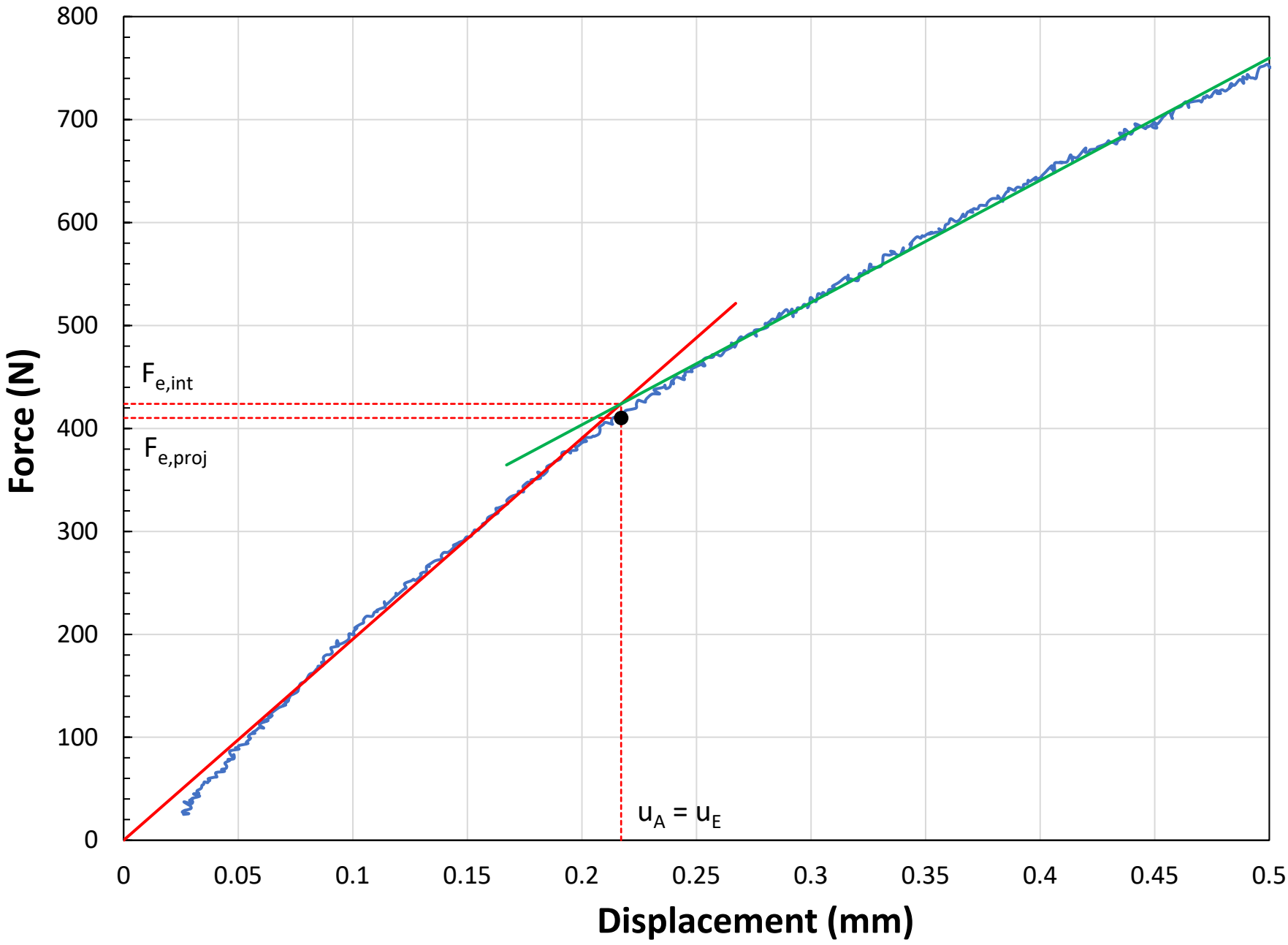

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP6
Material: AM Ti-64
Test speed: 0.001153 mm/s
Max strain rate: 1.15E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	410.2	N
$F_{e,int}$ =	423.9	N
$F_{h0/10,off}$ =	590.8	N
$F_{0.1mm,off}$ =	712.0	N
$F_{0.1mm}$ =	200.5	N
$F_{0.48mm}$ =	728.9	N
$F_{0.5mm}$ =	753.7	N
$F_{0.65mm}$ =	902.6	N
$F_{0.9mm}$ =	1027.1	N
F_{ept} =	847.9	N
$F_{e1.5}$ =	807.9	N
F_m =	1057.0	N
F_{infl} =	632.8	N
F_f =	845.6	N
Displacement values		
u_e =	0.217	mm
$u_{h0/10,off}$ =	0.353	mm
$u_{0.1mm,off}$ =	0.465	mm
$u_{e1.5}$ =	0.559	mm
u_m =	0.948	mm
u_{infl} =	1.994	mm
u_f =	1.708	mm
Initial linear slope		
$Slope_{ini}$ =	1952.20	N/mm
Energy values		
E_{SP} =	1.38	J
E_m =	0.63	J
E_{PL} =	0.34	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
u_m
1
1.2
1.4
1.6
u_f
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

ANNEX 11

SP Test Results for

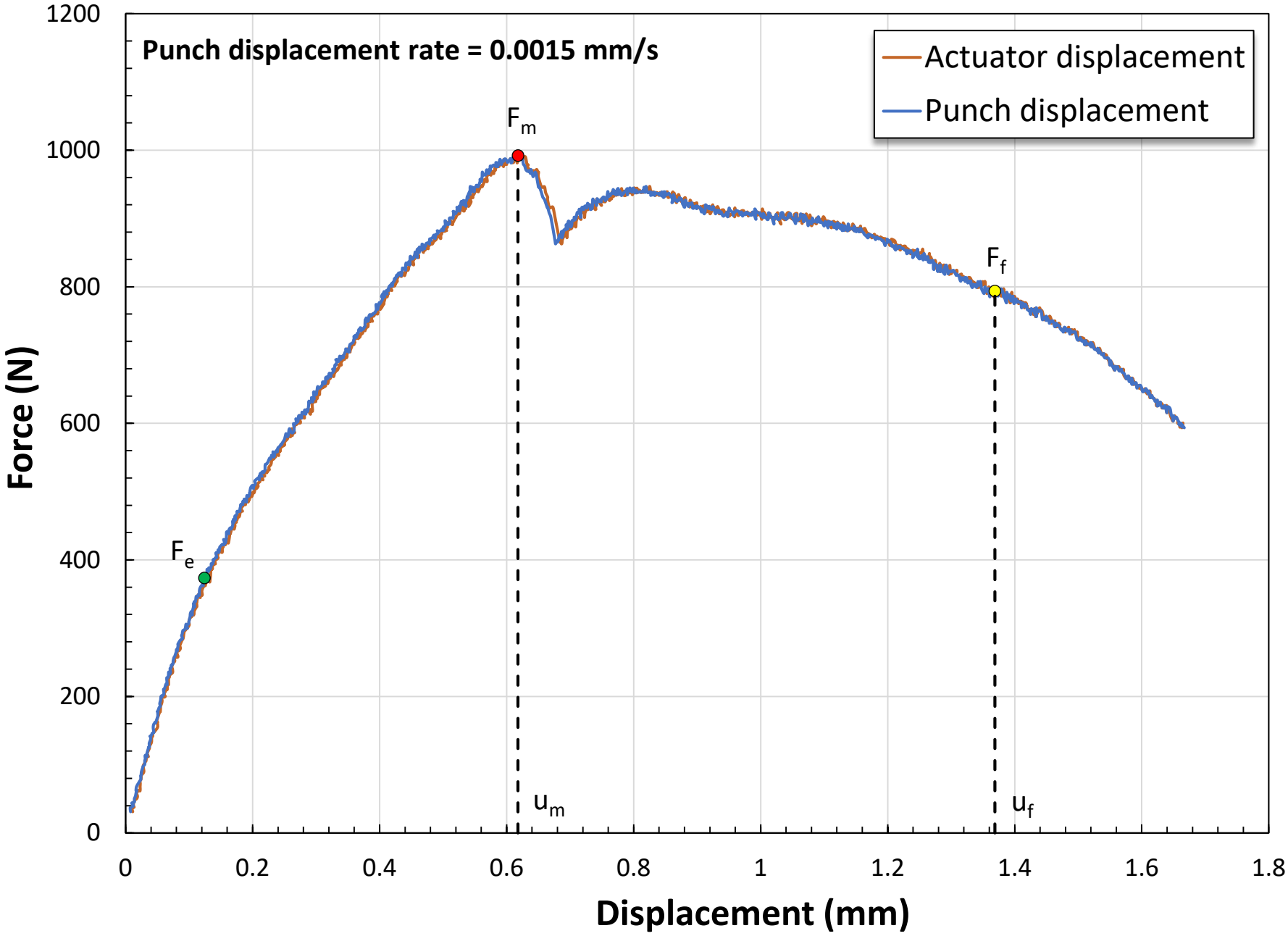
900 °C HIP, scan length = 26 mm, non-supported

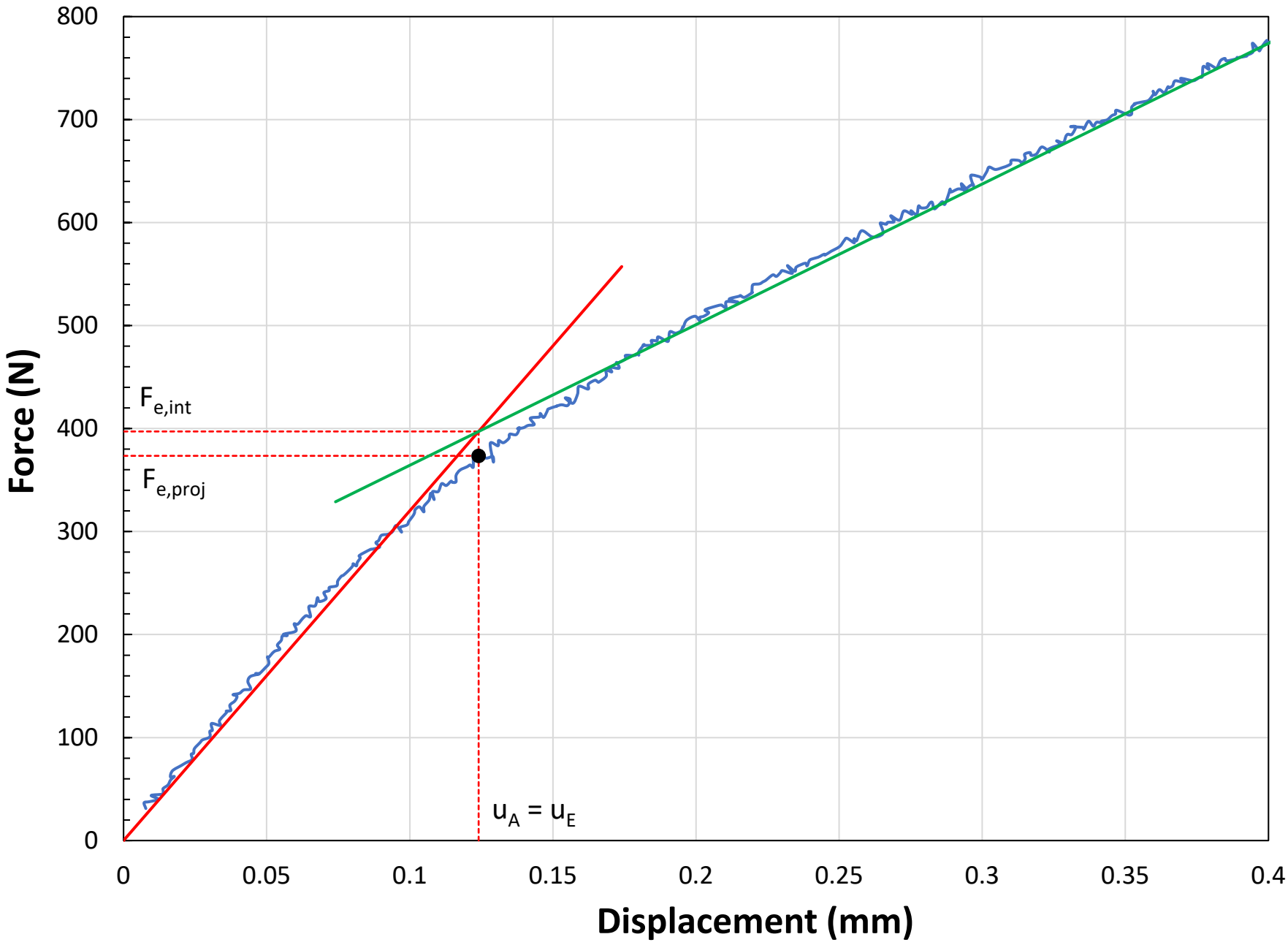
(polished specimens)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP7 (pc
Material: AM Ti-64
Test speed: 0.001441 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	373.5	N
$F_{e,int}$ =	397.2	N
$F_{h0/10,off}$ =	522.2	N
$F_{0.1mm,off}$ =	653.3	N
$F_{0.1mm}$ =	309.9	N
$F_{0.48mm}$ =	870.1	N
$F_{0.5mm}$ =	882.4	N
$F_{0.65mm}$ =	965.2	N
$F_{0.9mm}$ =	918.4	N
F_{ept} =	831.9	N
$F_{e1.5}$ =	600.9	N
F_{m} =	992.2	N
F_{infl} =	593.6	N
F_{f} =	793.7	N
Displacement values		
u_{e} =	0.124	mm
$u_{h0/10,off}$ =	0.209	mm
$u_{0.1mm,off}$ =	0.305	mm
$u_{e1.5}$ =	0.269	mm
u_{m} =	0.618	mm
u_{infl} =	1.667	mm
u_{f} =	1.369	mm
Initial linear slope		
$Slope_{ini}$ =	3201.67	N/mm
Energy values		
E_{SP} =	1.05	J
E_{m} =	0.38	J
E_{PL} =	0.23	J

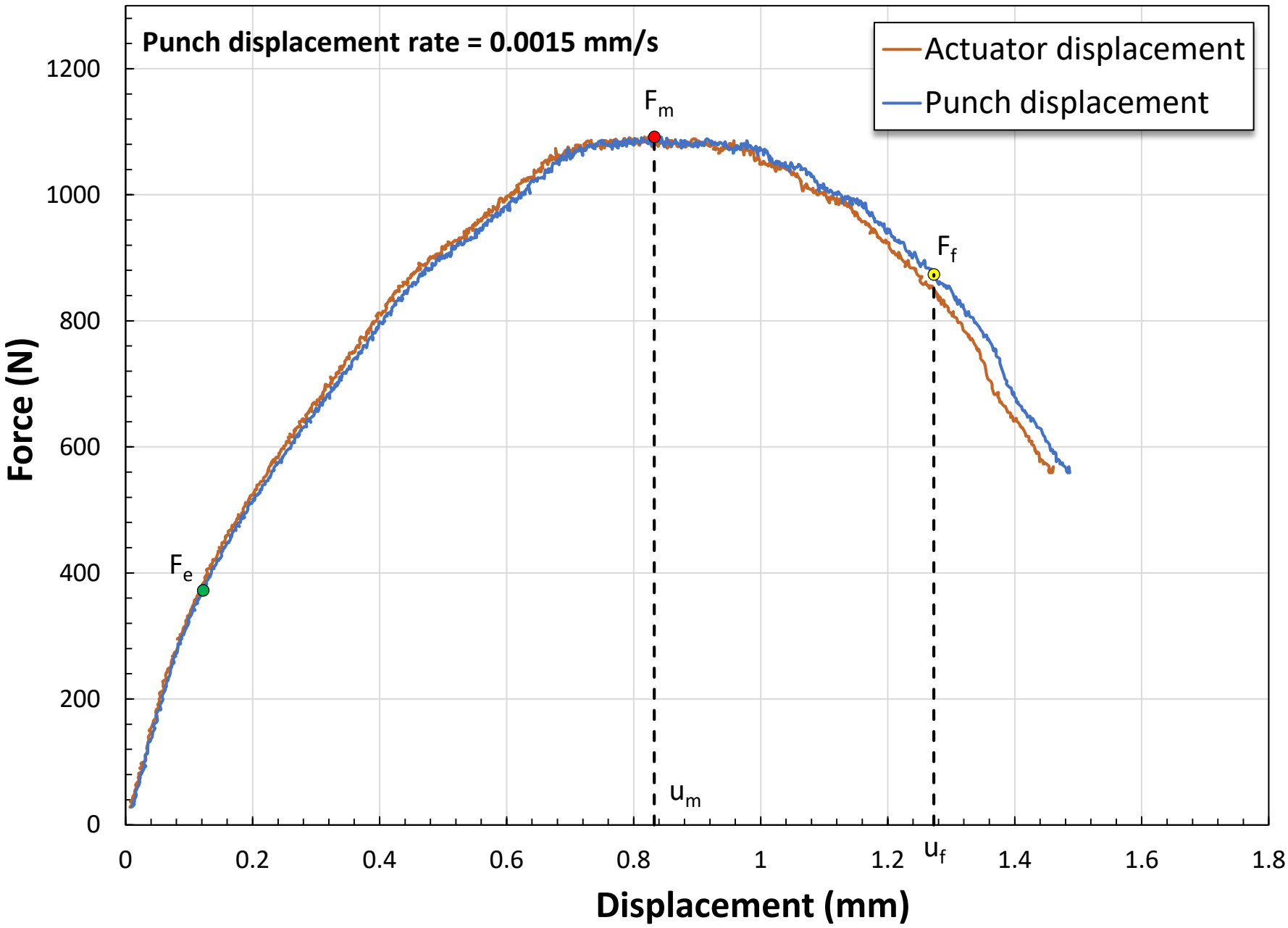

Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

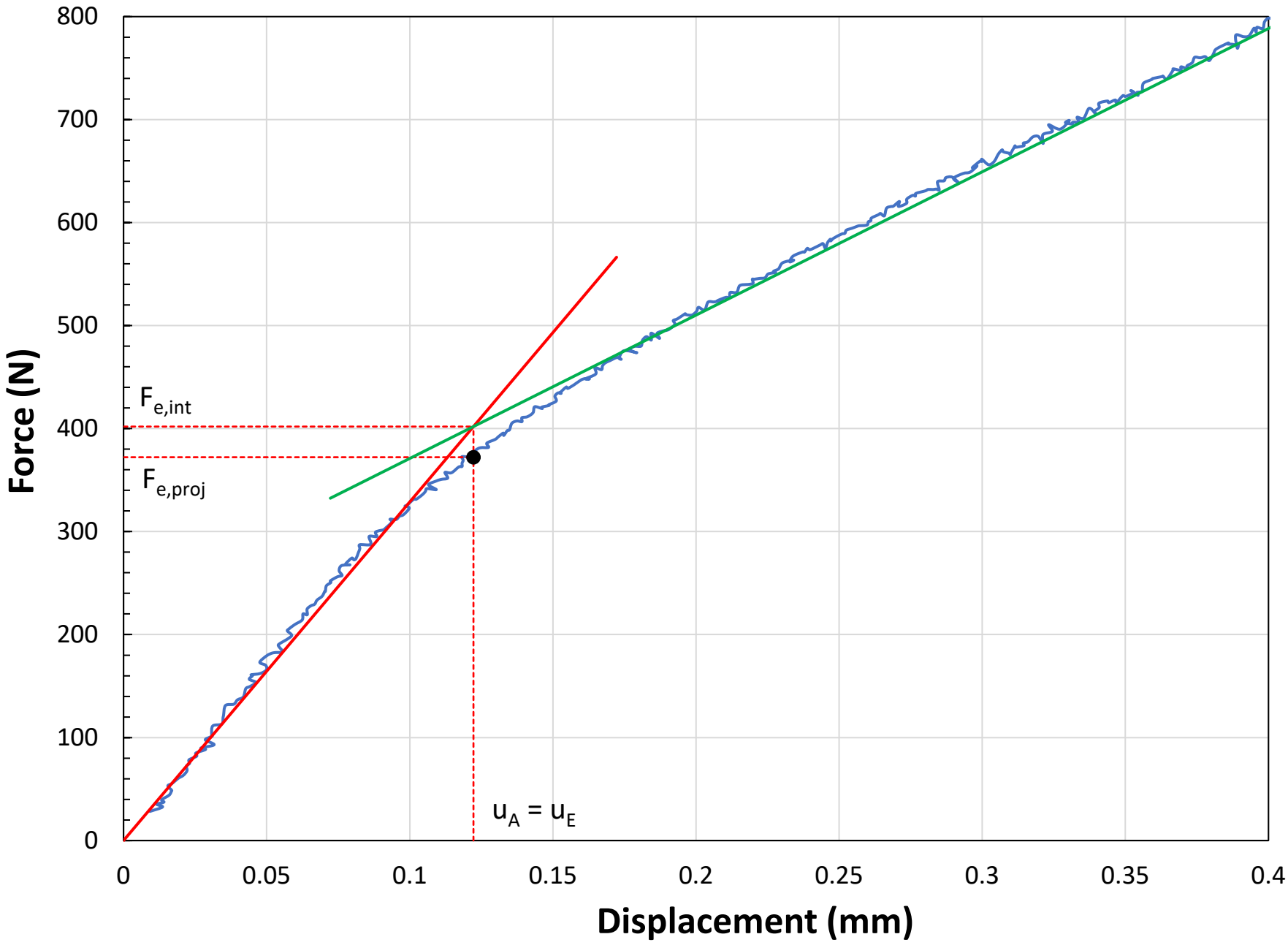

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP8 (pc
Material: AM Ti-64
Test speed: 0.001426 mm/s
Max strain rate: 1.43E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	372.2	N
$F_{e,int}$ =	402.0	N
$F_{h0/10,off}$ =	515.6	N
$F_{0.1mm,off}$ =	660.5	N
$F_{0.1mm}$ =	324.6	N
$F_{0.48mm}$ =	882.8	N
$F_{0.5mm}$ =	902.5	N
$F_{0.65mm}$ =	1026.6	N
$F_{0.9mm}$ =	1079.7	N
F_{ept} =	369.2	N
$F_{e1.5}$ =	735.9	N
F_m =	1091.8	N
F_{infl} =	559.0	N
F_f =	873.4	N
Displacement values		
u_e =	0.122	mm
$u_{h0/10,off}$ =	0.203	mm
$u_{0.1mm,off}$ =	0.302	mm
$u_{e1.5}$ =	0.357	mm
u_m =	0.832	mm
u_{infl} =	1.487	mm
u_f =	1.273	mm
Initial linear slope		
$Slope_{ini}$ =	3288.00	N/mm
Energy values		
E_{SP} =	1.06	J
E_m =	0.62	J
E_{PL} =	0.43	J

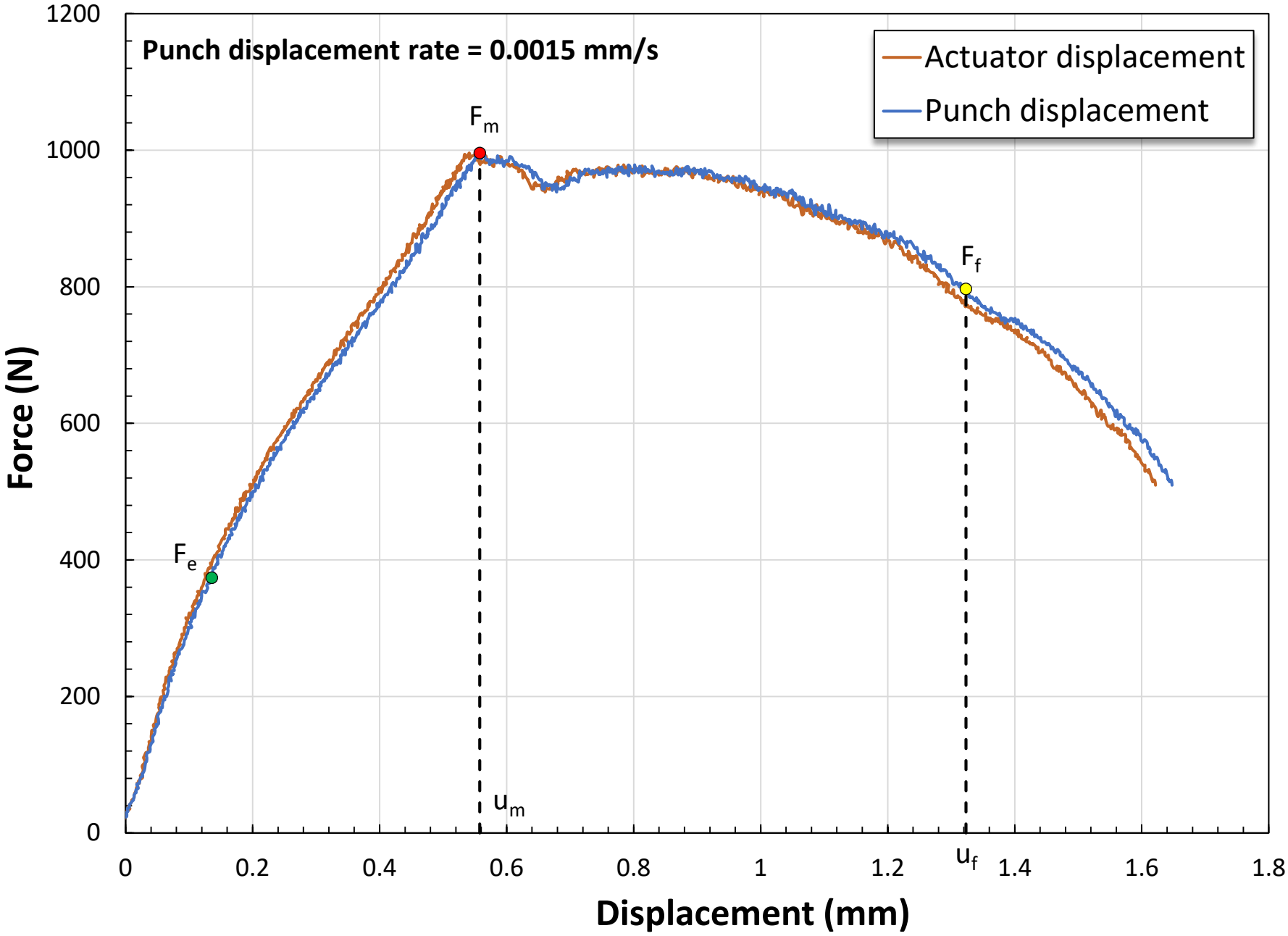

Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

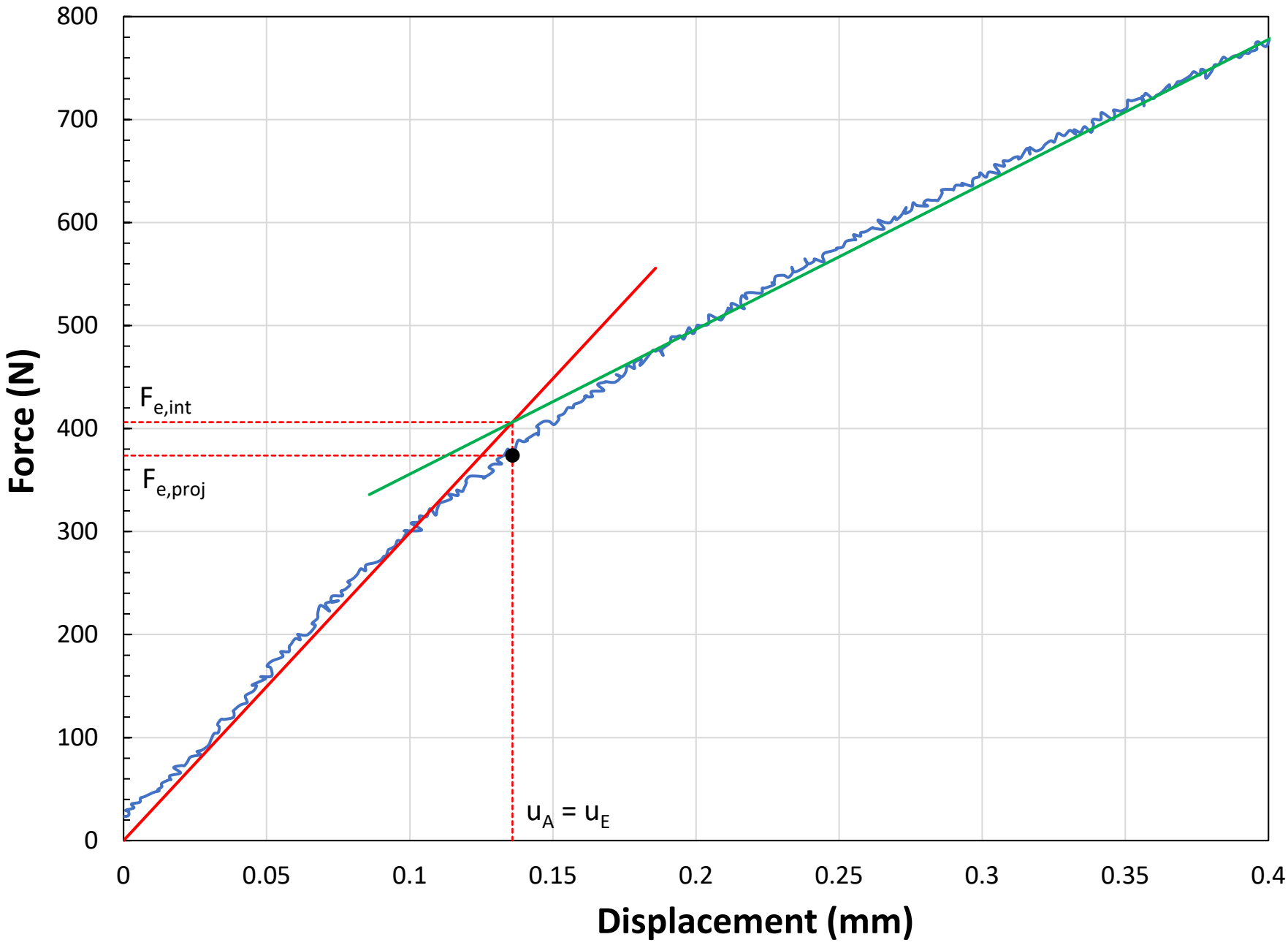

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP9 (pc
Material: AM Ti-64
Test speed: 0.001459 mm/s
Max strain rate: 1.46E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	373.8	N
$F_{e,int}$ =	406.2	N
$F_{h0/10,off}$ =	531.7	N
$F_{0.1mm,off}$ =	690.7	N
$F_{0.1mm}$ =	300.6	N
$F_{0.48mm}$ =	882.8	N
$F_{0.5mm}$ =	915.7	N
$F_{0.65mm}$ =	961.6	N
$F_{0.9mm}$ =	969.8	N
F_{ept} =	721.9	N
$F_{e1.5}$ =	746.2	N
F_m =	995.9	N
F_{infl} =	509.4	N
F_f =	796.7	N
Displacement values		
u_e =	0.136	mm
$u_{h0/10,off}$ =	0.223	mm
$u_{0.1mm,off}$ =	0.333	mm
$u_{e1.5}$ =	0.380	mm
u_m =	0.558	mm
u_{infl} =	1.648	mm
u_f =	1.323	mm
Initial linear slope		
$Slope_{ini}$ =	2989.78	N/mm
Energy values		
E_{SP} =	1.04	J
E_m =	0.32	J
E_{PL} =	0.16	J

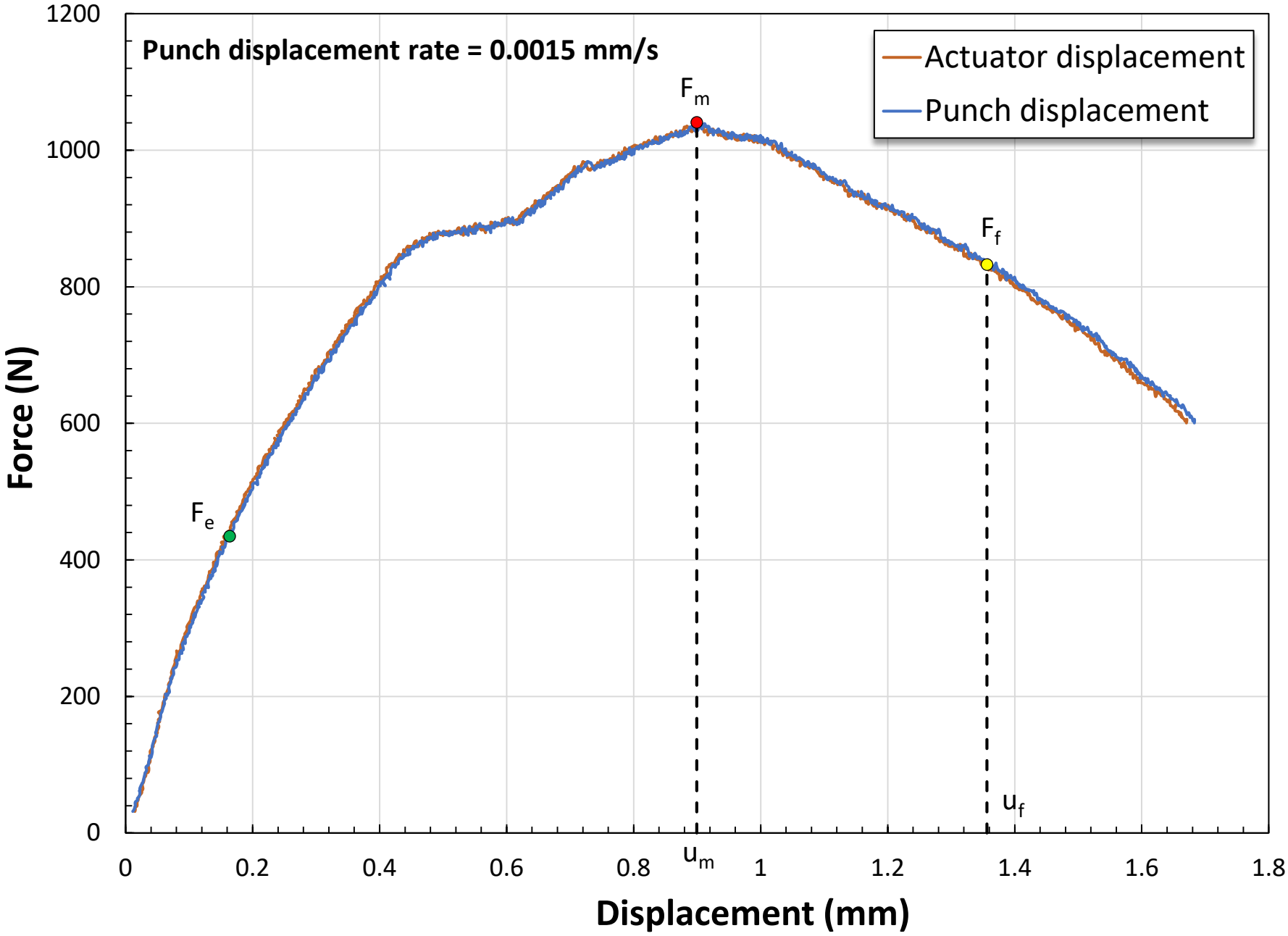

Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

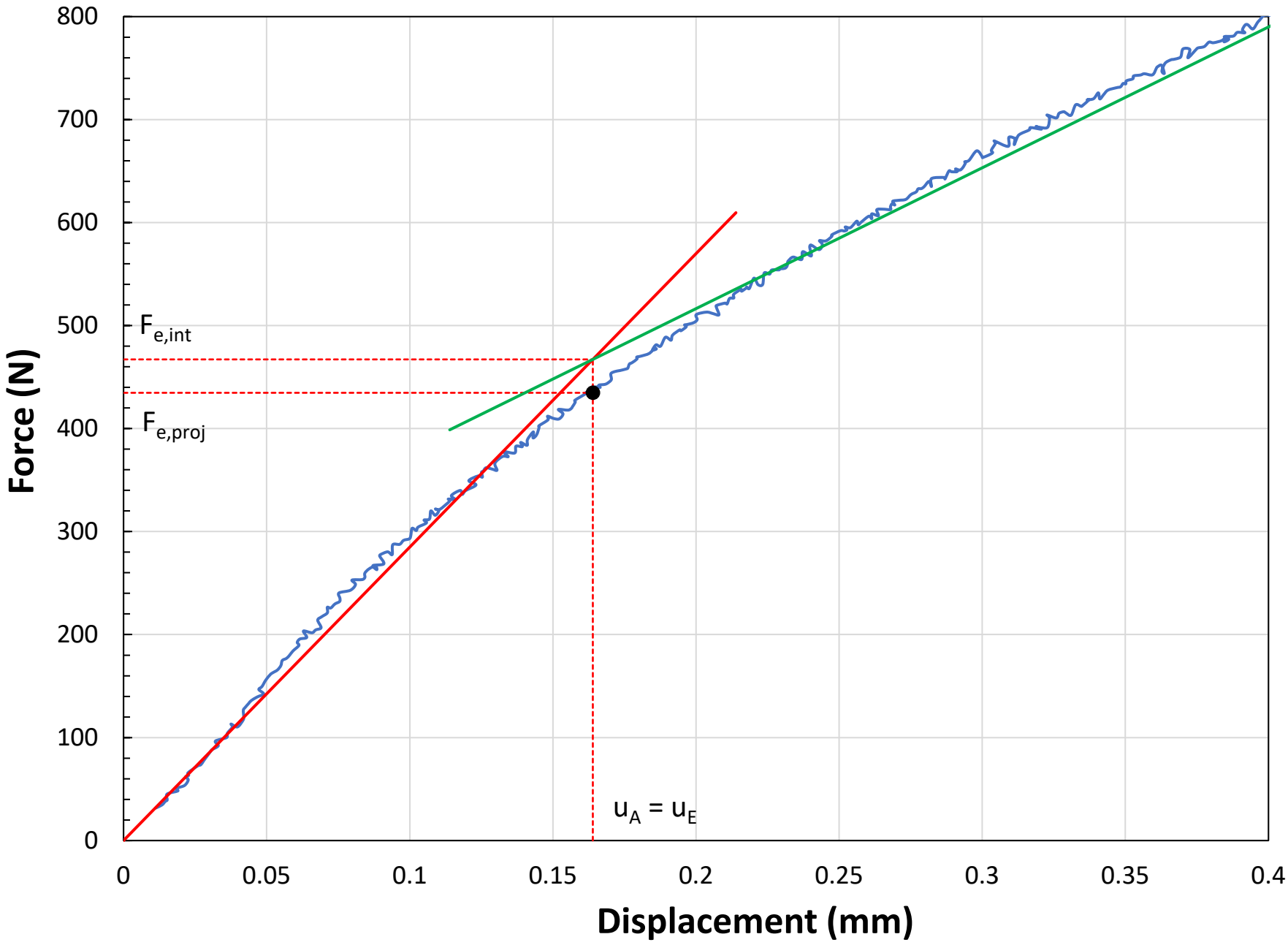

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP10 (p
Material: AM Ti-64
Test speed: 0.001444 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	434.7	N
$F_{e,int}$ =	467.2	N
$F_{h0/10,off}$ =	595.3	N
$F_{0.1mm,off}$ =	748.0	N
$F_{0.1mm}$ =	293.0	N
$F_{0.48mm}$ =	872.8	N
$F_{0.5mm}$ =	878.4	N
$F_{0.65mm}$ =	921.6	N
$F_{0.9mm}$ =	1033.5	N
F_{ept} =	884.7	N
$F_{e1.5}$ =	858.4	N
F_m =	1040.8	N
F_{infl} =	967.1	N
F_f =	832.7	N
Displacement values		
u_e =	0.164	mm
$u_{h0/10,off}$ =	0.254	mm
$u_{0.1mm,off}$ =	0.364	mm
$u_{e1.5}$ =	0.457	mm
u_m =	0.899	mm
u_{infl} =	0.707	mm
u_f =	1.356	mm
Initial linear slope		
$Slope_{ini}$ =	2849.28	N/mm
Energy values		
E_{SP} =	1.09	J
E_m =	0.65	J
E_{PL} =	0.46	J


Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

ANNEX 12

SP Test Results for

1050 °C + 800 °C HIP, scan length = 78 mm, non-supported

(“rough” specimens)

Small Punch Test Results

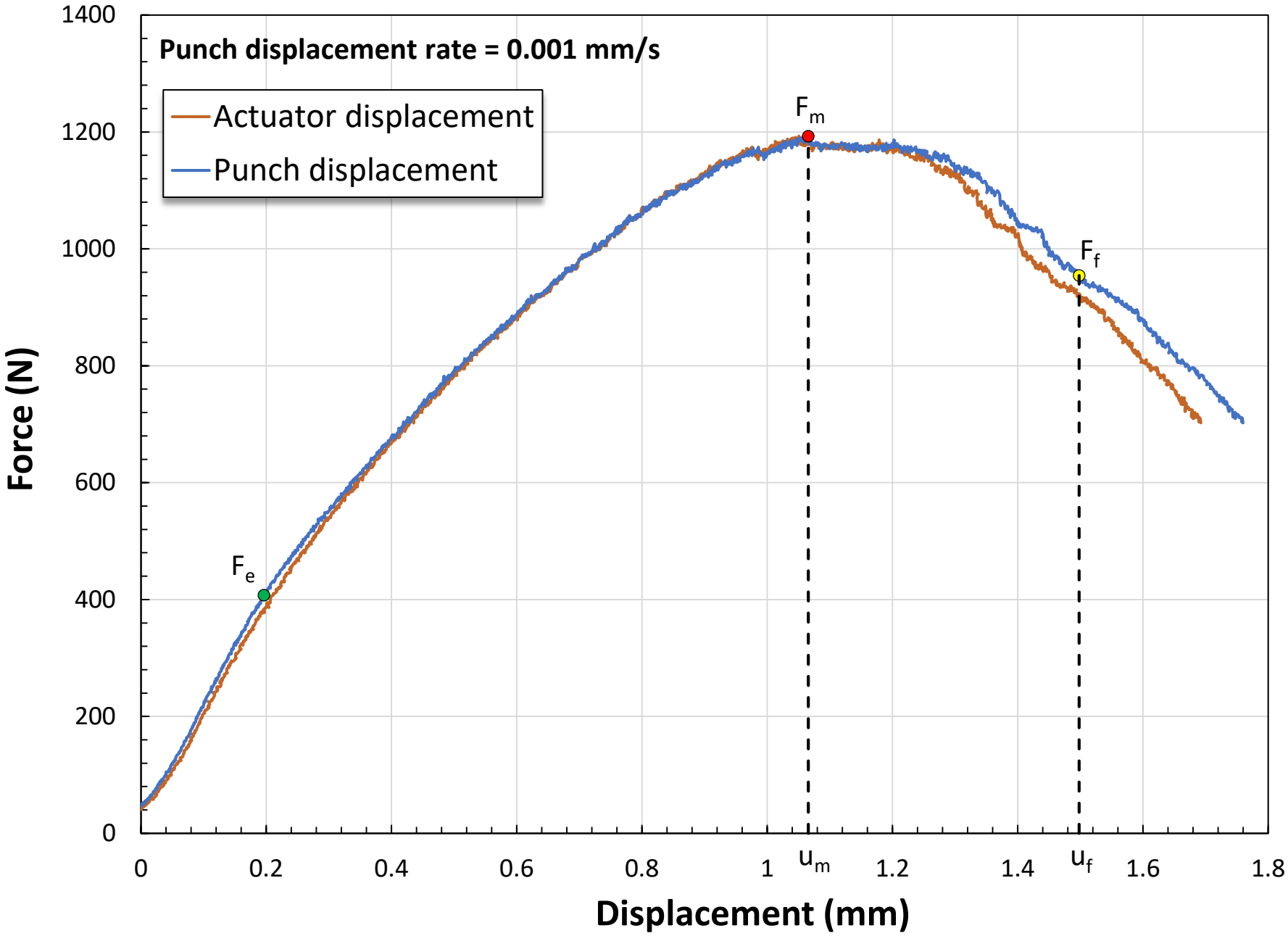
Specimen ID: SuperB_1_N_a_SP1

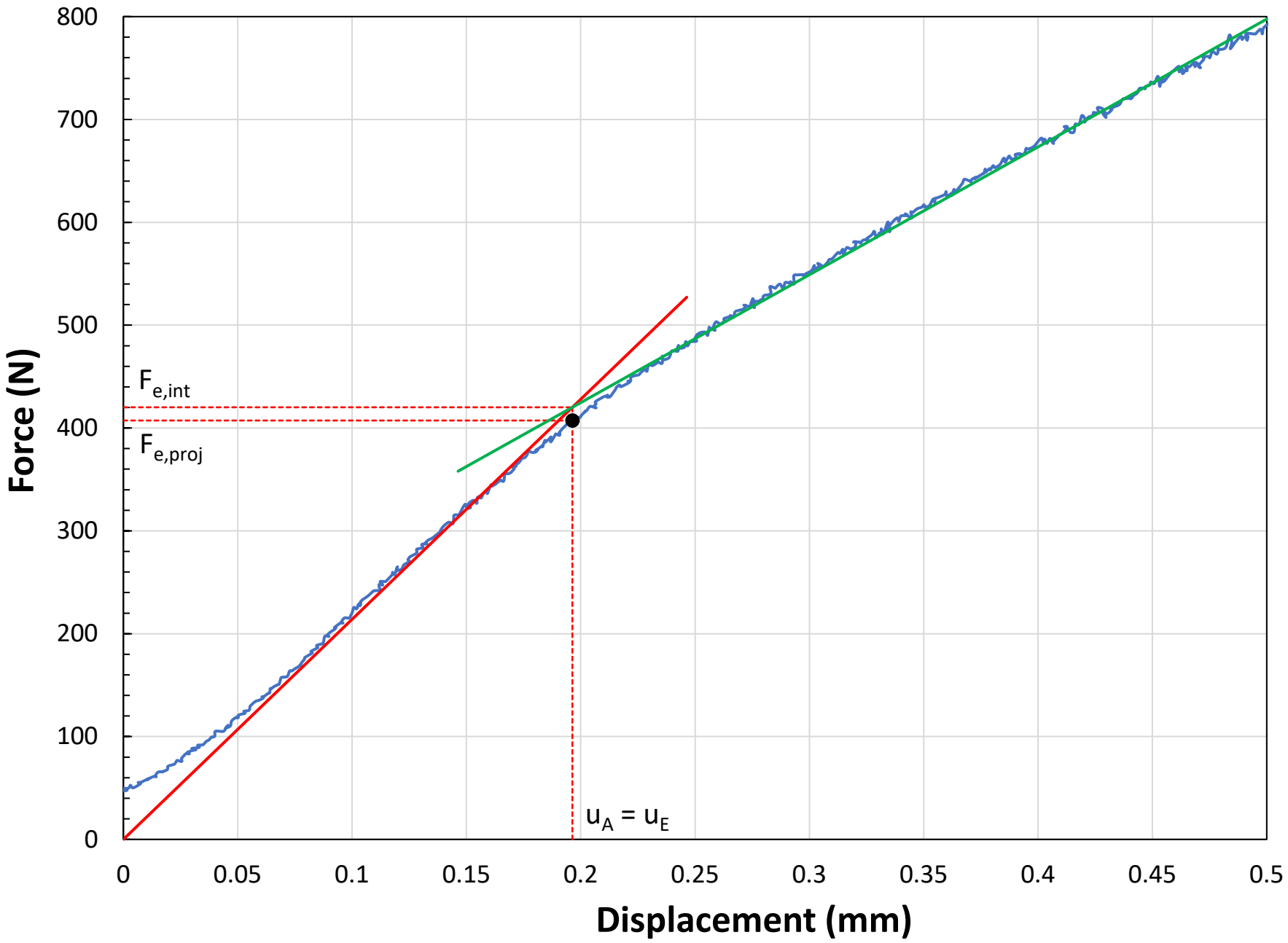
Material: AM Ti-64

Test speed: 0.001043 mm/s

Max strain rate: 1.04E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	407.3	N
$F_{e,int}$ =	420.1	N
$F_{h0/10,off}$ =	576.8	N
$F_{0.1mm,off}$ =	703.8	N
$F_{0.1mm}$ =	218.3	N
$F_{0.48mm}$ =	768.0	N
$F_{0.5mm}$ =	791.8	N
$F_{0.65mm}$ =	932.3	N
$F_{0.9mm}$ =	1126.7	N
F_{ept} =	1179.1	N
$F_{e1.5}$ =	231.7	N
F_m =	1192.9	N
F_{infl} =	702.3	N
F_f =	954.3	N
Displacement values		
u_e =	0.196	mm
$u_{h0/10,off}$ =	0.320	mm
$u_{0.1mm,off}$ =	0.430	mm
$u_{e1.5}$ =	0.104	mm
u_m =	1.066	mm
u_{infl} =	1.760	mm
u_f =	1.498	mm
Initial linear slope		
$Slope_{ini}$ =	2139.70	N/mm
Energy values		
E_{SP} =	1.29	J
E_m =	0.81	J
E_{PL} =	0.48	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
1400
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

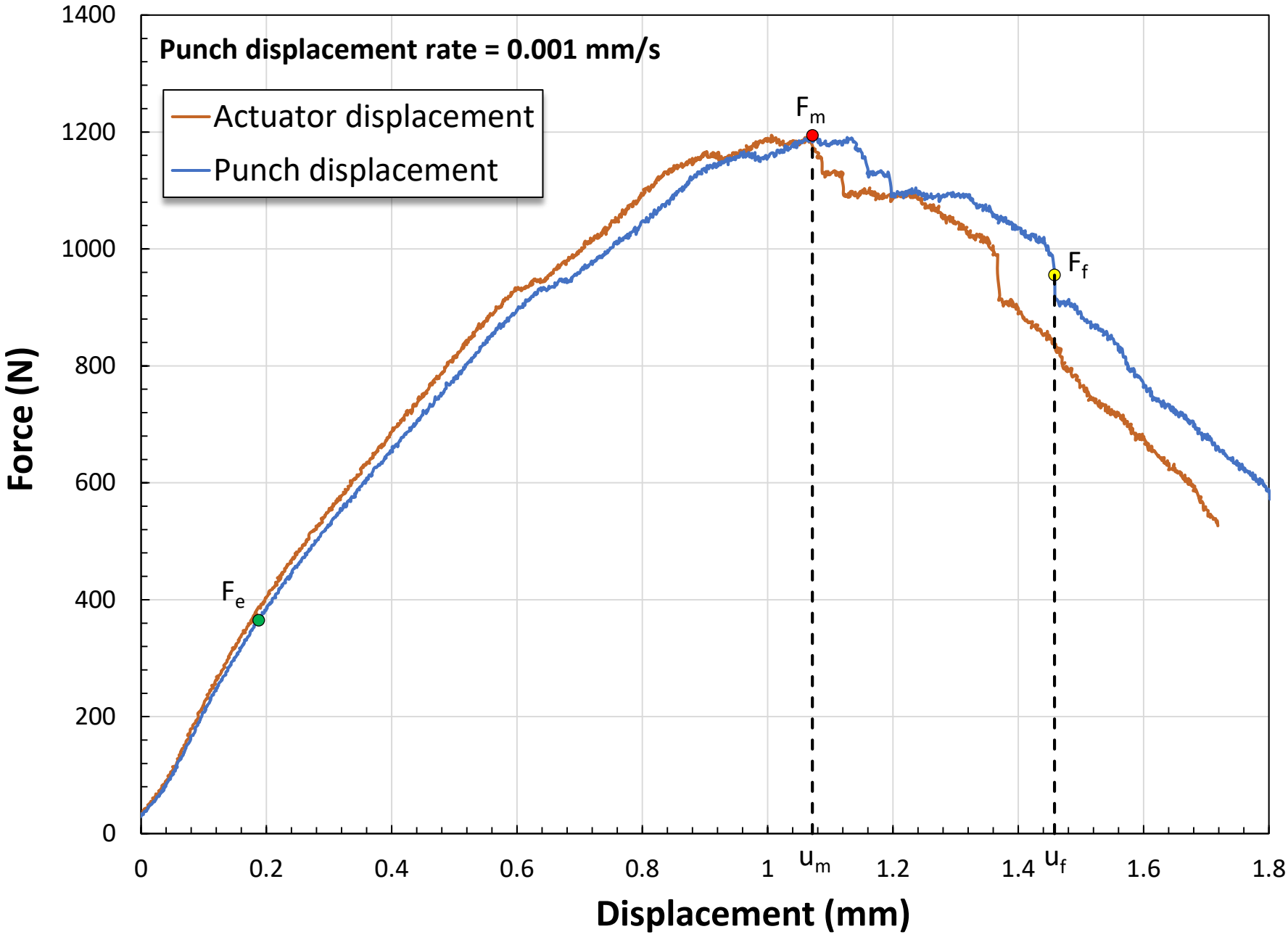
Specimen ID: SuperB_1_N_a_SP2

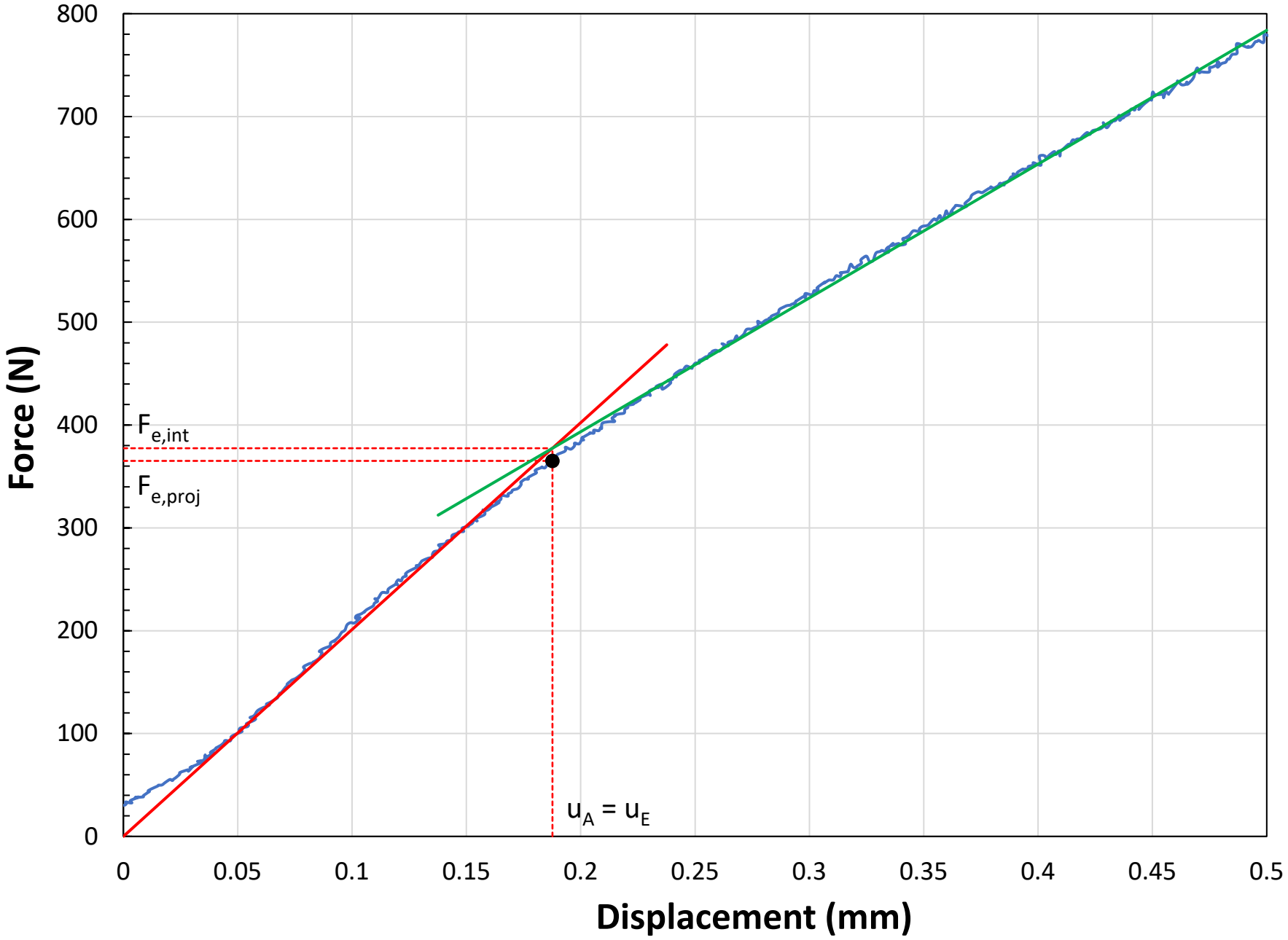
Material: AM Ti-64

Test speed: 0.001067 mm/s

Max strain rate: 1.07E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	365.1	N
$F_{e,int}$ =	377.5	N
$F_{h0/10,off}$ =	570.1	N
$F_{0.1mm,off}$ =	732.7	N
$F_{0.1mm}$ =	207.9	N
$F_{0.48mm}$ =	748.0	N
$F_{0.5mm}$ =	779.8	N
$F_{0.65mm}$ =	931.9	N
$F_{0.9mm}$ =	1138.0	N
F_{ept} =	1127.1	N
$F_{e1.5}$ =	146.1	N
F_{m} =	1194.5	N
F_{infl} =	1189.5	N
F_{f} =	955.6	N
Displacement values		
u_{e} =	0.188	mm
$u_{h0/10,off}$ =	0.335	mm
$u_{0.1mm,off}$ =	0.465	mm
$u_{e1.5}$ =	0.072	mm
u_{m} =	1.071	mm
u_{infl} =	1.077	mm
u_{f} =	1.458	mm
Initial linear slope		
$Slope_{ini}$ =	2011.63	N/mm
Energy values		
E_{SP} =	1.23	J
E_{m} =	0.80	J
E_{PL} =	0.45	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
1400
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

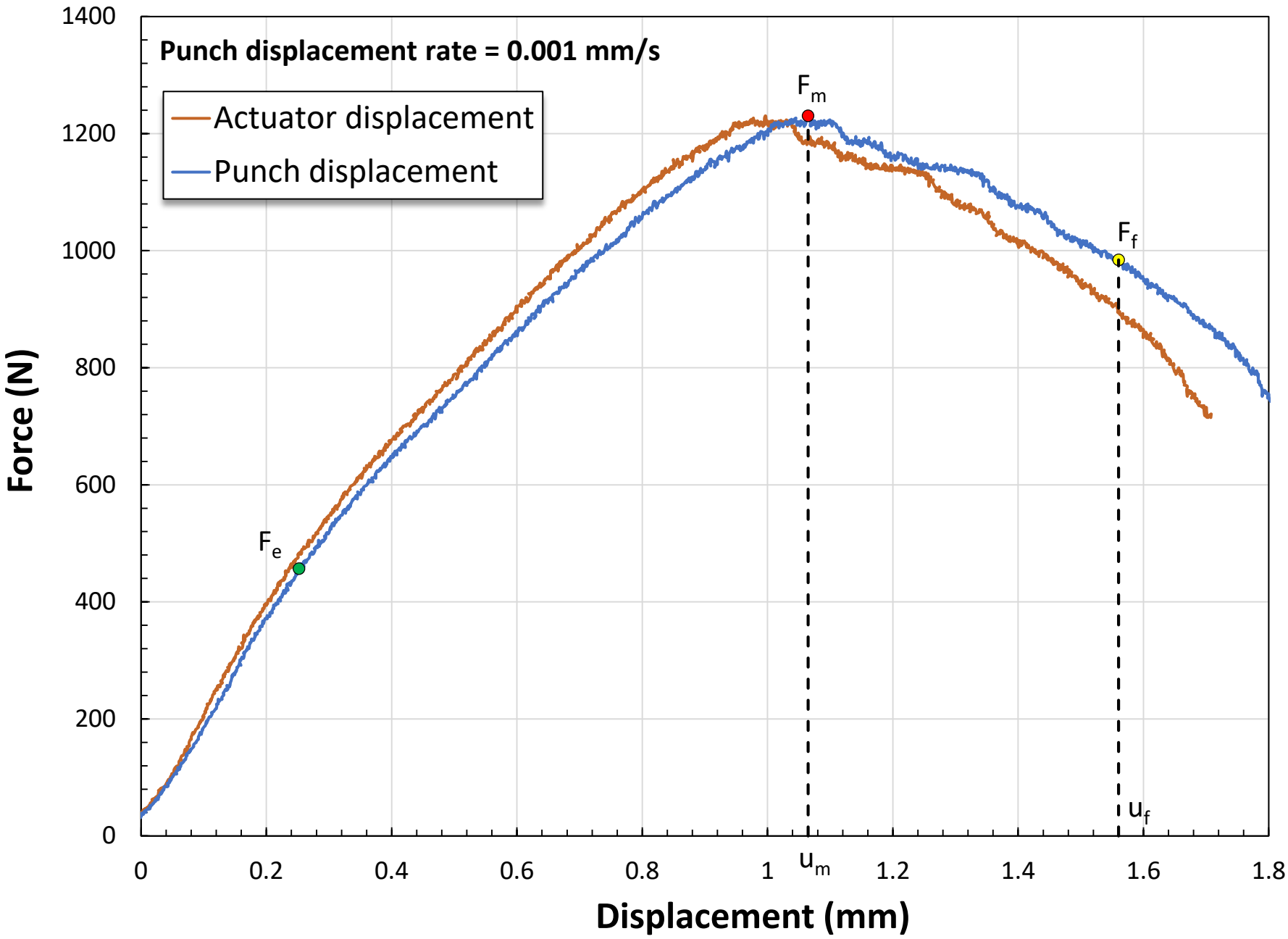
Specimen ID: SuperB_1_N_a_SP4

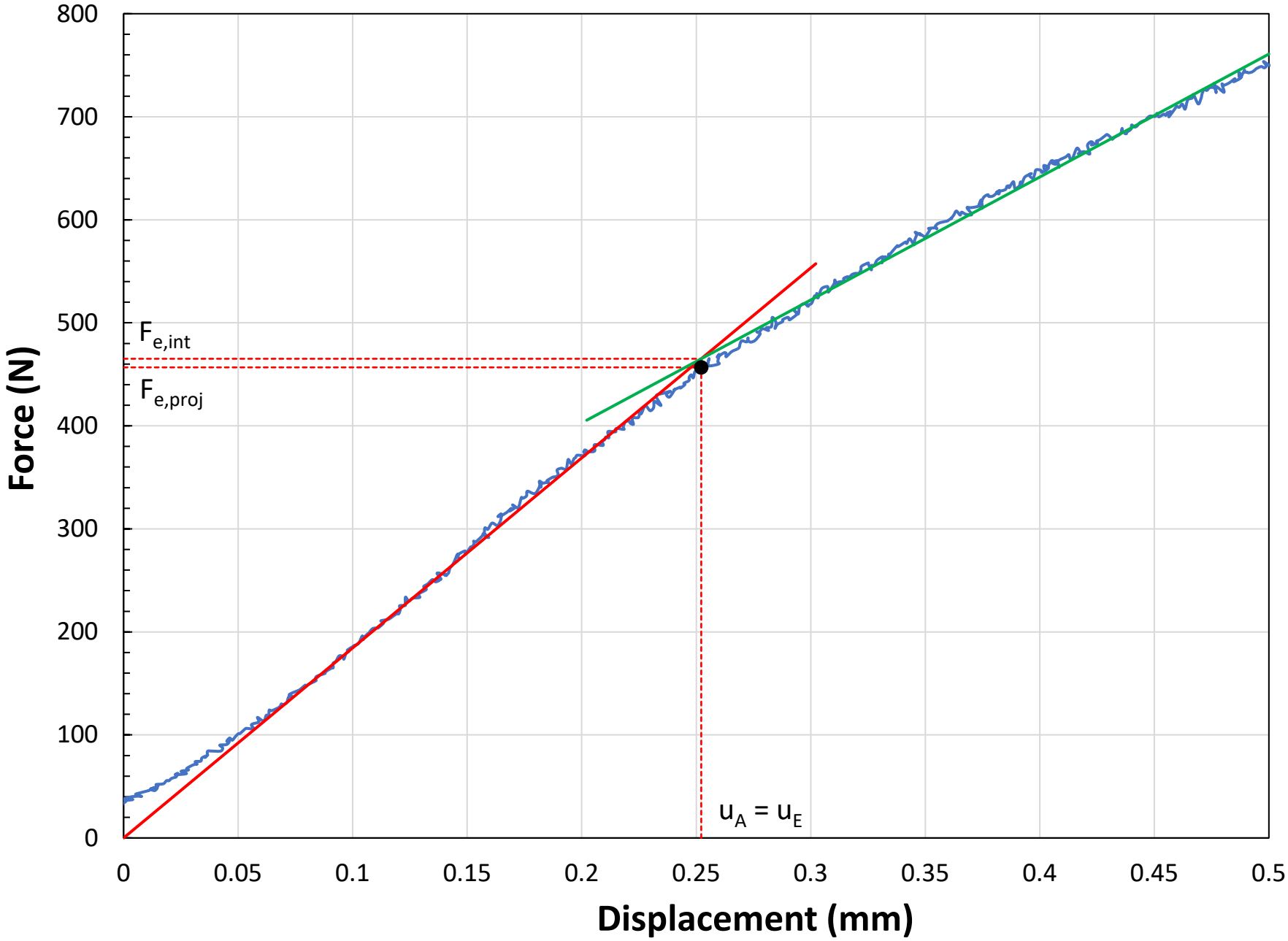
Material: AM Ti-64

Test speed: 0.00107 mm/s

Max strain rate: 1.07E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	456.7	N
$F_{e,int}$ =	465.1	N
$F_{h0/10,off}$ =	646.7	N
$F_{0.1mm,off}$ =	771.7	N
$F_{0.1mm}$ =	182.3	N
$F_{0.48mm}$ =	731.7	N
$F_{0.5mm}$ =	753.7	N
$F_{0.65mm}$ =	910.0	N
$F_{0.9mm}$ =	1138.2	N
F_{ept} =	868.4	N
$F_{e1.5}$ =	173.5	N
F_{m} =	1230.4	N
F_{infl} =	714.9	N
F_{f} =	984.3	N
Displacement values		
u_{e} =	0.252	mm
$u_{h0/10,off}$ =	0.401	mm
$u_{0.1mm,off}$ =	0.519	mm
$u_{e1.5}$ =	0.096	mm
u_{m} =	1.065	mm
u_{infl} =	1.831	mm
u_{f} =	1.560	mm
Initial linear slope		
$Slope_{ini}$ =	1844.34	N/mm
Energy values		
E_{SP} =	1.34	J
E_{m} =	0.79	J
E_{PL} =	0.38	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
1400
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

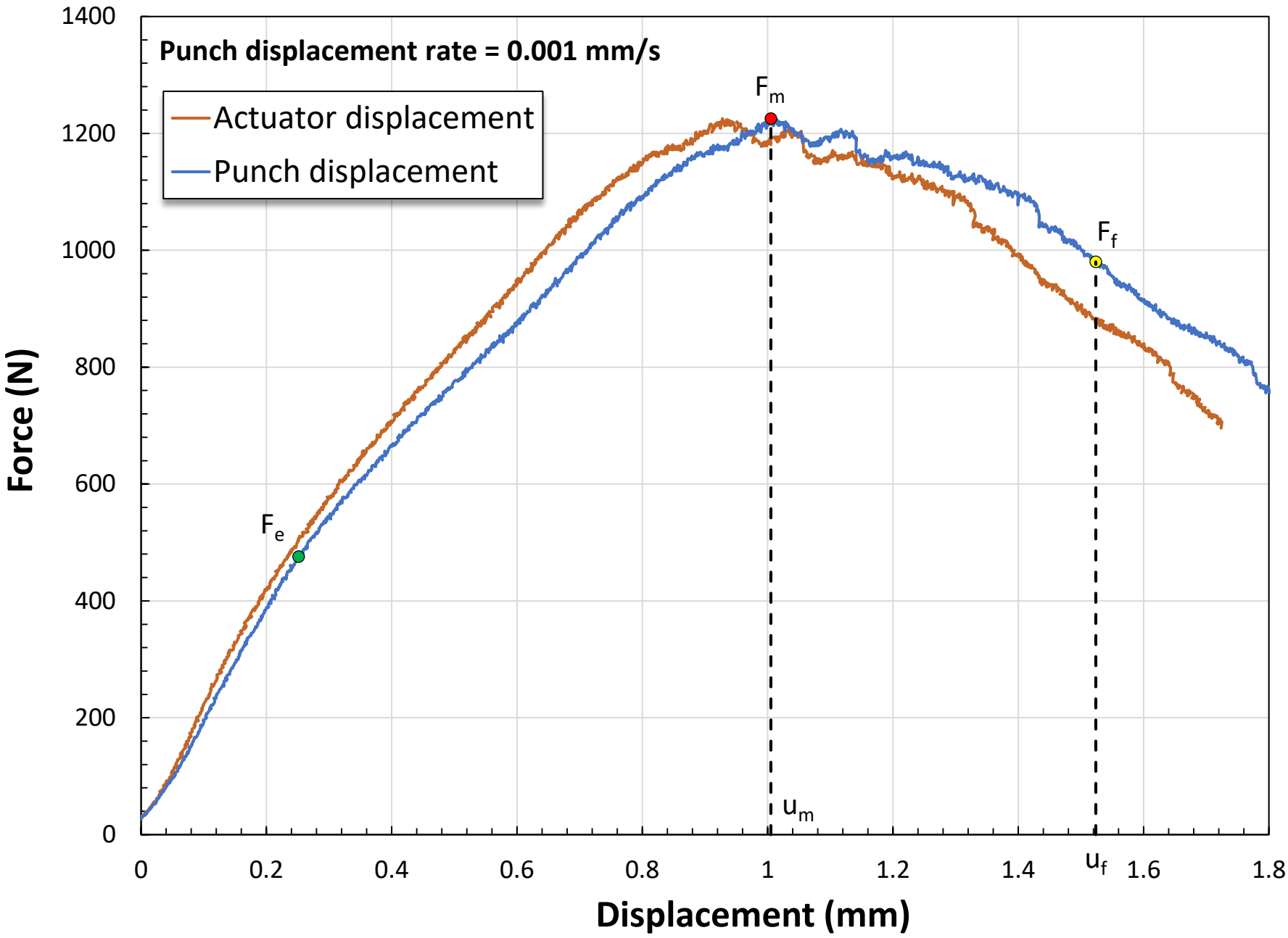
Specimen ID: SuperB_1_N_a_SP5

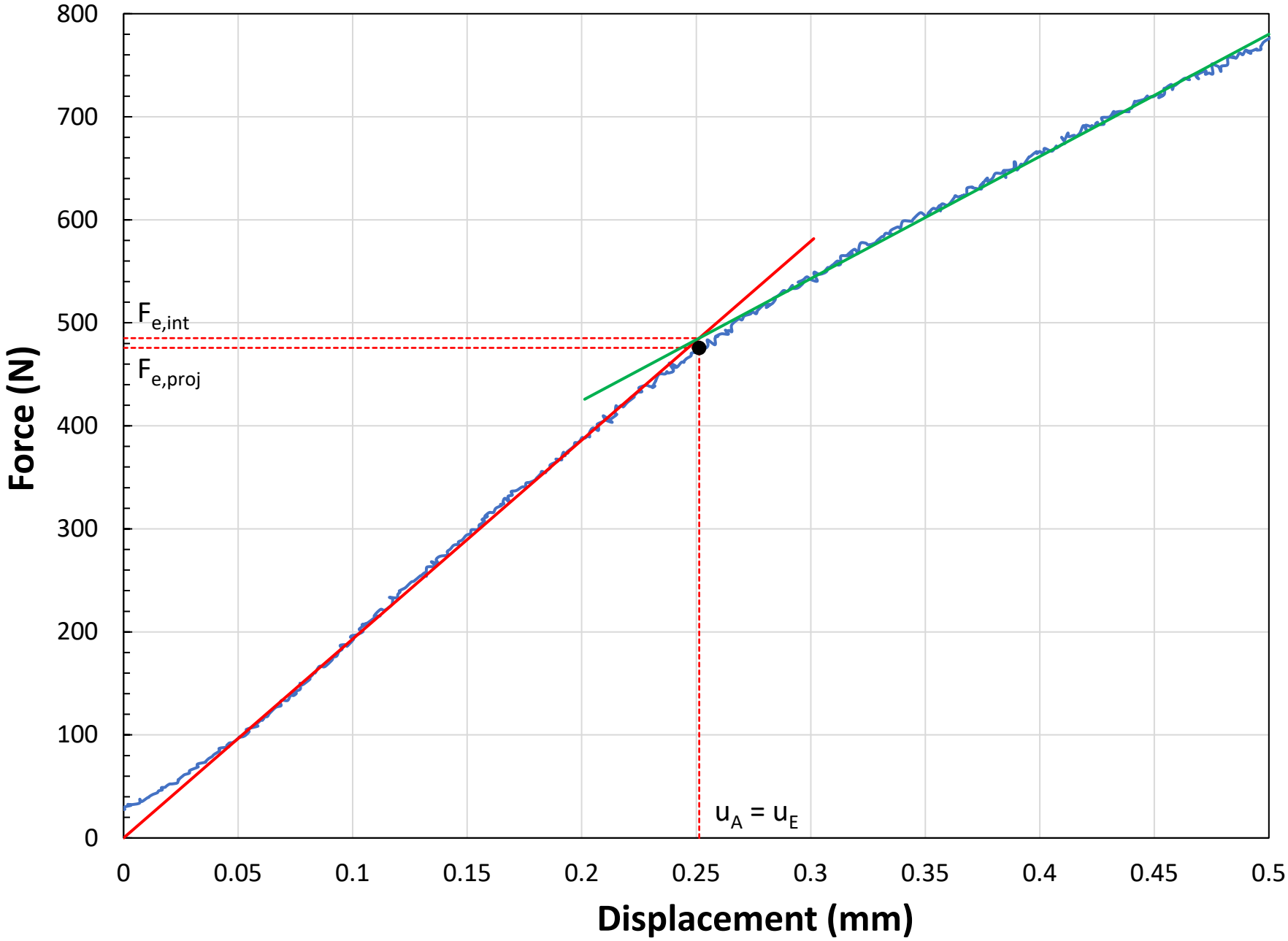
Material: AM Ti-64

Test speed: 0.001076 mm/s

Max strain rate: 1.08E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	475.7	N
$F_{e,int}$ =	485.1	N
$F_{h0/10,off}$ =	644.0	N
$F_{0.1mm,off}$ =	765.3	N
$F_{0.1mm}$ =	196.2	N
$F_{0.48mm}$ =	748.9	N
$F_{0.5mm}$ =	772.8	N
$F_{0.65mm}$ =	928.4	N
$F_{0.9mm}$ =	1162.1	N
F_{ept} =	539.2	N
$F_{e1.5}$ =	126.7	N
F_m =	1225.3	N
F_{infl} =	61.4	N
F_f =	980.2	N
Displacement values		
u_e =	0.251	mm
$u_{h0/10,off}$ =	0.385	mm
$u_{0.1mm,off}$ =	0.496	mm
$u_{e1.5}$ =	0.066	mm
u_m =	1.005	mm
u_{infl} =	0.027	mm
u_f =	1.524	mm
Initial linear slope		
$Slope_{ini}$ =	1930.46	N/mm
Energy values		
E_{SP} =	1.32	J
E_m =	0.74	J
E_{PL} =	0.35	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
1400
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

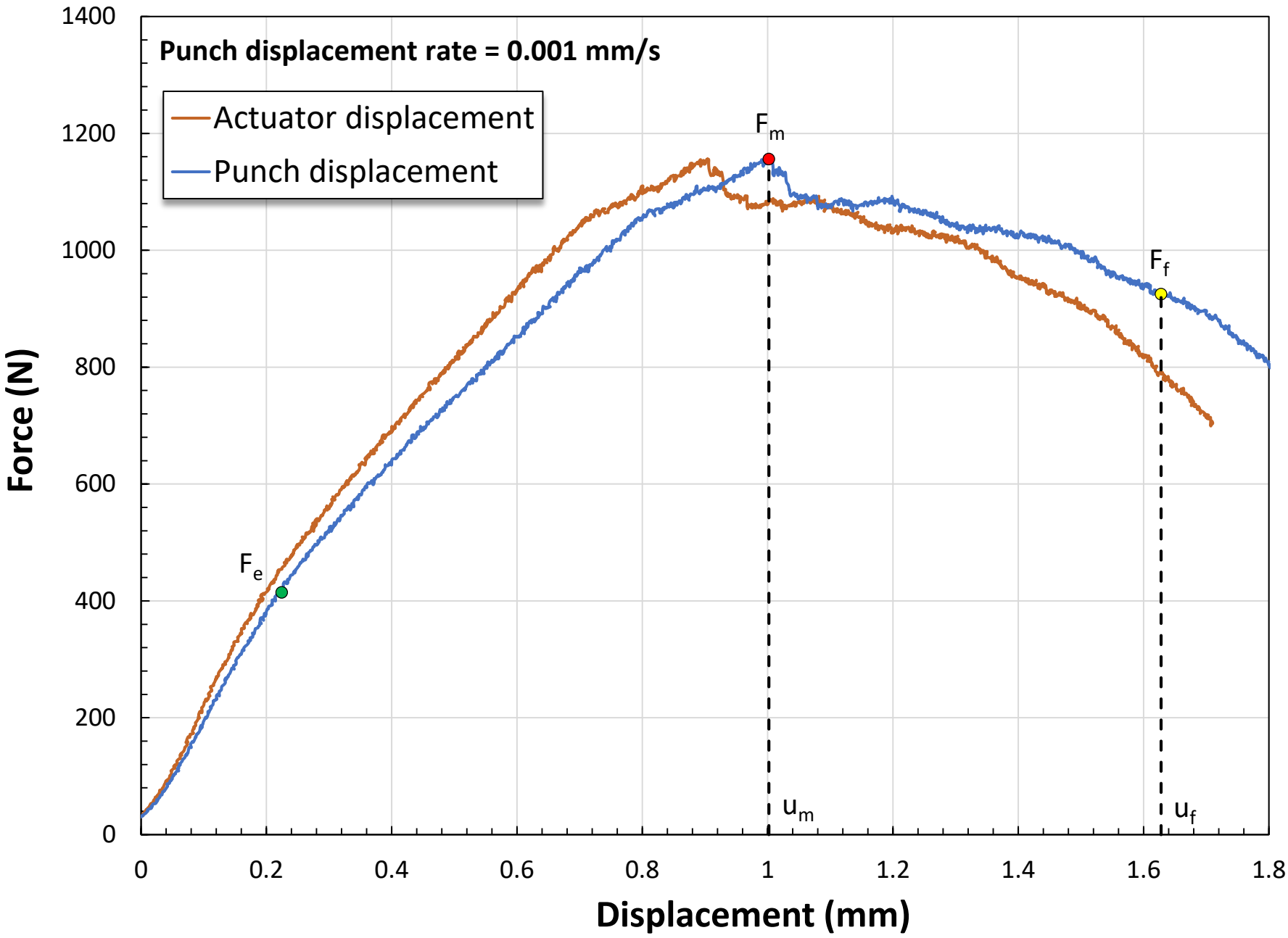
Specimen ID: SuperB_1_N_a_SP6

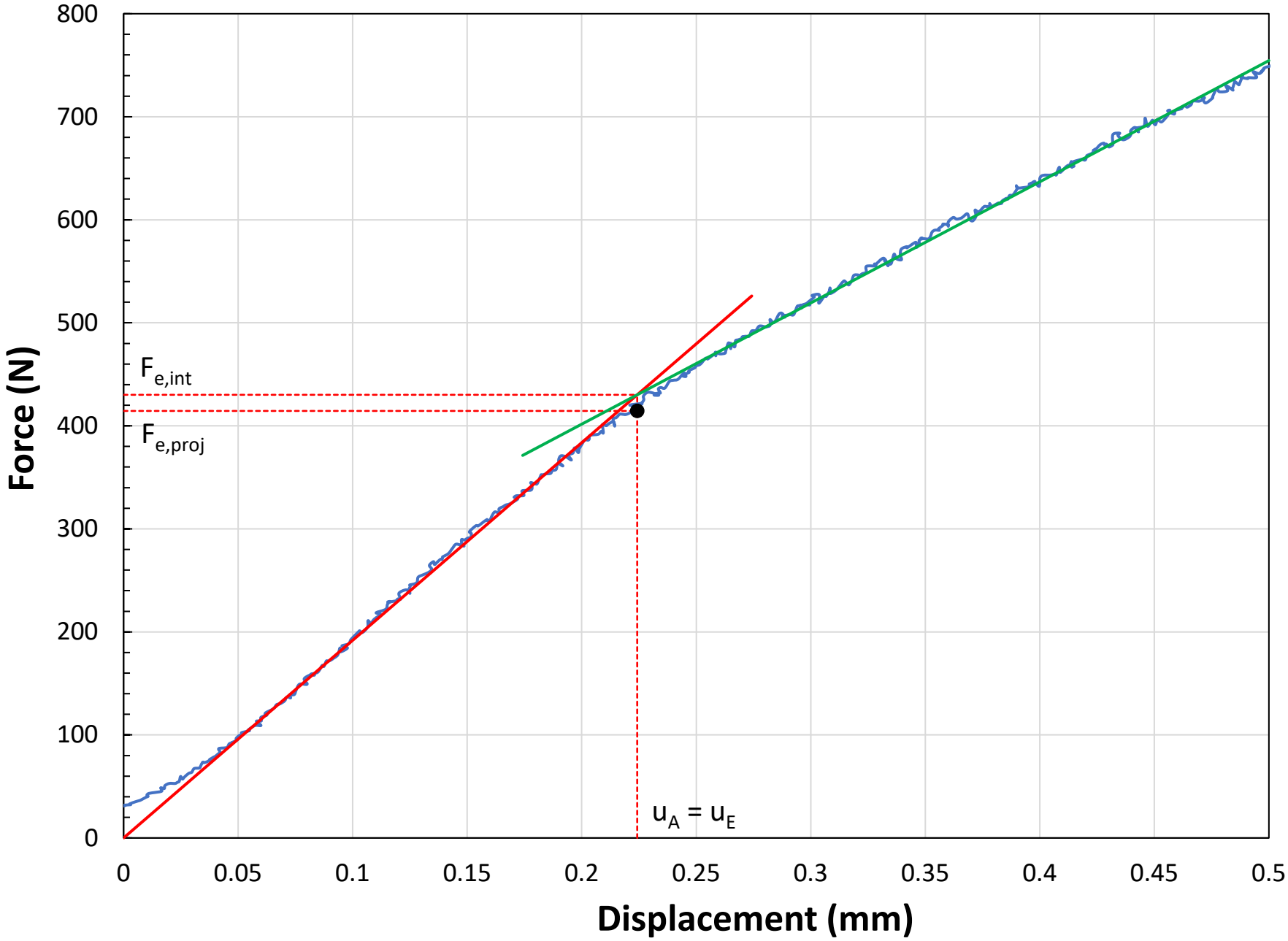
Material: AM Ti-64

Test speed: 0.001113 mm/s

Max strain rate: 1.11E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	414.5	N
$F_{e,int}$ =	430.1	N
$F_{h0/10,off}$ =	594.2	N
$F_{0.1mm,off}$ =	713.8	N
$F_{0.1mm}$ =	193.2	N
$F_{0.48mm}$ =	724.3	N
$F_{0.5mm}$ =	747.6	N
$F_{0.65mm}$ =	901.9	N
$F_{0.9mm}$ =	1106.7	N
F_{ept} =	431.9	N
$F_{e1.5}$ =	143.3	N
F_m =	1156.0	N
F_{infl} =	901.5	N
F_f =	924.8	N
Displacement values		
u_e =	0.224	mm
$u_{h0/10,off}$ =	0.360	mm
$u_{0.1mm,off}$ =	0.472	mm
$u_{e1.5}$ =	0.075	mm
u_m =	1.002	mm
u_{infl} =	0.649	mm
u_f =	1.628	mm
Initial linear slope		
$Slope_{ini}$ =	1918.27	N/mm
Energy values		
E_{SP} =	1.36	J
E_m =	0.71	J
E_{PL} =	0.36	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
1400
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

Small Punch Test Results

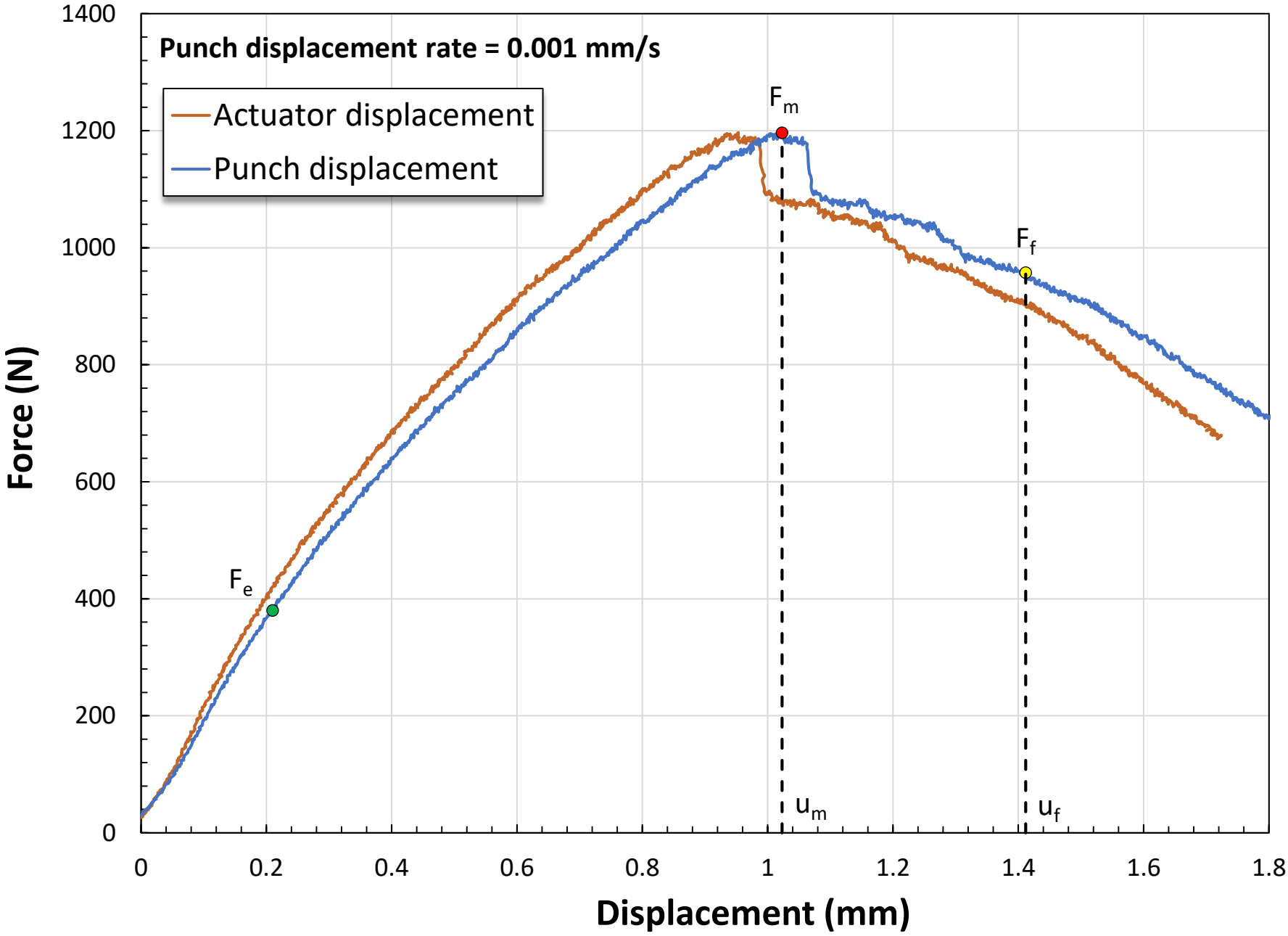
Specimen ID: SuperB_1_N_a_SP7

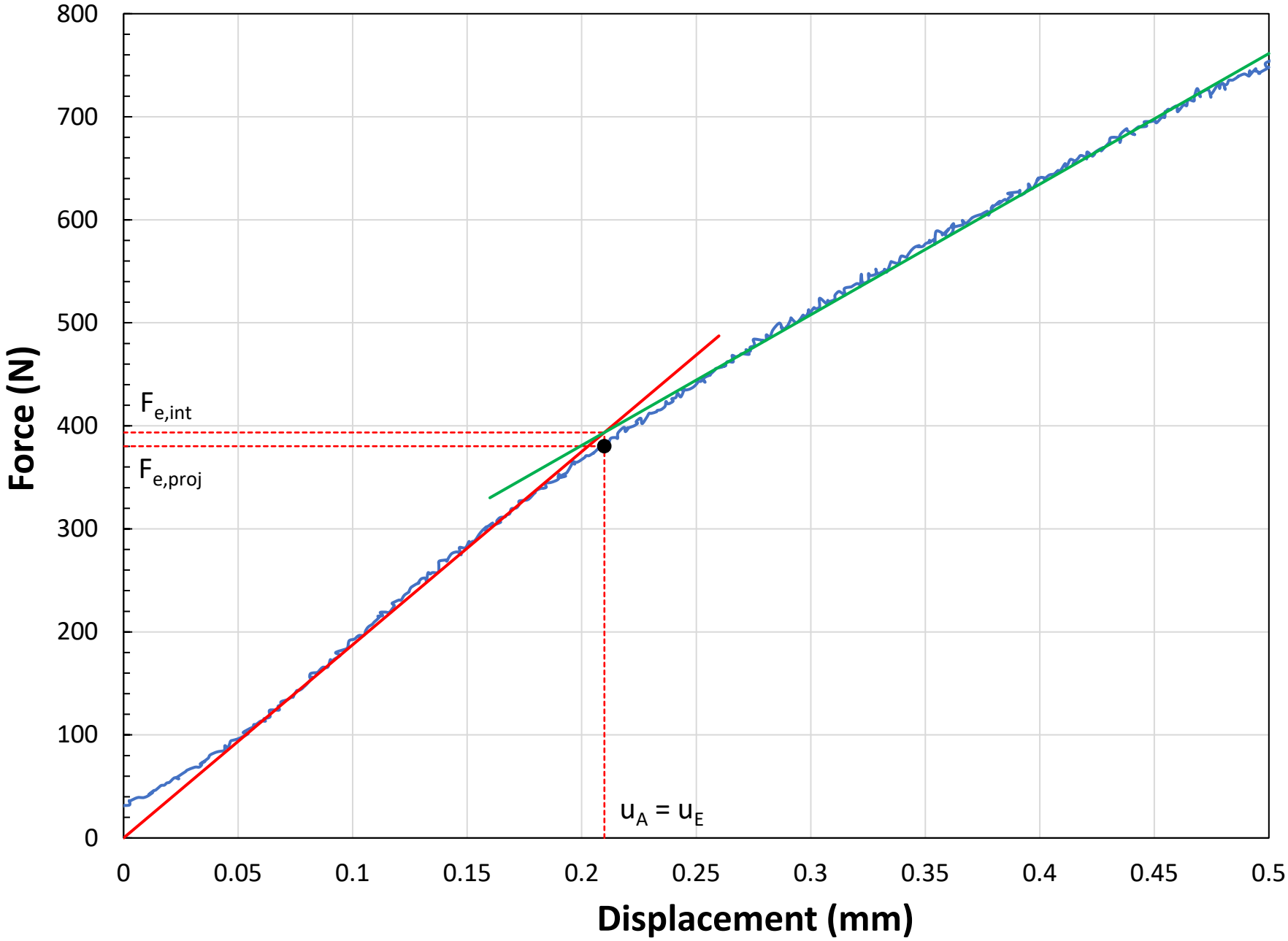
Material: AM Ti-64

Test speed: 0.001064 mm/s

Max strain rate: 1.06E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	380.2	N
$F_{e,int}$ =	393.6	N
$F_{h0/10,off}$ =	604.0	N
$F_{0.1mm,off}$ =	742.3	N
$F_{0.1mm}$ =	191.4	N
$F_{0.48mm}$ =	732.4	N
$F_{0.5mm}$ =	752.2	N
$F_{0.65mm}$ =	912.0	N
$F_{0.9mm}$ =	1122.9	N
F_{ept} =	1096.6	N
$F_{e1.5}$ =	155.8	N
F_{m} =	1196.6	N
F_{infl} =	678.8	N
F_{f} =	957.2	N
Displacement values		
u_{e} =	0.210	mm
$u_{h0/10,off}$ =	0.372	mm
$u_{0.1mm,off}$ =	0.496	mm
$u_{e1.5}$ =	0.082	mm
u_{m} =	1.023	mm
u_{infl} =	1.843	mm
u_{f} =	1.412	mm
Initial linear slope		
$Slope_{ini}$ =	1874.92	N/mm
Energy values		
E_{SP} =	1.14	J
E_{m} =	0.73	J
E_{PL} =	0.35	J


Punch displacement rate = 0.001 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
1400
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (mm)

ANNEX 13

SP Test Results for

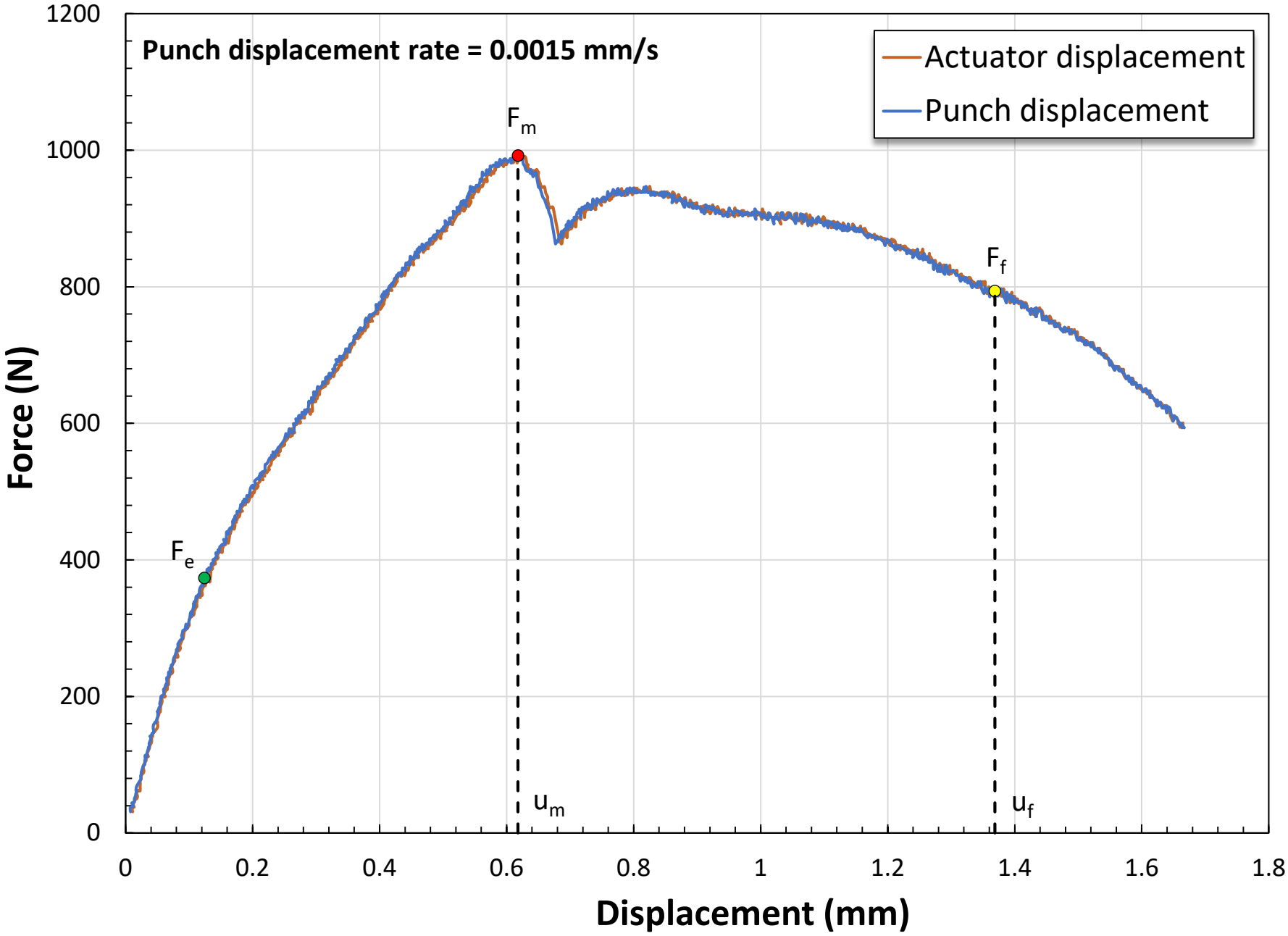
1050 °C + 800 °C HIP, scan length = 78 mm, non-supported

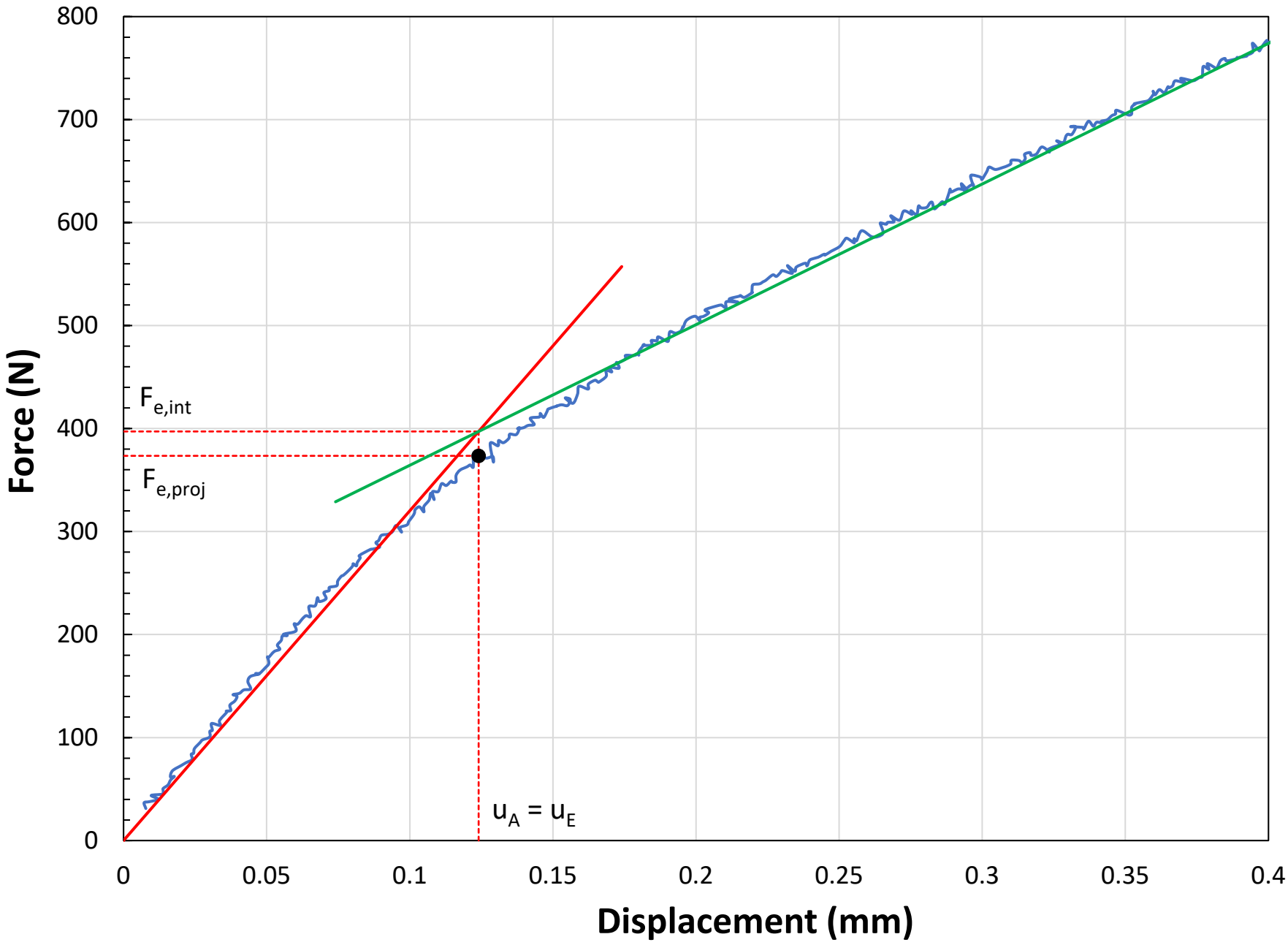
(polished specimens)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP7 (pc
Material: AM Ti-64
Test speed: 0.001441 mm/s
Max strain rate: 1.44E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	373.5	N
$F_{e,int}$ =	397.2	N
$F_{h0/10,off}$ =	522.2	N
$F_{0.1mm,off}$ =	653.3	N
$F_{0.1mm}$ =	309.9	N
$F_{0.48mm}$ =	870.1	N
$F_{0.5mm}$ =	882.4	N
$F_{0.65mm}$ =	965.2	N
$F_{0.9mm}$ =	918.4	N
F_{ept} =	831.9	N
$F_{e1.5}$ =	600.9	N
F_{m} =	992.2	N
F_{infl} =	593.6	N
F_{f} =	793.7	N
Displacement values		
u_{e} =	0.124	mm
$u_{h0/10,off}$ =	0.209	mm
$u_{0.1mm,off}$ =	0.305	mm
$u_{e1.5}$ =	0.269	mm
u_{m} =	0.618	mm
u_{infl} =	1.667	mm
u_{f} =	1.369	mm
Initial linear slope		
$Slope_{ini}$ =	3201.67	N/mm
Energy values		
E_{SP} =	1.05	J
E_{m} =	0.38	J
E_{PL} =	0.23	J

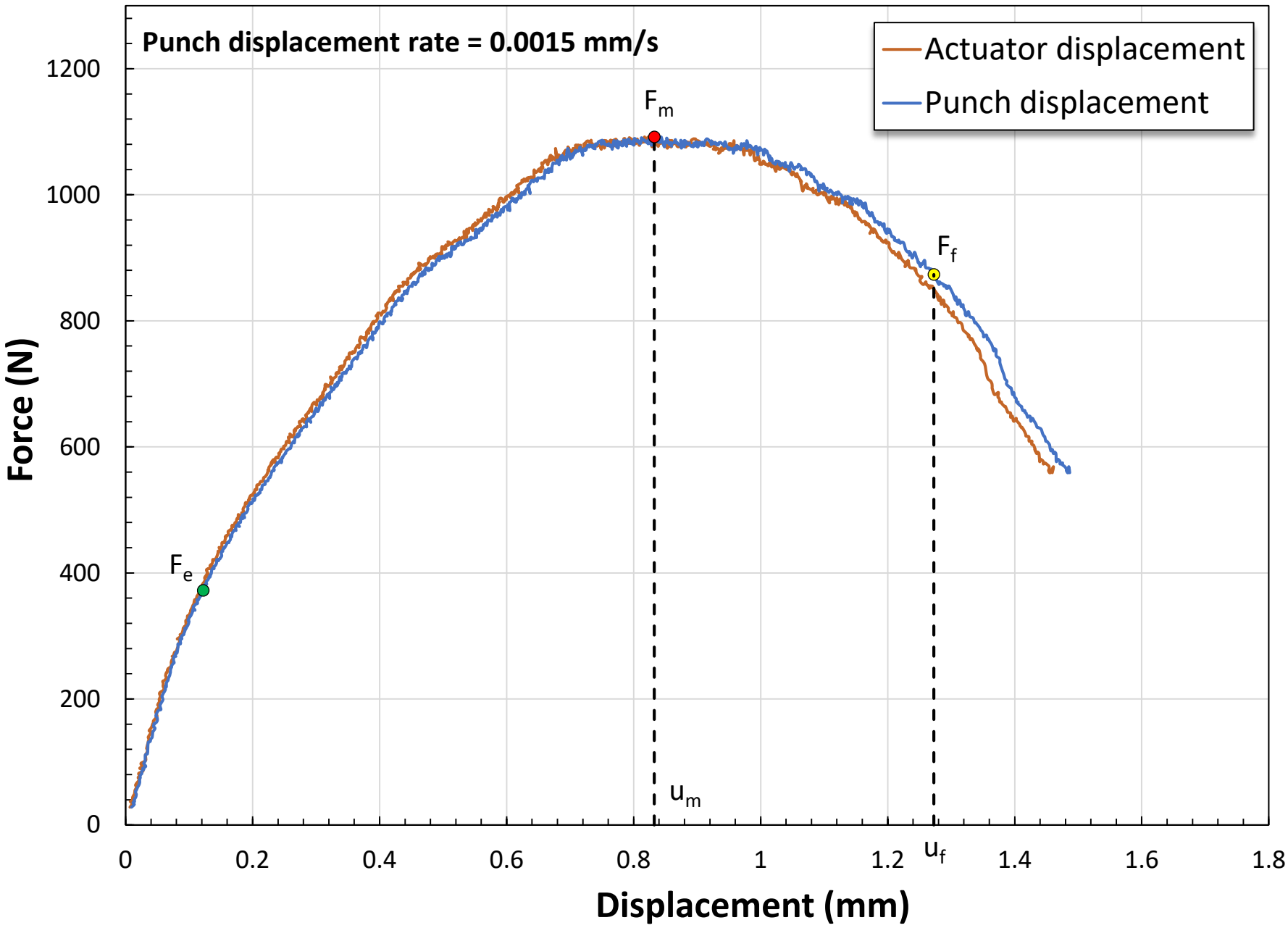

Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

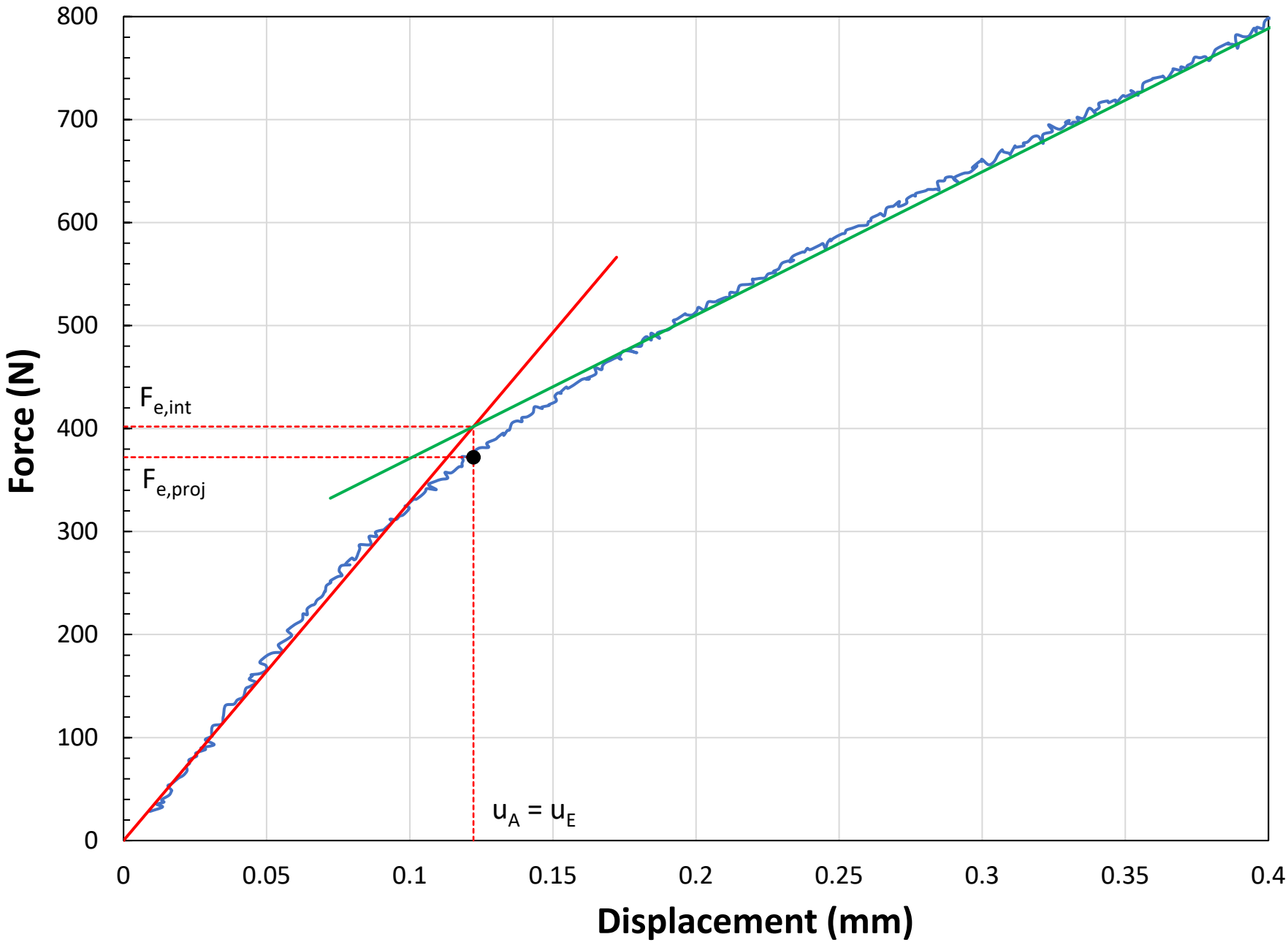

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP8 (pc
Material: AM Ti-64
Test speed: 0.001426 mm/s
Max strain rate: 1.43E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	372.2	N
$F_{e,int}$ =	402.0	N
$F_{h0/10,off}$ =	515.6	N
$F_{0.1mm,off}$ =	660.5	N
$F_{0.1mm}$ =	324.6	N
$F_{0.48mm}$ =	882.8	N
$F_{0.5mm}$ =	902.5	N
$F_{0.65mm}$ =	1026.6	N
$F_{0.9mm}$ =	1079.7	N
F_{ept} =	369.2	N
$F_{e1.5}$ =	735.9	N
F_m =	1091.8	N
F_{infl} =	559.0	N
F_f =	873.4	N
Displacement values		
u_e =	0.122	mm
$u_{h0/10,off}$ =	0.203	mm
$u_{0.1mm,off}$ =	0.302	mm
$u_{e1.5}$ =	0.357	mm
u_m =	0.832	mm
u_{infl} =	1.487	mm
u_f =	1.273	mm
Initial linear slope		
$Slope_{ini}$ =	3288.00	N/mm
Energy values		
E_{SP} =	1.06	J
E_m =	0.62	J
E_{PL} =	0.43	J

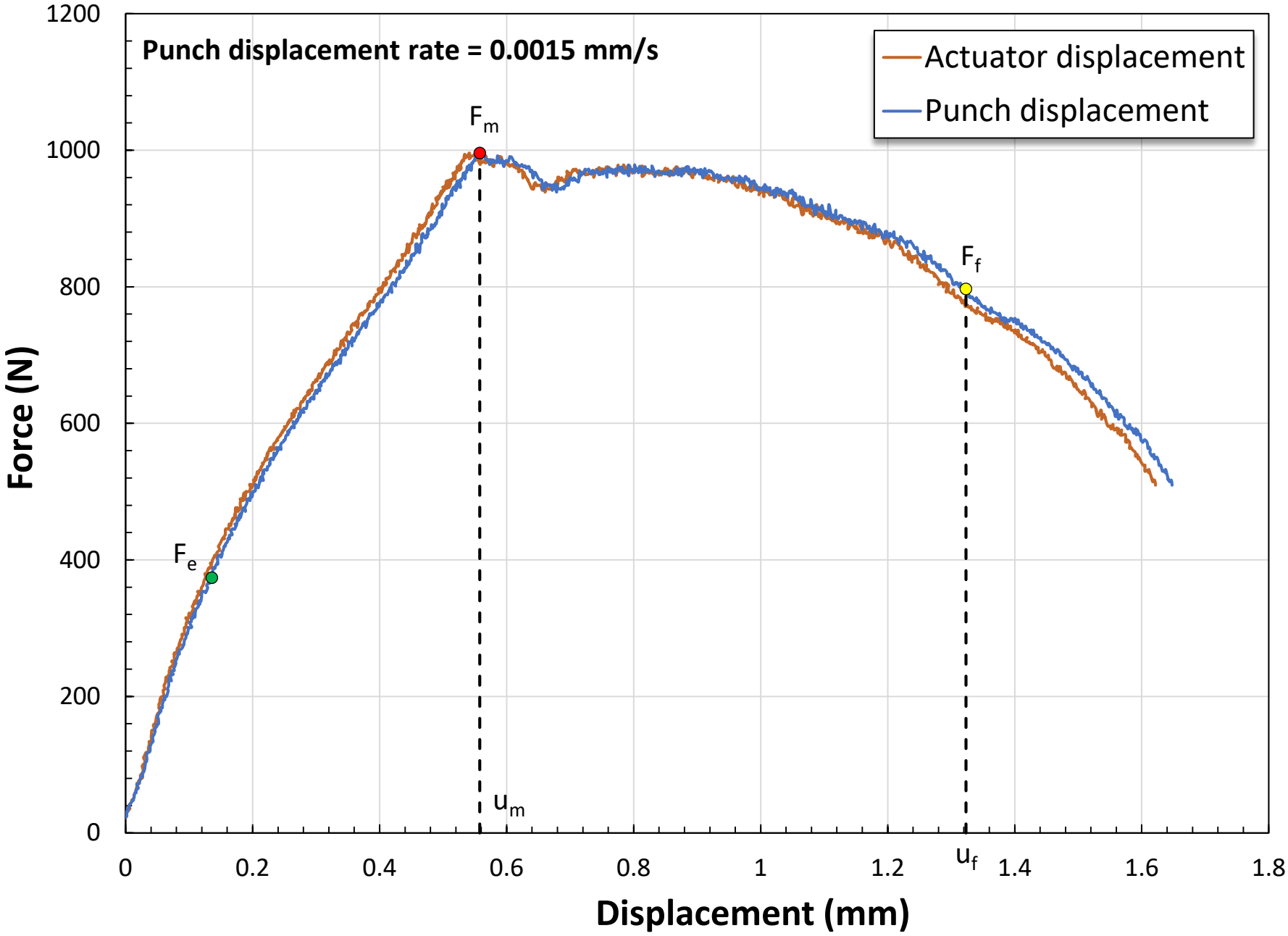

Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

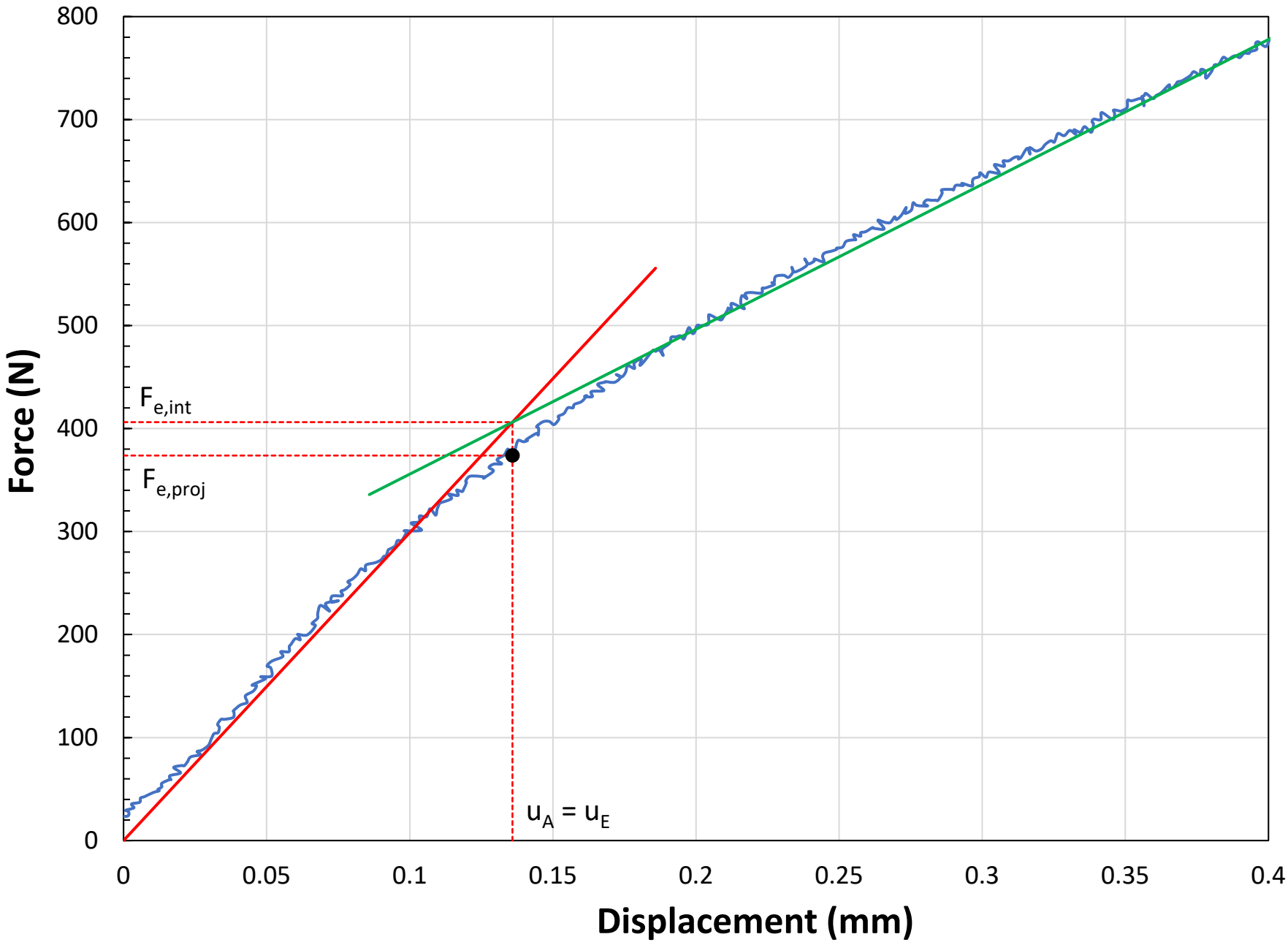

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP9 (pc
Material: AM Ti-64
Test speed: 0.001459 mm/s
Max strain rate: 1.46E-03 s^{-1}

TEST RESULTS		
Force values		
$F_{e,proj}$ =	373.8	N
$F_{e,int}$ =	406.2	N
$F_{h0/10,off}$ =	531.7	N
$F_{0.1mm,off}$ =	690.7	N
$F_{0.1mm}$ =	300.6	N
$F_{0.48mm}$ =	882.8	N
$F_{0.5mm}$ =	915.7	N
$F_{0.65mm}$ =	961.6	N
$F_{0.9mm}$ =	969.8	N
F_{ept} =	721.9	N
$F_{e1.5}$ =	746.2	N
F_m =	995.9	N
F_{infl} =	509.4	N
F_f =	796.7	N
Displacement values		
u_e =	0.136	mm
$u_{h0/10,off}$ =	0.223	mm
$u_{0.1mm,off}$ =	0.333	mm
$u_{e1.5}$ =	0.380	mm
u_m =	0.558	mm
u_{infl} =	1.648	mm
u_f =	1.323	mm
Initial linear slope		
$Slope_{ini}$ =	2989.78	N/mm
Energy values		
E_{SP} =	1.04	J
E_m =	0.32	J
E_{PL} =	0.16	J

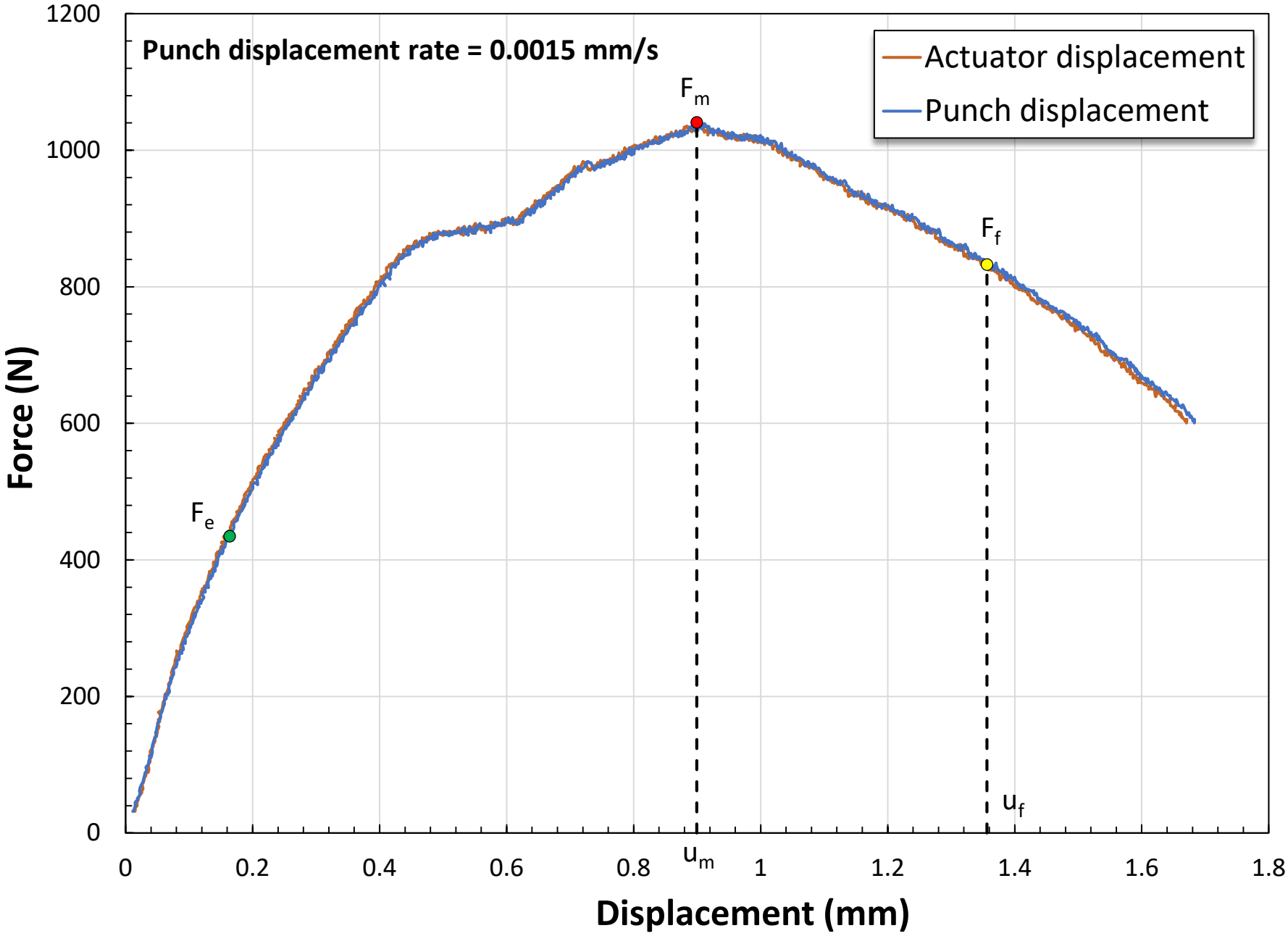

Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_m
u_f
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

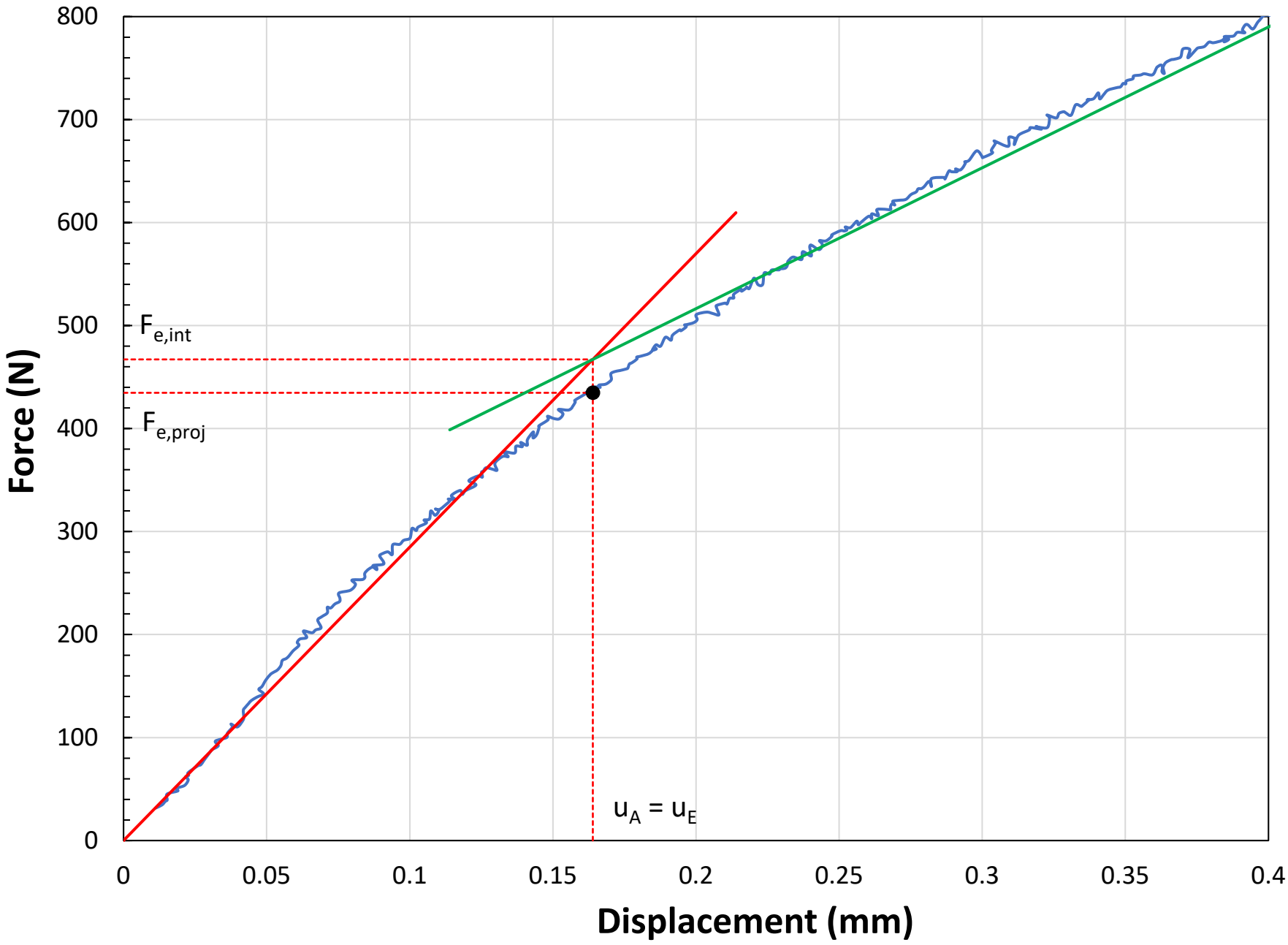

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Small Punch Test Results

Specimen ID: 900HIP_3_N_a_SP10 (p
Material: AM Ti-64
Test speed: 0.001444 mm/s
Max strain rate: 1.44E-03 s^{-1}

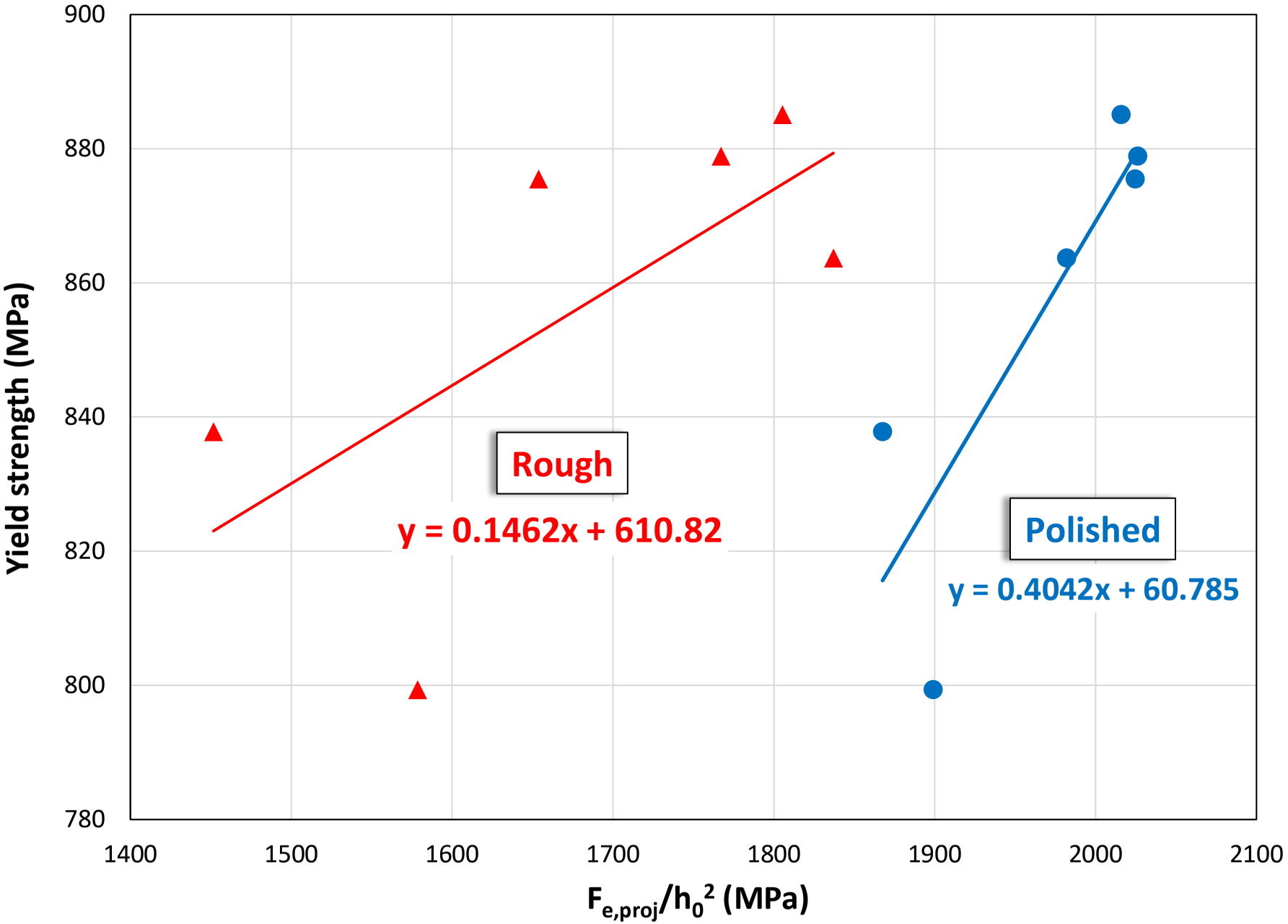
TEST RESULTS		
Force values		
$F_{e,proj}$ =	434.7	N
$F_{e,int}$ =	467.2	N
$F_{h0/10,off}$ =	595.3	N
$F_{0.1mm,off}$ =	748.0	N
$F_{0.1mm}$ =	293.0	N
$F_{0.48mm}$ =	872.8	N
$F_{0.5mm}$ =	878.4	N
$F_{0.65mm}$ =	921.6	N
$F_{0.9mm}$ =	1033.5	N
F_{ept} =	884.7	N
$F_{e1.5}$ =	858.4	N
F_m =	1040.8	N
F_{infl} =	967.1	N
F_f =	832.7	N
Displacement values		
u_e =	0.164	mm
$u_{h0/10,off}$ =	0.254	mm
$u_{0.1mm,off}$ =	0.364	mm
$u_{e1.5}$ =	0.457	mm
u_m =	0.899	mm
u_{infl} =	0.707	mm
u_f =	1.356	mm
Initial linear slope		
$Slope_{ini}$ =	2849.28	N/mm
Energy values		
E_{SP} =	1.09	J
E_m =	0.65	J
E_{PL} =	0.46	J

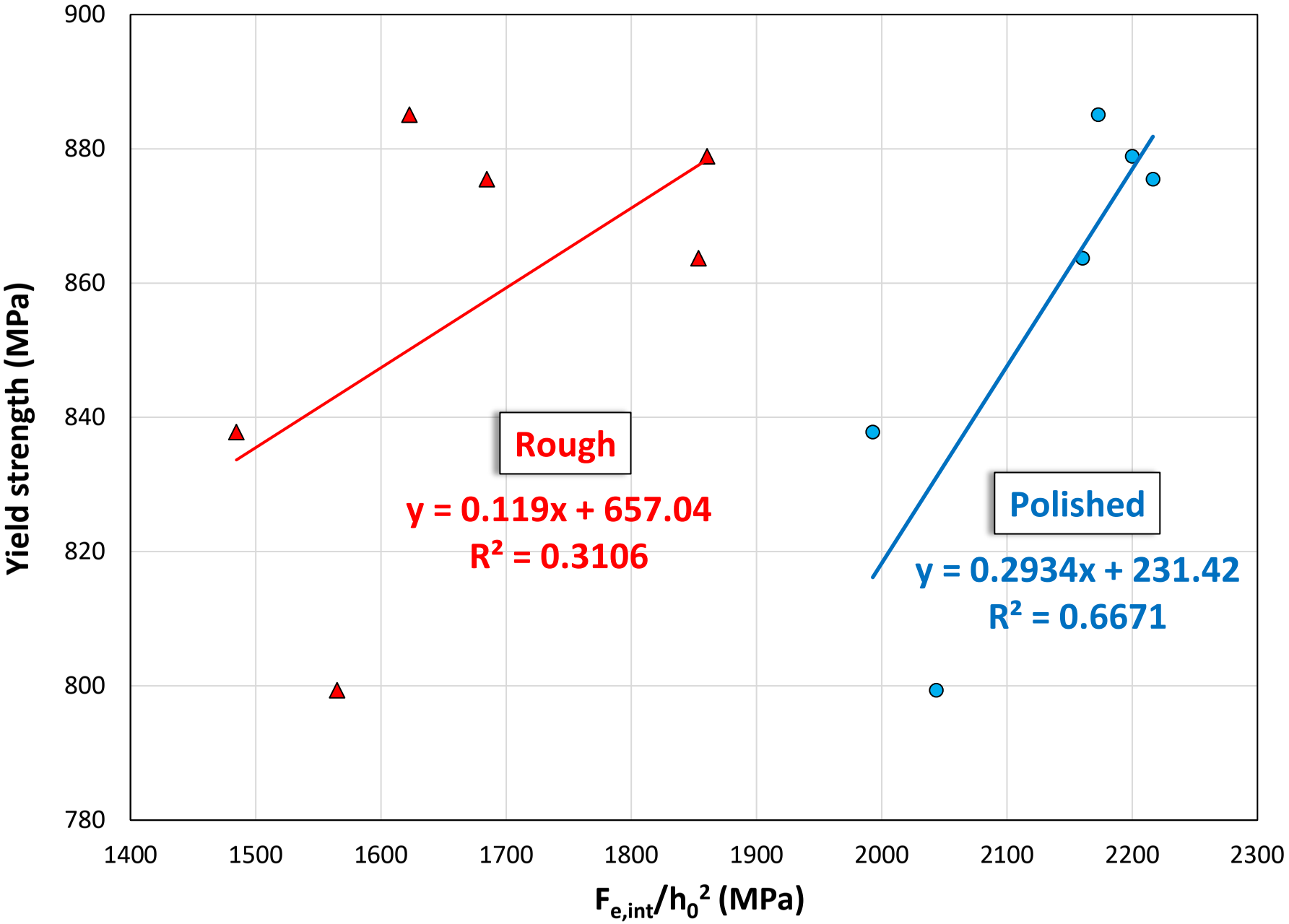

Punch displacement rate = 0.0015 mm/s
Actuator displacement
Punch displacement
F_m
F_f
F_e
u_f
u_m
Force (N)
Displacement (mm)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

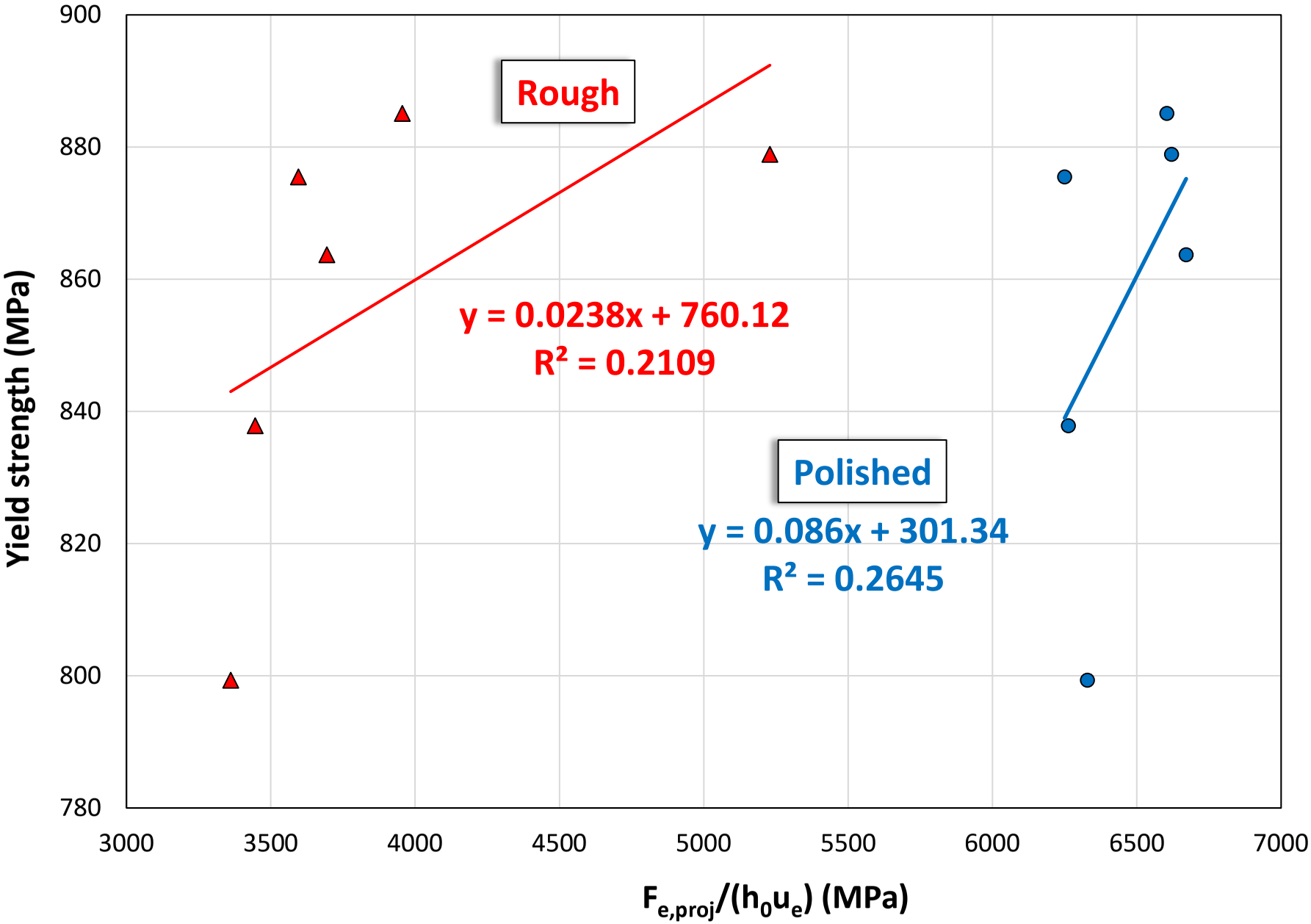

800
700
600
500
400
300
200
100
0
Force (N)
$F_{e,int}$
$F_{e,proj}$
$u_A = u_E$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

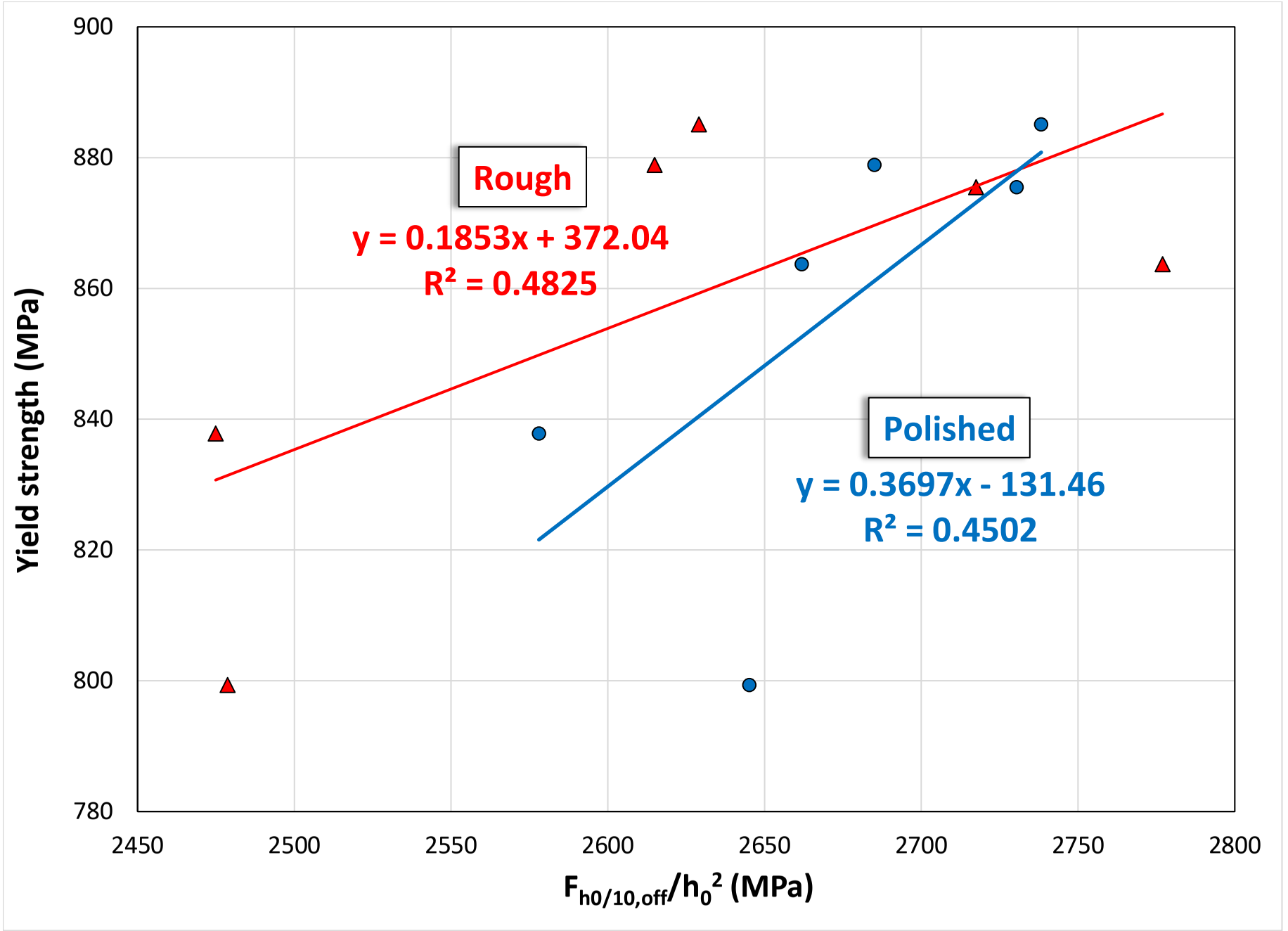
ANNEX 14

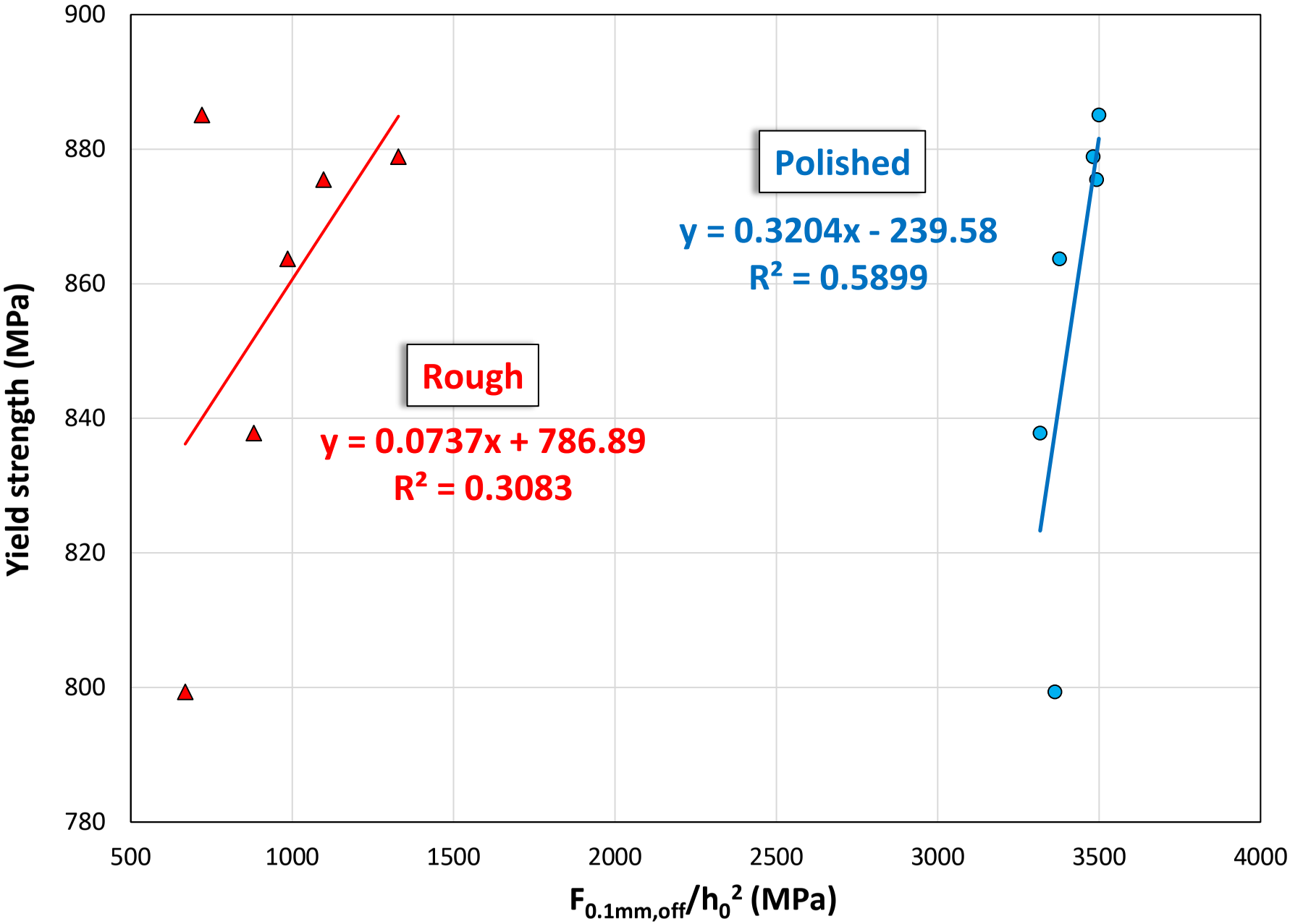
Correlations obtained for AM Ti64 between yield strength and SP parameters

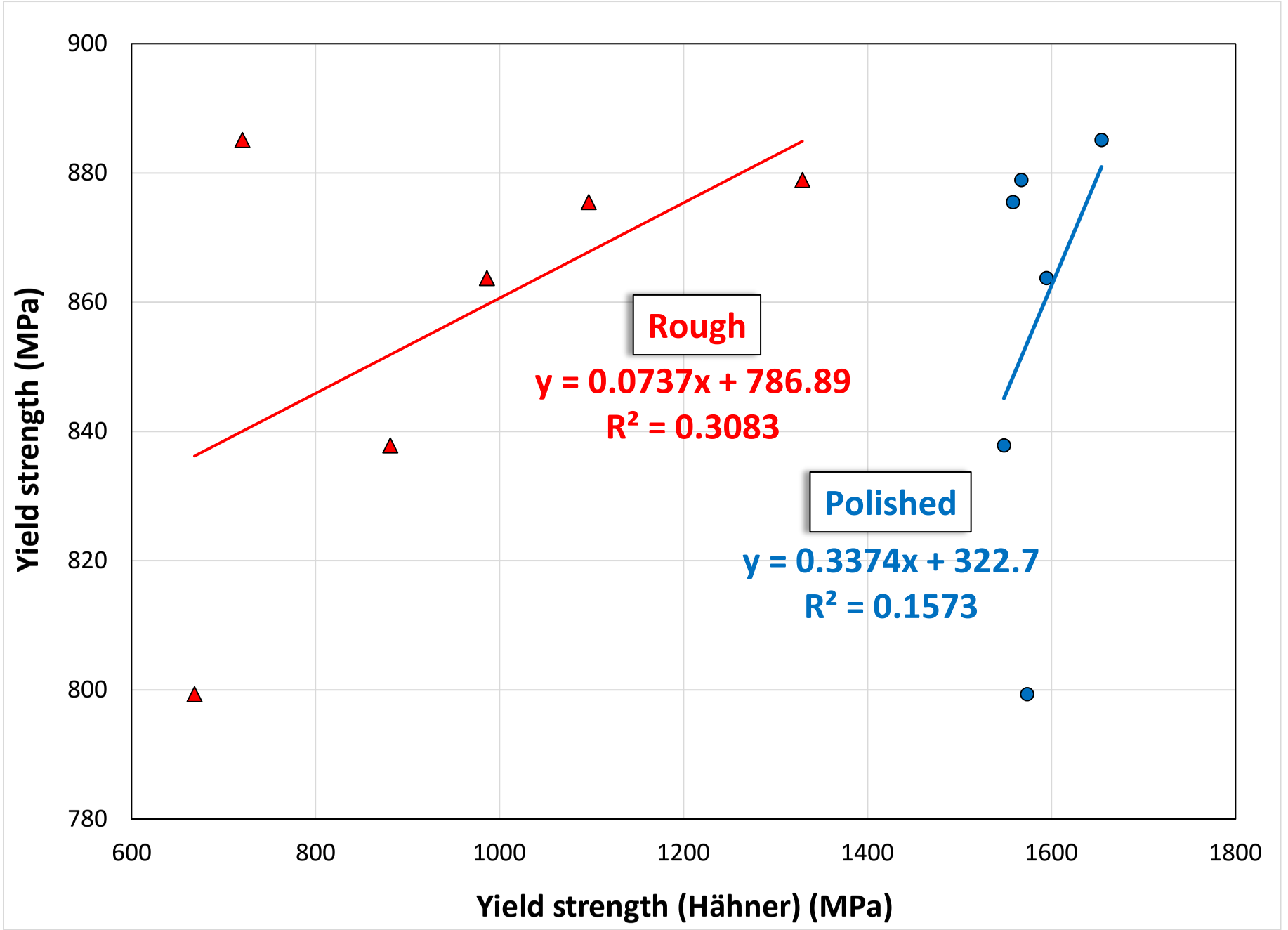

900
880
860
840
820
800
780
Yield strength (MPa)
1400
1500
1600
1700
1800
1900
2000
2100
$F_{e,proj}/h_0^2$ (MPa)
Rough
y = 0.1462x + 610.82
Polished
y = 0.4042x + 60.785

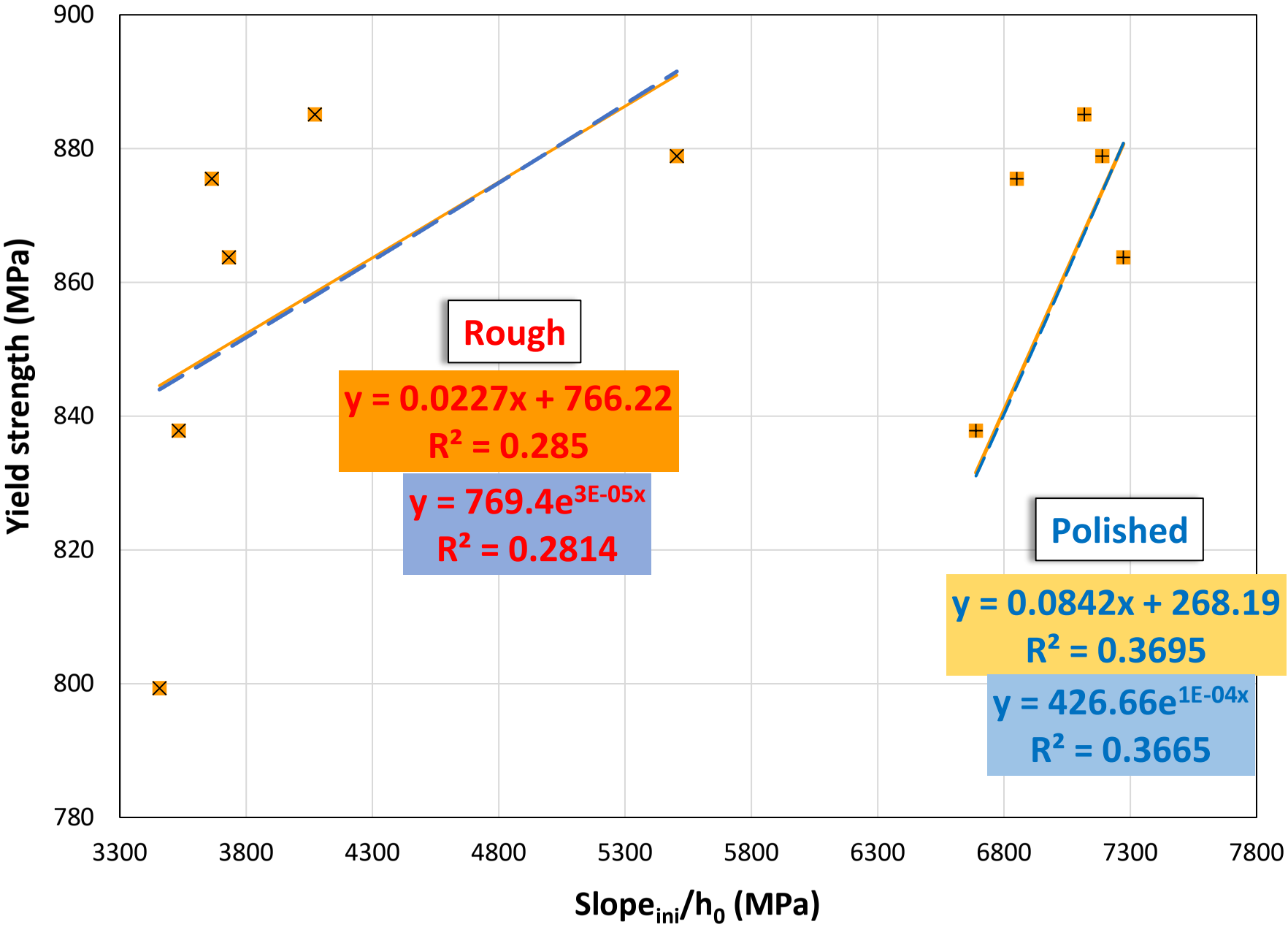

900
880
860
840
820
800
780
Yield strength (MPa)
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
$F_{e,int}/h_0^2$ (MPa)
Rough
y = 0.119x + 657.04
R² = 0.3106
Polished
y = 0.2934x + 231.42
R² = 0.6671


Rough
y = 0.0238x + 760.12
R² = 0.2109
Polished
y = 0.086x + 301.34
R² = 0.2645
Yield strength (MPa)
900
880
860
840
820
800
780
3000
3500
4000
4500
5000
5500
6000
6500
7000
F_e,proj/(h_0u_e) (MPa)


900
880
860
840
820
800
780
Yield strength (MPa)
2450
2500
2550
2600
2650
2700
2750
2800
$F_{h0/10,off}/h_0^2$ (MPa)
Rough
y = 0.1853x + 372.04
R² = 0.4825
Polished
y = 0.3697x - 131.46
R² = 0.4502

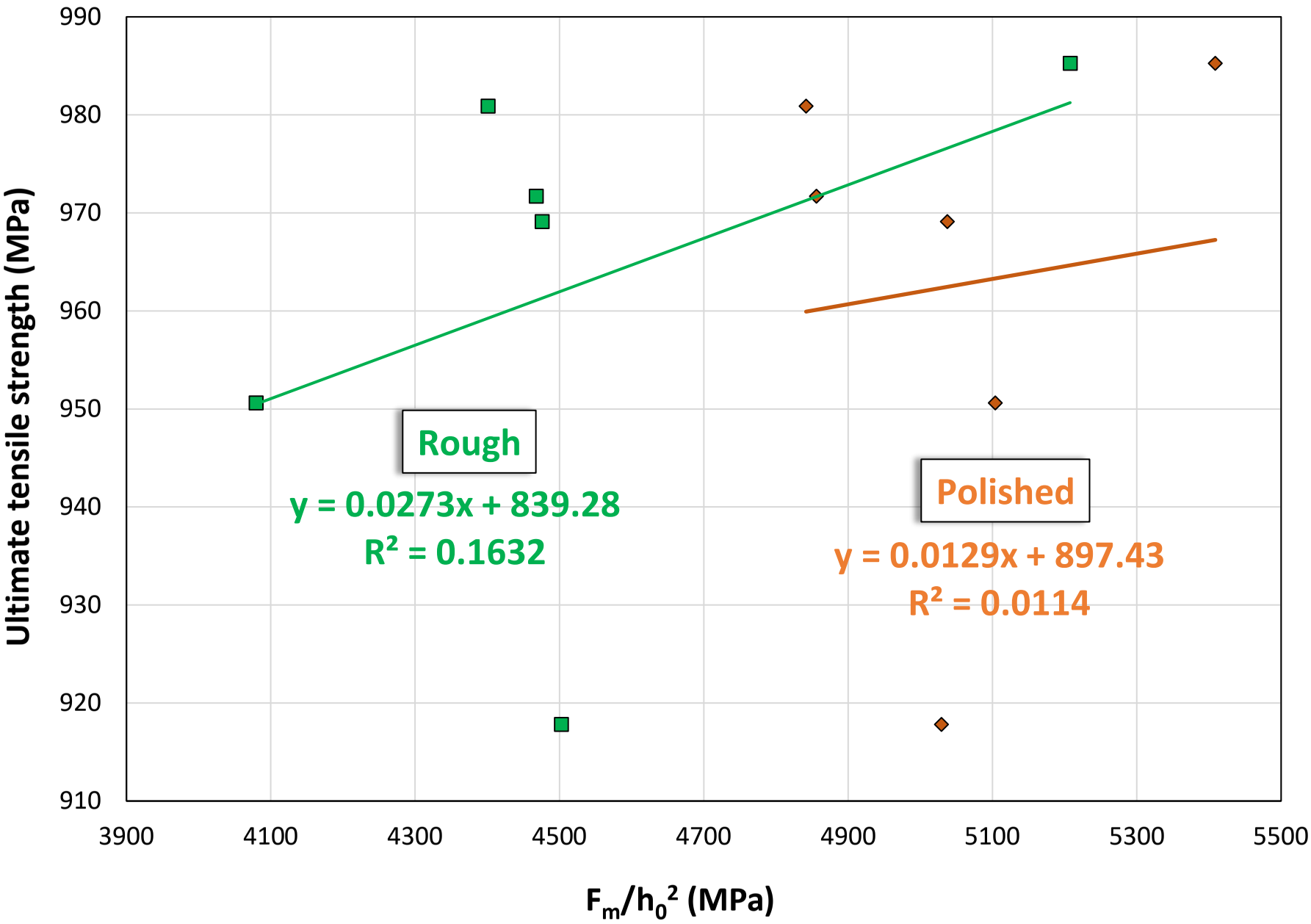

900
880
860
840
820
800
780
Yield strength (MPa)
500
1000
1500
2000
2500
3000
3500
4000
$F_{0.1mm,off}/h_0^2$ (MPa)
Polished
y = 0.3204x - 239.58
R² = 0.5899
Rough
y = 0.0737x + 786.89
R² = 0.3083

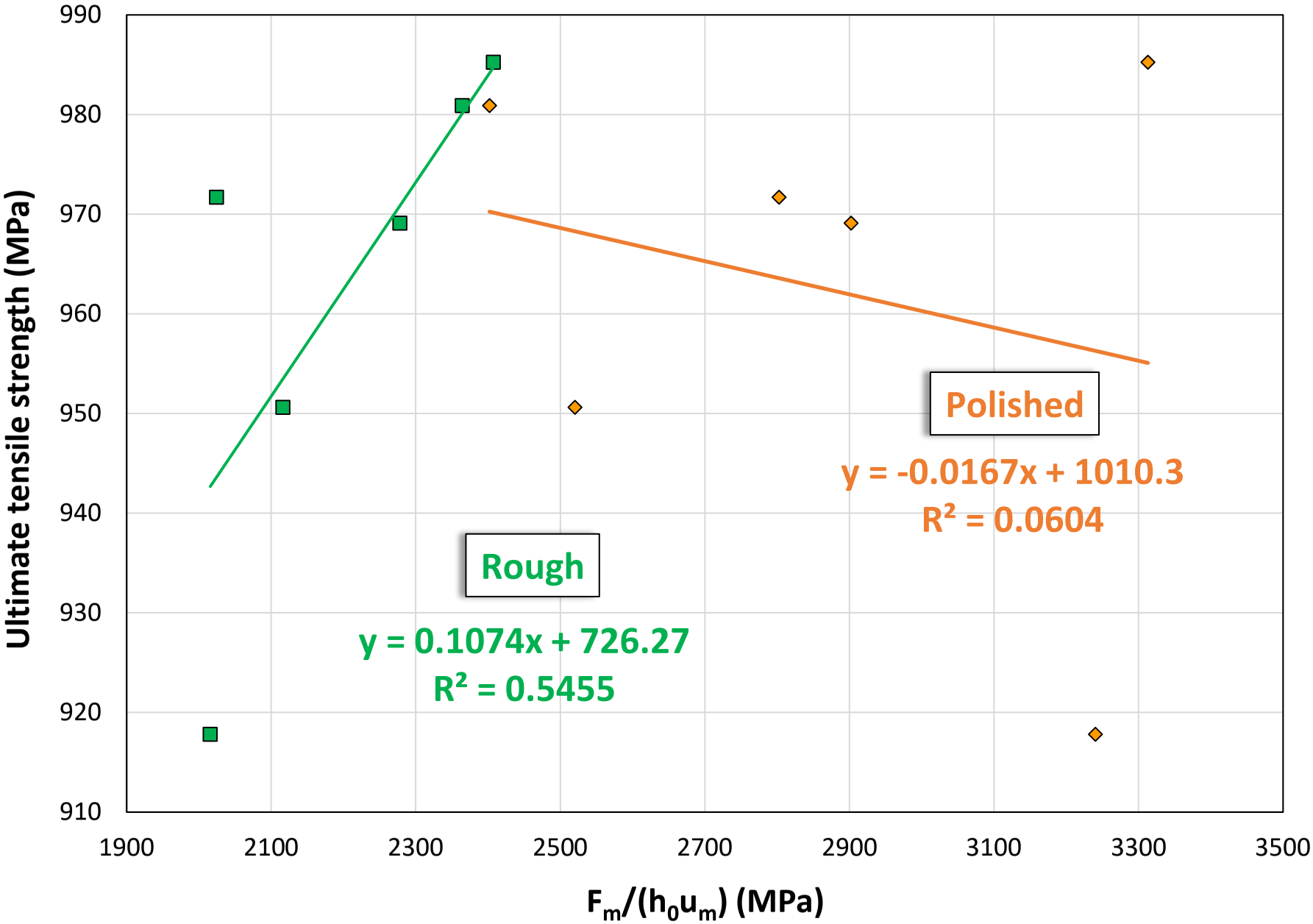

900
880
860
840
820
800
780
600
800
1000
1200
1400
1600
1800
Yield strength (MPa)
Yield strength (Hähner) (MPa)
Rough
y = 0.0737x + 786.89
R² = 0.3083
Polished
y = 0.3374x + 322.7
R² = 0.1573

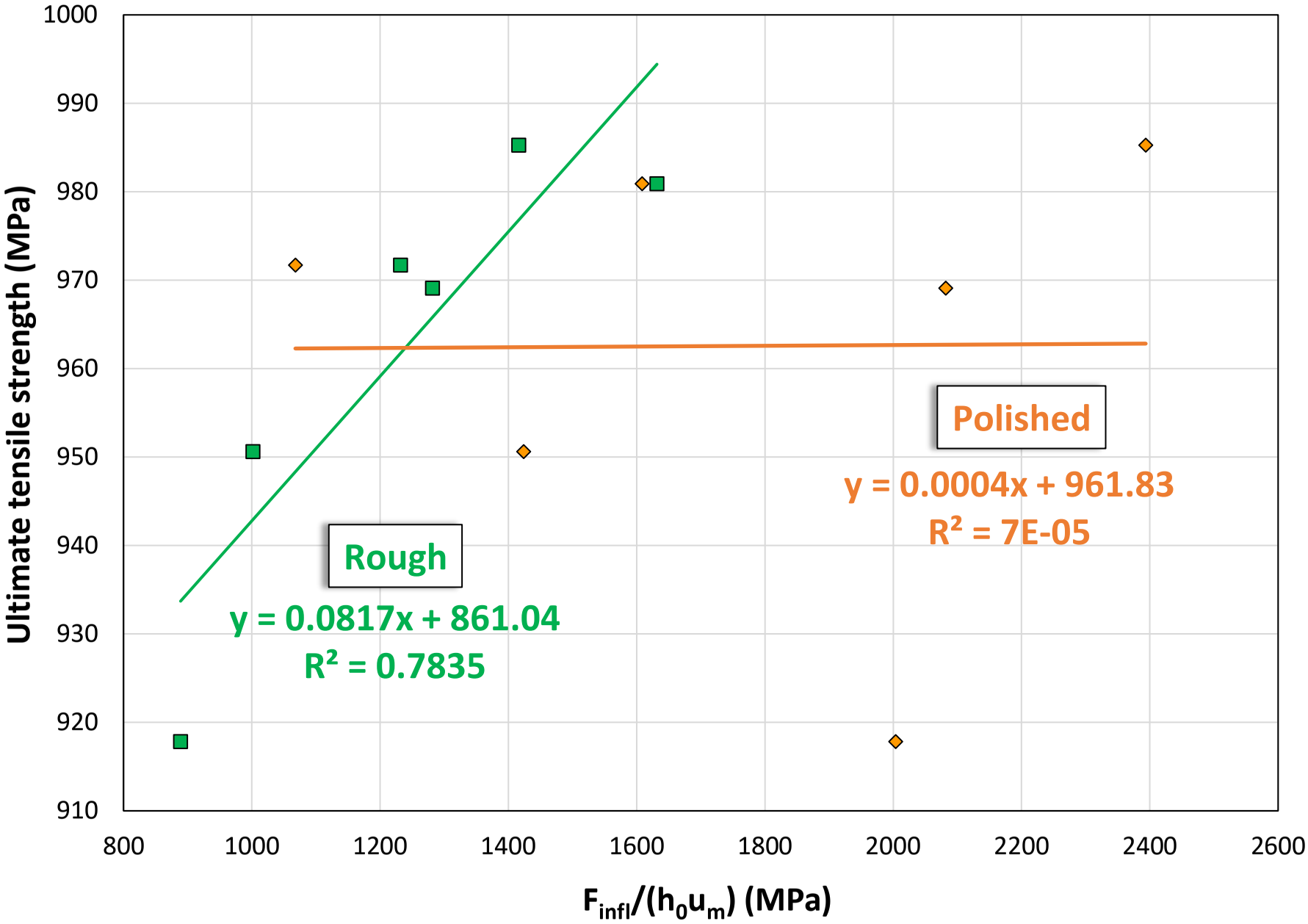

900
880
860
840
820
800
780
Yield strength (MPa)
3300
3800
4300
4800
5300
5800
6300
6800
7300
7800
Slope$_{ini}$/h$_0$ (MPa)
Rough
y = 0.0227x + 766.22
R² = 0.285
y = 769.4e^3E-05x
R² = 0.2814
Polished
y = 0.0842x + 268.19
R² = 0.3695
y = 426.66e^1E-04x
R² = 0.3665

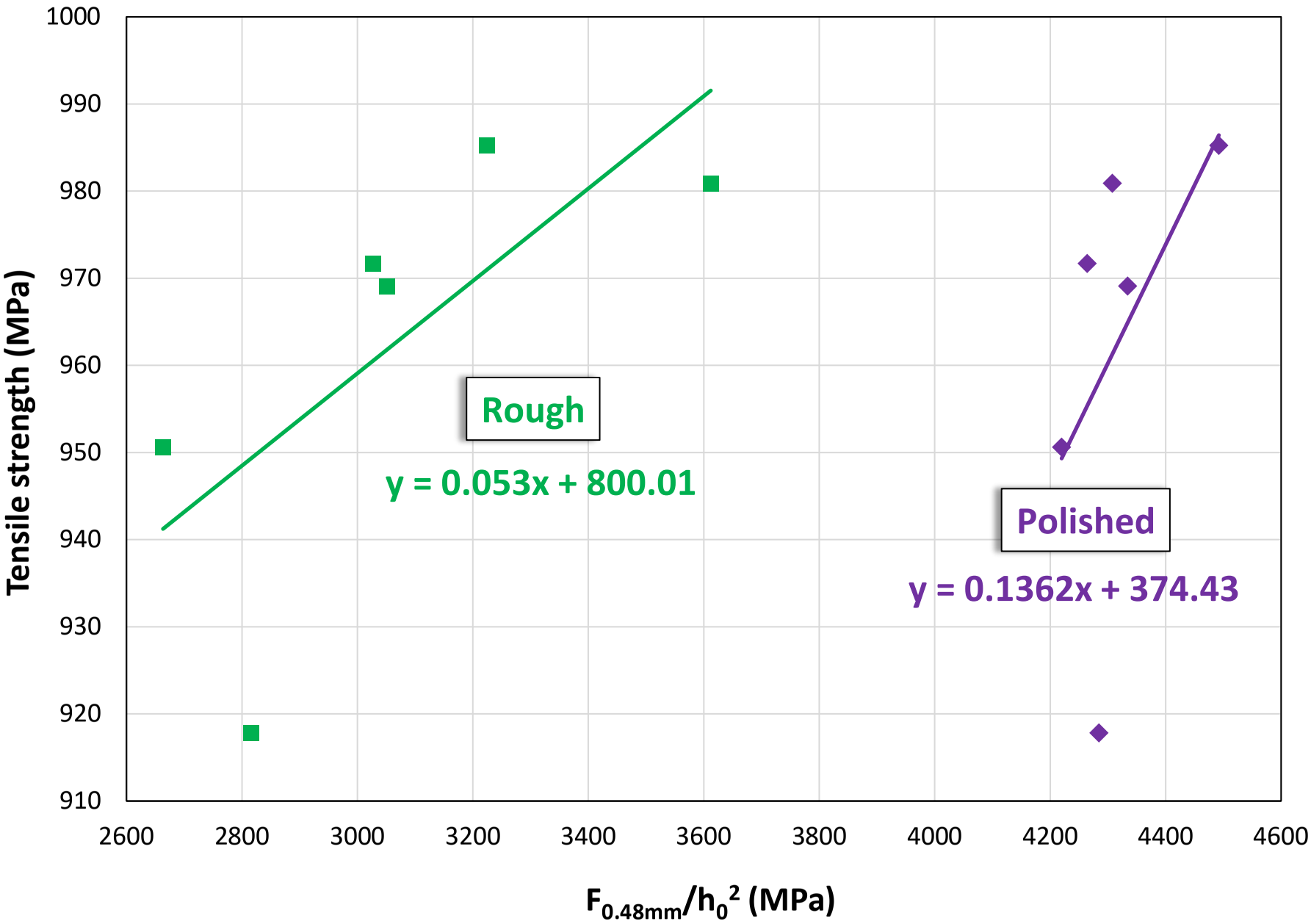
ANNEX 15

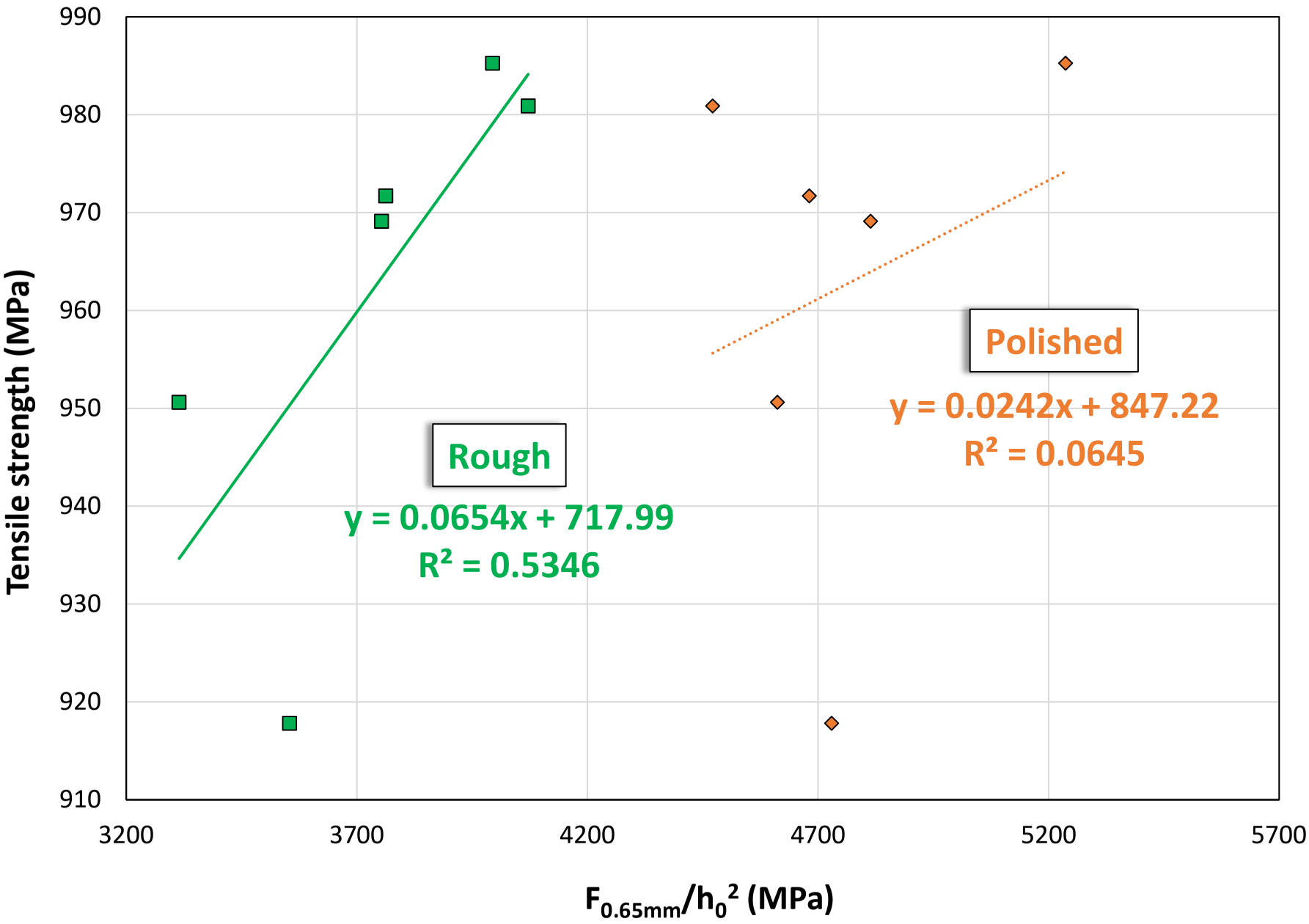
Correlations obtained for AM Ti64 between ultimate tensile strength and SP parameters


990
980
970
960
950
940
930
920
910
Ultimate tensile strength (MPa)
3900
4100
4300
4500
4700
4900
5100
5300
5500
F_m/h_0^2 (MPa)
Rough
y = 0.0273x + 839.28
R² = 0.1632
Polished
y = 0.0129x + 897.43
R² = 0.0114


Ultimate tensile strength (MPa)
990
980
970
960
950
940
930
920
910
1900
2100
2300
2500
2700
2900
3100
3300
3500
$F_m/(h_0u_m)$ (MPa)
Rough
y = 0.1074x + 726.27
R² = 0.5455
Polished
y = -0.0167x + 1010.3
R² = 0.0604

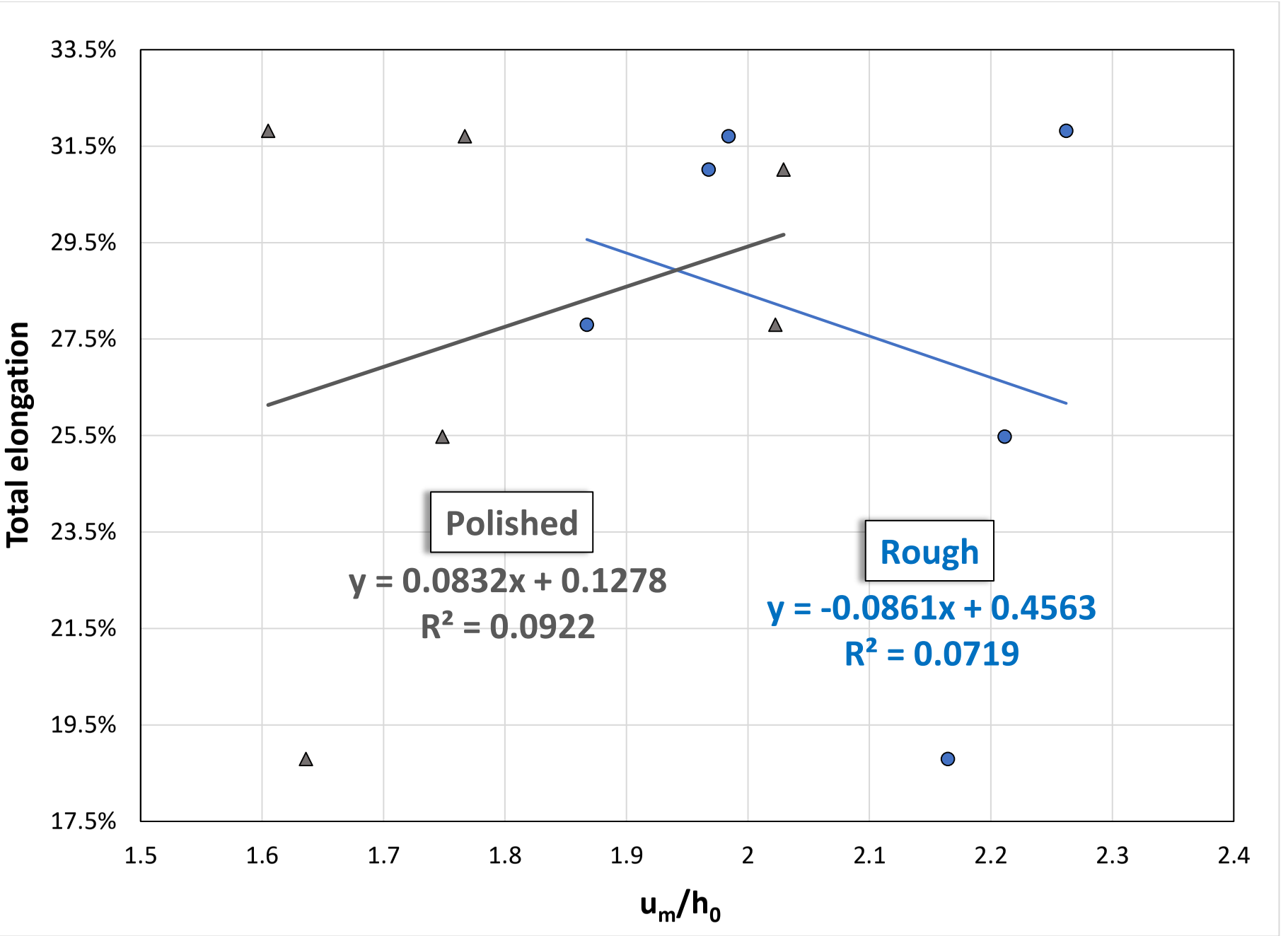

Ultimate tensile strength (MPa)
1000
990
980
970
960
950
940
930
920
910
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
$F_{infl}/(h_0u_m)$ (MPa)
Rough
y = 0.0817x + 861.04
R² = 0.7835
Polished
y = 0.0004x + 961.83
R² = 7E-05

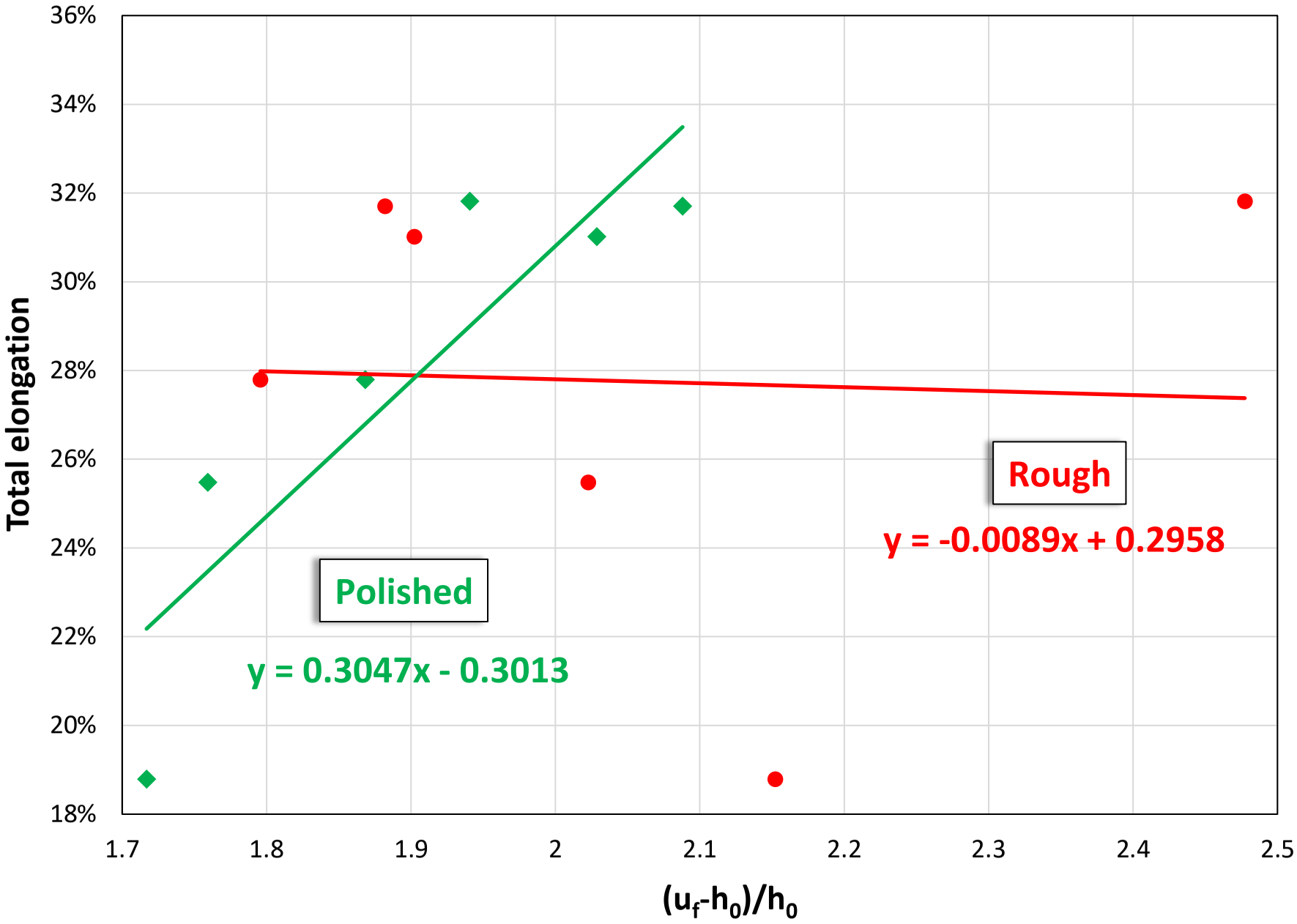

1000
990
980
970
960
950
940
930
920
910
Tensile strength (MPa)
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
$F_{0.48mm}/h_0^2$ (MPa)
Rough
y = 0.053x + 800.01
Polished
y = 0.1362x + 374.43

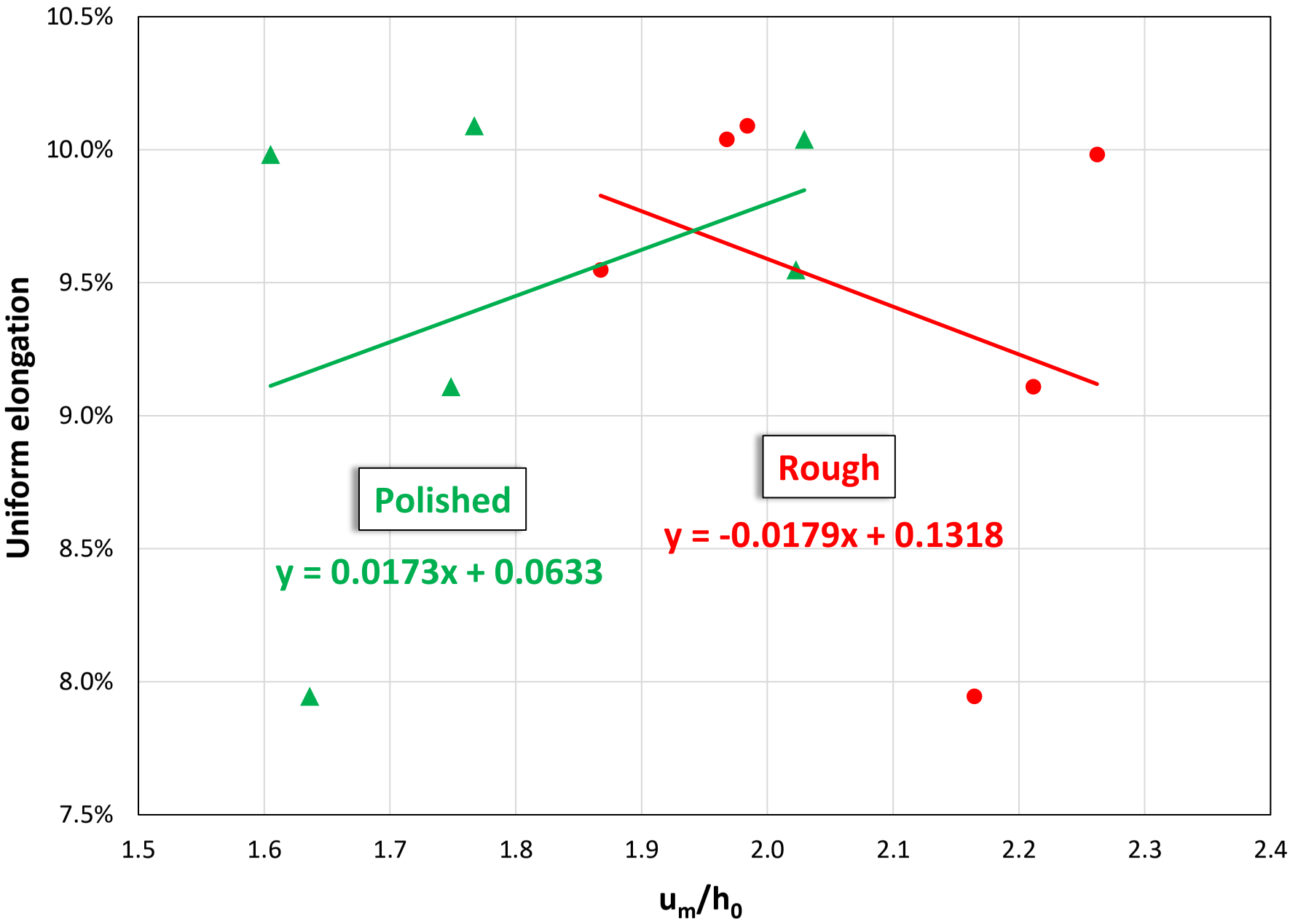

990
980
970
960
950
940
930
920
910
Tensile strength (MPa)
3200
3700
4200
4700
5200
5700
F0.65mm/h0² (MPa)
Rough
y = 0.0654x + 717.99
R² = 0.5346
Polished
y = 0.0242x + 847.22
R² = 0.0645

ANNEX 16

Correlations obtained for AM Ti64 between total/uniform elongation and SP parameters


33.5%
31.5%
29.5%
27.5%
25.5%
23.5%
21.5%
19.5%
17.5%
Total elongation
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
u_m/h_0
Polished
y = 0.0832x + 0.1278
R² = 0.0922
Rough
y = -0.0861x + 0.4563
R² = 0.0719


36%
34%
32%
30%
28%
26%
24%
22%
20%
18%
Total elongation
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
$(u_f-h_0)/h_0$
Rough
y = -0.0089x + 0.2958
Polished
y = 0.3047x - 0.3013


10.5%
10.0%
9.5%
9.0%
8.5%
8.0%
7.5%
Uniform elongation
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
u_m/h_0
Polished
y = 0.0173x + 0.0633
Rough
y = -0.0179x + 0.1318