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LEAD ERRORS IN COMMERCIAL SCREW THREADS, TAPS, AND DIES

by

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(This letter circular is to be offered for publication as a Technologic Paper of the Bureau of Standards. It is presented in this form for consideration and criticism by those interested in the subject).

ABSTRACT

The decrease in strength and tendency toward loosening of a screw thread fastening, resulting from lead errors in the threads, necessitates the control of their magnitude within proper limits. Lead error equivalents of tolerances on effective size, which is determined by the pitch diameter, lead error, and angle error, specified for four classes of fit of commercial threaded product by the National Screw Thread Commission, are tabulated.

In order that the maintenance of the magnitude of lead errors to within specified limits may be practicable, in the quantity production of screw threads, efficient means and methods of control must be available. Such control first requires the elimination, so far as practicable, of the causes of the three types of lead error, namely, progressive, local, and periodic, which are listed. Four methods of control by gaging are described, and control by the inspection of threading tools is discussed. The problem of distortion of taps and chasers in hardening is analyzed, and a bibliography relating to the hardening of steel with minimum distortion is appended.

Recommended lead, angle, and pitch diameter tolerances for ordinary commercial and for ground solid taps, and lead and angle tolerances for chasers in adjustable taps and dies are derived and tabulated. These are based on the National Screw Thread Commission tolerance specifications for the "Free Fit" and "Close Fit" classes, taking into account the effect of each type of lead error on the effective size of the thread produced by a tap or die. A method for testing the performance of a tap is also given.

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I. Introduction

The reliability of screw threads as fastenings, particularly when subject to great stresses and unusual vibration, as in automotive vehicles, depends upon the quality of fit as secured by maintaining the dimensions of their individual elements within certain specified limits. These elements are the thread angle, lead, major diameter, pitch diameter, and minor diameter. However, the major and minor diameters of both external and internal threads, as generally specified, permit a clearance between crest and root of mating threads, and these elements, therefore, do not affect the fit of the thread when within the specified limits, with the possible exception of thewrench or stud fits. Variations in pitch diameter, lead, and angle consequently combine to determine the effective size of a screw thread.

1. Importance of Lead Errors

It is well known that the presence of errors in lead not only affects the quality of fit, but also the strength of a screw thread, often causing the load intended to be nearly uniformly distributed over all of the threads to be concentrated on a few threads. The failure of a screw thread is often directly traceable to this concentration of stress resulting from errors in lead in either or both of the component members. The action which takes place is as follows: When there is a difference in lead between mating parts, the threads tend to become deformed, and if the difference is sufficiently great, the threads are deformed beyond the elastic limit, as shown in Fig. 1. If a stress is applied, it falls largely on one, or on a small number of threads, instead of being uniformly distributed over all. These threads deform under the strain until other threads take up a share of the pressure. The first effect is to increase the distance between the bearing point at the face of the nut or bolt head and the point on the external thread in contact with the internal thread. This is equivalent to loosening the fastening. If, however, the threads have been deformed beyond the elastic limit, the adjacent threads to which the load is transferred in turn give way, and thus failure by distortion or shearing of one thread after another may result until all of the threads of one of the components are stripped. In case the lead error is uniformly progressive, the stress falls first on the end threads of the nut, and these have the least support at the base.

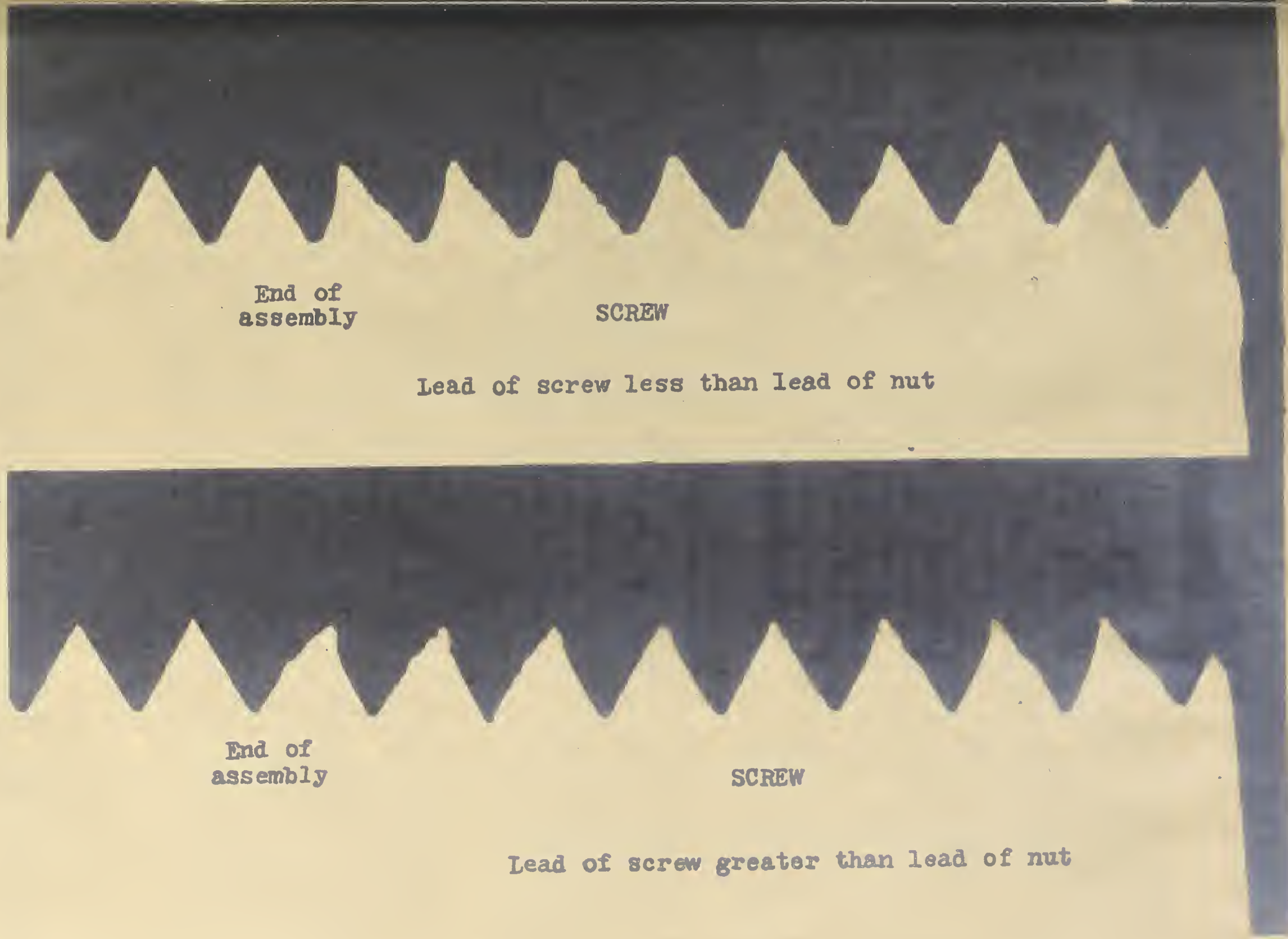

Fig. 1. Effect of Difference in Lead of 5.5% in Deforming Threads in Assembly

In practice, a slight uniform difference in lead or pitch in the proper direction, between tapped hole and screw under tension, is sometimes preferable to no difference in lead. A slightly plus pitch in the nut will shorten through compression, while a slightly minus pitch in the screw will lengthen through tension, as the result of the stresses, the amount being dependent on the elasticity of the materials and on the stresses imposed. Thus, the difference in pitch diminishes under stress and under a certain stress is practically zero, so that, as far as pitch is concerned, each thread comes nearer bearing its share of the total load under these conditions than is possible when the pitch of both component parts is identical. If, however, the directions of the lead errors are reversed, a condition is created which increases in seriousness more rapidly than the difference in lead error, and cracks, fractures, and stripping of the thread result. Examples of this are given in a paper by C. E. Stromeyer in connection with the failure of the threads of large piston rods and main bearing bolts[1].

Again, a close fit may be desired, the purpose of which is to prevent disassembly as the result of vibration. In case the intimate metallic contact of bolt and nut threads is the result of difference in lead instead of an intended small positive allowance (clearance), or of a negative allowance (interference) on pitch diameter, there is a tendency for the threads bearing the load to become distorted beyond the elastic limit, with the result that the fit may degenerate into looseness and the object originally aimed for is not attained.

The control of errors in lead is, therefore, of special importance, and it is the purpose of this paper to consider the magnitude of lead errors permissible in commercial threaded products, in view of certain tolerance specifications laid down by the National Screw Thread Commission; to discuss the control of accuracy in lead by the prevailing methods of inspection; to indicate what progress is being made toward accurate control of lead of commercial threading tools, particularly taps and die chasers, to present recommended lead tolerances for such tools and give the basis for such recommendations; and to suggest a practical method of inspecting the thread of a tap, to determine whether it is within proper commercial limits.

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[1]See "Stress Distribution in Bolts and Nuts", by C. E. Stromeyer. Transactions of the Institution of Naval Architects, Vol. 60, 1918, pp. 112-122.

2. Types and Causes of Lead Errors

Errors in lead are of three classes, as follows:

(1). A uniformly progressive error, which is an error in the total length of the screw, the distances between corresponding points of threads equally separated as to number, at all points of the screw, being equal;

(2). Local errors, which are variations in the distances between corresponding points of threads equally separated as to number, and which may or may not affect the total length of the screw; and

(3). Periodic errors, which are variations of the helix angle of the thread recurring within equal intervals, usually within every turn, along the screw.

Lead errors occur in threaded product as the result of a variety of causes, but may be traced to certain fundamental factors. In cutting a thread on a lathe or other machine embodying a lead screw, using a single-point cutting tool or single milling cutter, progressive lead errors are caused by:

(1). A residual progressive lead error in the lead screw;

(2). Lack of parallelism of the motion of the cutting tool, the axis of the lead screw, and the axis of the part to be threaded; and

(3). Incorrect ratio of the rate of revolution of the spindle to that of the lead screw, due to an incorrect combination of gears, (when a gear of exactly the required number of teeth is lacking).

Local lead errors are caused by:

(1). Residual local lead errors in the lead screw;

(2). Lost motion in the mounting of the lead screw;

(3). Varying frictional resistance of the carriage, on which the cutting tool is mounted, with its ways, or of the nut with the lead screw;

(4). When a live center is used, irregular play of its spindle in the bearings; and

(5). Irregular variations in the amount of metal removed by the cutting tool, causing a rough thread.

Periodic lead errors are caused by:

(1). Residual periodic lead errors in the lead screw;

(2). Eccentricity of rotation of the lead screw;

(3). Lack of perpendicularity of thrust bearings to the axis of rotation of either the spindle or lead screw;

(4). Variations in the spacing of gear teeth, or eccentric mounting of a gear;

(5). When a live center is used, eccentricity of rotation of its spindle or regular variations of the play in the spindle bearings; and

(6). Periodic variations in the amount of metal removed, due to lack of uniformity of the diameter of the piece to be threaded, or of the straightness of its axis of rotation.

If, in cutting a thread on a lathe or other machine embodying a lead screw, a thread chaser or multiple-toothed milling cutter is used, variations from correct spacing of the teeth of the chaser or cutter are superimposed on the lead errors resulting from any of the above causes in that portion of the thread not passed over by every tooth of the chaser. In the portion of the thread completely passed over by the chaser, the effect of the difference in lead between the chaser and lead screw is to produce a thin thread.

When a thread is cut by means of a tap or die, which, as ordinarily used, is self-leading and not positively controlled by a lead screw, lead errors may occur as the result of:

(1). Incorrect lead of the tap or die;

(2). Too much or too little relief at the throat of the die or on the chamfer at the end of the tap;

(3). The setting of an adjustable die or tap chaser to cut a thread with a helix angle considerably different from the helix angle of the chaser;

(4). Excessive resistance to longitudinal motion;

(5). Improper alinement of the axis of the tap or die with that of the work, etc.

The accuracy of the lead of the tap or of the chasers in the die is the most difficult of these sources of error to control, and indeed presents serious difficulties. There is, first, the difficulty of cutting a tap or chaser which is free from lead errors resulting from any of the causes outlined above; and, second, the distortion which the steel composing the tap or die undergoes in hardening.

II. Permissible Lead Errors in Commercial Threaded Product

1. Tolerance Specifications of the National Screw Thread Commission

Allowances for four classes of fit, and corresponding tolerances on major and minor diameters, and on the effective size[2] of screw threads, are laid down in the Progress Report of the National Screw Thread Commission. The tolerances on effective size are tabulated therein as maximum variations of pitch diameter, and the report contains the following statement on page 56[3].

> " (b) Pitch Diameter Tolerances Include Lead and Angle Variations. -- The tolerance limits established represent, in reality, the sizes of the "Go" and "Not Go" master gages. Errors in lead and angle which occur on the threaded work can be offset by a suitable alteration of the pitch diameter of the work. If the "Go" gage passes the threaded work, interchangeability is secured, and the thread profile may differ from that of the "Go" gage in either pitch diameter, lead, or angle. The "Not Go" gage checks pitch diameter only, and thus insures that the pitch diameter is such that the fit will not be too loose."

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[2]Defined as the pitch diameter combined with increments derived from lead errors and angle errors present in the length of engagement. It is the pitch diameter of a mating screw thread, perfect in lead and angle and having crest clearance, that will just fit. For the derivation of the formulas giving the values of such increments, see Bureau of Standards Letter Circular No. 23, Appendix 3.

[3]First Progress Report of the National Screw Thread Commission, Bureau of Standards Miscellaneous Publication No. 42.

In the revised report of the National Screw Thread Commission to be issued in 1934, it is expected that this paragraph will read as follows:

"Pitch Diameter Tolerances Represent Variations of Effective Size. -- The tolerance limits established represent, in reality, the sizes of the "Go" and "Not Go" master gages, and, therefore, include lead and angle variations as well as variations of the pitch diameter. Errors in lead and angle which occur on the threaded work can be offset by a suitable alteration of the pitch diameter of the work. If the "Go" gage passes the threaded work, interchangeability is secured and the thread profile may differ from that of the "Go" gage in either pitch diameter, lead, or angle. The "Not Go" gage checks pitch diameter only, and thus insures that the pitch diameter is such that the fit will not be too loose."

2. Relation of Lead Error to Effective Size

The fit of an internal thread on an external thread, as affected by lead error, depends entirely on the maximum difference in lead present within the length of engagement, regardless of the number of threads in the interval within which it occurs. When a screw having a given pitch diameter and correct thread form, but having an error in lead, fits snugly in a nut having correct lead, angle, and thread form, the thread in the nut must have a pitch diameter which is larger than that of the screw. If the lead error is in the nut, and the nut is fitted to a screw having correct lead, angle, and thread form, the pitch diameter of the screw must be smaller than that of the nut. For a straight thread, the formula which gives the amount of this necessary difference between the pitch diameters of the screw and nut as the result of the maximum lead error present between any two threads engaged, is as follows:

$$E' = \pm\, p' \cot a,$$

in which

- E' = pitch diameter increment due to lead error; or difference between pitch diameter of incorrect screw and perfect nut, or vice versa
- p' = the maximum lead error between any two of the threads engaged
- a = half-angle of thread.

Then, for all threads having a thread angle of 60°:

$$E' = \pm\, 1.73205\, p'.$$

The quantity E' is always added to the actual pitch diameter in the case of a plug, and it is always subtracted in the case of a ring, to obtain the effective size. That is, a lead error in a nut decreases the effective size of the nut; when in a screw the effective size is increased by the presence of error in lead. This is true regardless of whether the lead error p' is plus or minus. However, when both components have uniformly progressive lead errors in the same direction, and of equal amount, such compensation in pitch diameter is, evidently, not necessary.

3. Lead Error Equivalents of Tolerances on Effective Size.

As the pitch diameter tolerances specified in the report of the National Screw Thread Commission include lead and angle variations, there are given in Table 1, for information, the error in lead, in the length of thread engaged, which can be compensated for by one-half of the pitch diameter tolerance specified for each pitch and for each class of fit. Thus, the remaining half of the pitch diameter tolerance can be used to compensate error in thread angle or cover variation of pitch diameter from minimum metal size, or cover a combination of both.

Table 1. - Lead Errors in Length of Engagement Consuming One-Half of the Pitch Diameter Tolerances

1	2	3	4	5	6	7	8	9
Number of threads per inch	Class 1, - Loose Fit		Class 2, - Free Fit		Class 3, - Medium Fit		Class 4, - Close Fit	
	Extreme tolerance	Lead variation	Extreme tolerance	Lead variation	Extreme tolerance	Lead variation	Extreme tolerance	Lead variation
	Inch	Inch	Inch	Inch	Inch	Inch	Inch	Inch
80	0.0024	0.0007	0.0017	0.0005	0.0013	0.0004	0.0006	0.0002
72	.0025	.0007	.0018	.0005	.0013	.0004	.0007	.0002
64	.0026	.0008	.0019	.0005	.0014	.0004	.0007	.0002
56	.0028	.0008	.0020	.0006	.0015	.0004	.0007	.0002
48	.0031	.0009	.0022	.0006	.0016	.0005	.0008	.0002
44	.0032	.0009	.0023	.0007	.0016	.0005	.0008	.0002
40	.0034	.0010	.0024	.0007	.0017	.0005	.0009	.0003
36	.0036	.0010	.0025	.0007	.0018	.0005	.0009	.0003
32	.0038	.0011	.0027	.0008	.0019	.0005	.0010	.0003
28	.0043	.0012	.0031	.0009	.0022	.0006	.0011	.0003
24	.0046	.0013	.0033	.0010	.0024	.0007	.0012	.0003
20	.0051	.0015	.0036	.0010	.0026	.0008	.0013	.0004
18	.0057	.0016	.0041	.0012	.0030	.0009	.0015	.0004
16	.0063	.0018	.0045	.0013	.0032	.0009	.0016	.0005
14	.0070	.0020	.0049	.0014	.0036	.0010	.0018	.0005
13	.0074	.0021	.0052	.0015	.0037	.0011	.0019	.0005
12	.0079	.0023	.0056	.0016	.0040	.0012	.0020	.0006
11	.0085	.0025	.0059	.0017	.0042	.0012	.0021	.0006
10	0092	.0027	.0064	.0018	.0045	.0013	.0023	.0007
9	.0100	.0029	.0070	.0020	.0049	.0014	.0024	.0007
8	.0111	.0032	.0076	.0022	.0054	.0016	.0027	.0008
7	.0124	.0036	.0085	.0025	.0059	.0017	.0030	.0009
6	.0145	.0042	.0101	.0029	.0071	.0020	.0036	.0010
5	.0169	.0049	.0116	.0033	.0083	.0024	.0041	.0012
4 1/2	.0184	.0053	.0137	.0037	.0089	.0026	.0044	.0013
4	0304	.0059	.0140	.0040	.0097	.0028	.0048	.0014

III. Control of the Magnitude of Lead Error in Commercial Screw Threads

The magnitude of the lead error, as well as errors in the other thread elements of commercial threaded product, is kept within desirable limits by gaging the product, and by inspecting the thread cutting or forming tools.

1. Control by Gaging

In gaging screw threads, the accuracy of the lead may be checked as follows:

(1). By means of "Go" and "Not Go" thread plug and ring gages.

(2). By means of snap gages of special form.

(3). By means of indicating gages.

(4). By optical gaging.

(1). The approved form of a "Go" thread inspection or working thread gage is that of a thread plug or ring having a thread of full form and equal in length to the length of engagement of the assembled screw and nut. In the case of a Free or Medium fit, it represents, in principle, the limiting outline of the mating part. The gaging surface of such a gage passes by every point of the thread, and thereby insures that accepted product will assemble without interference when a positive allowance (clearance) between them has been specified.

In order that the "Not Go" thread plug or ring gage may check the pitch diameter only, as previously stated herein and specified in the report of the National Screw Thread Commission, it is necessary that it be of such form that it will make contact with both sides of the same thread, and only along portions of the sides of the thread at, and adjacent to, the pitch line. If the gage thread is of full form, an error in thread angle in the product will prevent its touching at the pitch line. It should, therefore, have a short gaging surface at the position of the pitch diameter. The thread form for "Not Go" thread gages recommended by this Bureau is that shown in Fig. 2, in which the crest of the thread is truncated to a depth of about one-fourth the depth of the V-thread, and the groove is widened, to prevent contact near the crest and root of the thread to be gaged, from a position one-fourth the depth of the sharp V-thread below the pitch diameter line to the bottom of the V-thread groove. This form of thread checks, principally, the pitch diameter and has sufficient gaging surface to provide against rapid wear. Furthermore, the "Not Go" gage should be short in length, three to four threads being the maximum length recommended. Theoretically, a "Not Go" thread gage should not

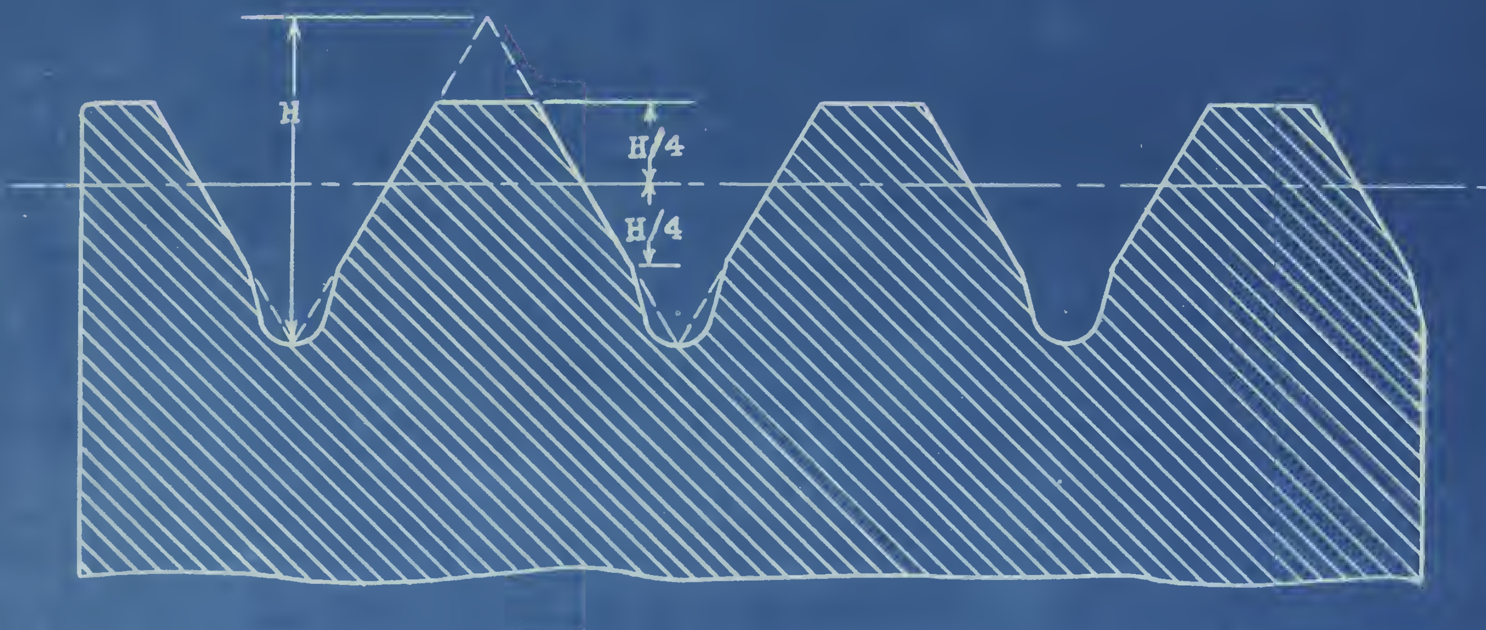

Fig. 2. Recommended Thread Form for "Not Go" Thread Gages

exceed one turn in length, for the reason that a lead error in the product gaged will prevent a gage of greater length from touching both sides of the same thread, and thus work which just fails to engage with a longer "Not Go" gage may be actually smaller than the lower limit on pitch diameter in the case of a screw, or larger than the upper limit on pitch diameter in the case of a nut. It is evident, also, that an undersize screw and an oversize nut passed by reason of this compensating lead error would, if assembled, result in a much looser fit than that intended, if the lead errors of both are in the same direction. It is, however, desirable that the gage be longer than a single turn to provide a greater wearing surface, and as lead error does not seriously affect tue result obtained with a gage having a length of three turns, the latter length is recommended but should not be exceeded. In gaging a thread, such a "Not Go" gage may engage with the work for a distance not exceeding half the length of engagement of the work before becoming tight when turned by hand. In case a "Not Go" gage longer than three turns is used, all work should be rejected which engages a distance greater than three turns.

With the use of a "Go" thread plug or ring gage which checks all thread elements, and of a "Not Go" gage of a form which checks pitch diameter only, it is apparent that the lead error in the length of full engagement may be such that the "Go" gage will just engage without clearance or play, and the "Not Go" gage will just fail to engage with the work. Under these conditions, the entire pitch diameter tolerance is taken up by the lead error, and E' of the above formula represents the diametrical equivalent of this lead error or the pitch diameter tolerance.

"Go" gages equal in length to the nominal diameter are frequently used when the actual length of engagement is one and one-half diameters. When product gaged in this way is assembled, interference will occur if a screw near the maximum diameter, and having a maximum lead error in one direction, is engaged with a nut near the minimum diameter and having a maximum lead error in the opposite direction. The chances of this particular combination occuring in actual production are so small that there is no practical objection to the practice. However, the use of a "Go" gage, one diameter in length, for checking a length of engagement of over one and one-half diameters, is not recommended.

(2). Adjustable thread snap gages, having contact points consisting of cone-pointed cylinders, wedge-shaped prisms with rounded edges, serrated or grooved plates, or grooved or threaded cylinders adjustably mounted and suitably spaced in a U-shaped frame are used to some extent in gaging external threads, and have the advantages that work may be inspected with great rapidity by the single motion of passing it between

the anvils of the gage and given a visual examination for clearance as well as a tactile inspection. The positions of the anvils are set by master threaded check plugs, and the anvils are then clamped in position and sealed.

The usual form of cone-pointed snap gage has a single point on each side of the frame, and is eminently suitable as a "Not Go" gage, provided that it has a short bearing surface which makes contact with the work at the pitch line. It does not, however, fully meet the requirements for a "Go" gage, as it does not check the lead, and, therefore, must be supplemented with some type of indicating gage to check the lead when used for checking pitch diameter, angle and thread form. Also, as it checks only a single diameter at a time, the "Go" snap gage must be tried at a series of points to determine whether the maximum diameter of an external thread is within the tolerance. When provided with three contact points, two on one side spaced an integral number of threads apart, and one on the other, such a gage checks the lead for progressive, but not always for local or periodic lead errors, and, thus, more nearly fulfills the requirements for a "Go" thread gage.

Thread snap gages having multiple toothed contact points, that is, toothed blades, serrated or grooved plates, or grooved or threaded cylinders are made in a variety of forms, either as separate or combined "Go" and "Not Go" gages. The fit of a screw in such a gage is affected by variations in pitch diameter, lead, and angle of the screw, and the gage accordingly checks the effective size. Such gages have been found suitable only for the less accurate classes of work, such as the Loose and Free Fit Classes.

(3). An indicating thread gage has movable contact points, which are set to master gages, and is intended to give an exact indication of the variations of the dimensions of a screw thread within the specified limits, rather than to show merely that the thread is within, or outside of, the specified limits, as is the case with limit gages. In such gages, the movable contact points actuate a multiplying lever system, or other means for magnifying their motion, and the amount of the motion is registered on a graduated dial or scale. Indicating gages are made according to a variety of designs, some to indicate progressive lead error only, some to indicate pitch diameter only, some to indicate both separately but on the same gage, others to indicate the major and minor diameters as well, and still others to indicate the effective size. They have been applied almost exclusively to external threads. Those which indicate the effective size may be considered as most nearly fulfilling the requirements of a gaging system. However, those indicating lead errors are very useful in controlling lead

errors in threading tools and screw thread products. Also certain types can be used to indicate the variation in roundness on pitch or major diameters.

(4). In optical gaging, that is, gaging by optical projection, which can only be applied to external threads, the screw is located at a definite position before a projection lens system and illuminated by a beam of parallel light whose direction is adjusted to the helix angle of the thread. The projected shadow-image of the screw is obtained on a screen consisting of a so-called tolerance chart, which is made up of superimposed outlines of the correct thread form enlarged to correspond to the magnification used, and separated a distance equal to the specified tolerance multiplied by the magnification. This chart is first definitely located in position by projecting a master gage having either the upper or lower limiting dimensions and located before the lenses in the same manner as the work to be inspected, and setting the corresponding outline of the chart to coincide with its shadow-image.

In one type of commercial projection comparator, the screw is supported in two cradles, one of which is threaded and fixed in proper relation to the vertical plane through the optical axis of the projection lens system. The function of the other cradle is merely to hold the screw with its axis horizontal, and it may bear on either a plain cylindrical portion of the threaded part or on the threaded portion. When the fixed cradle is located at a distance from the vertical plane through the optical axis equal to the length of engagement, variations in the position of the image of the thread on the top of the screw, with respect to the screen chart, represent variations in the effective size of the screw due to pitch diameter, progressive lead error, and angle error. The effects, on the effective size, of variations in roundness, and of local and periodic lead errors are indicated on the screen when the screw is rotated in its threaded cradle.

In another type of commercial projection comparator, the screen consists of a chart having adjustable members which may be set for a screw of any pitch and to any tolerance as desired. The work rests on two toothed blades adjusted so that both engage with the threads of the work, one of which is locked firmly in place in an angular position, while the other is lightly clamped so that it will adjust itself to the thread of the master gage or work engaged with the fixed blade. The blades are adjusted to point radially to the axis of the thread by turning a knob. The work is held in contact with the toothed blades by an upper straight-edge blade, which may be moved vertically by means of a lever and is constrained downward by a tension spring, thus causing the movable toothed blade to adjust itself to the thread. The effective size of the screw, as determined by the pitch diameter, all types of lead error, and angle error, is thus gaged.

2. Control by Inspection of Tools

The advantages of using tools and methods for cutting screw threads that will introduce the smallest practicable errors in the product are clearly indicated in the previous discussion. The sources of lead errors in a machine tool on which a threading operation is performed are outlined herein in the introduction. The simplest method of inspection of a machine tool to determine whether it will cut a screw thread within satisfactory limits is to carefully cut a sample screw on the machine and measure the lead errors of the screw. The obvious remedy for errors from such sources is the careful inspection of the various elements of the machine, and correction of the errors thus located, either by improving the design[4] or by carefully refinishing or remaking the parts to a greater degree of accuracy.

In the case of a self-leading threading tool, such as a tap or die, the sources of error are likewise previously mentioned. In the inspection of such thread forming tools, practically the same means and methods can be applied as in the measurement of screw thread gages. For checking the lead, indicating gages or some of the usual lead measuring devices for screw thread gages may be used.[5] To measure the lead of a die chaser, the chaser must be held in a fixture in such a position that the direction of measurement corresponds to the direction of longitudinal motion of the chaser threads when cutting a thread.

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[4]Information regarding the methods pursued in producing and applying precision screws may be obtained from the following: "On a Practical Solution of the Perfect Screw Problem", by William A. Rogers. Transactions of the American Society of Mechanical Engineers, Vol. 5, 1883-84, pp. 216-259, and Vol. 12, 1890-91, pp. 725-728; "Interchangeability in Screw Threads", by H. F. Donaldson. Proceedings of the Institution of Mechanical Engineers, 1909, pp. 253-292; "The Blythewood Dividing Engine for Ruling Diffraction Gratings", by W. A. Scoble. Collected Researches of the National Physical Laboratory, Vol. 8, 1912, pp. 215-251; "Building a Machine which Splits Millionths", by Donald M. Liddell, American Machinist, Vol. 40, June 4, 1914, pp. 969-973; "Making Precision Screws for Scientific Instruments", by Edward K. Hammond. Machinery (N.Y.) Vol. 23, June 1917, pp. 849-854; "Precision Screw Cutting Lathe". Engineering (London) Vol. 105, May 24, 1918, pp. 578-580; and "Screw Threads", Encyclopedia Brittanica.

[5]Lead testing devices for screw thread gages are described in American Machinist, Vol. 49, July 25, 1918, p. 160, and Vol. 50, March 13, 1919, pp. 517-518; Machinery (N.Y.) Vol. 23, March 1917, pp. 581-586, Vol. 24, October 1917, pp. 178-179, and August 1918, p. 1150; Proceedings of the Institution of Mechanical Engineers, 1917-I, pp. 50-54; and Mitteilungen über Forschungsarbeiten, Verein Deutcher Ingenieure, 1913, Heft 142.

IV. Recommended Lead Tolerances for Taps and Dies

1. Basis for Recommended Tolerances

A tap having only a progressive lead error will cut a thread having the same pitch diameter and lead as its own, provided that no errors are introduced from other sources and assuming that a perfect tap will cut a perfect thread of its own diameter. The same holds true for a die. The same lead error present in the tap or die will be transmitted to the thread produced. According to considerations previously outlined, the effective size of the hole tapped with a tap having a progressive lead error will be too small to fit a perfect screw of the pitch diameter which would otherwise fit it snugly, and the effective size of the screw with a progressive lead error will be too large to fit a perfect nut of the pitch diameter which would otherwise fit it snugly.

On the other hand, a tap having local errors in lead will cut a thread of greater pitch diameter than its own, since the dislocated cutting teeth will cut deeper into the sides of the thread, and will produce a thread whose flats will be narrower at the crest, and wider at the root than standard, and which will presumably be of the same average pitch as the tap. As to what the effective size of the thread in the nut will be, little can be said, since the local errors introduced into the nut would not be the same as those of the tap. Similar considerations apply to a thread cut by a die.

It is evident, then, that in determining lead tolerances for taps and dies, progressive and local lead errors should be considered separately. Further, in determining lead tolerances it is also necessary to take into consideration variations in thread angle and in pitch diameter, and the tolerances on effective size already specified for each class of fit. The question then arises: Into what proportions and in what manner should the tolerances on the effective sizes of an external and of an internal thread, specified for a given class of fit, be divided to separately cover each of these types of lead error, angle errors, and pitch diameter variations as to best meet the limitations imposed by manufacturing conditions?

In the discussion of this problem, we are more largely concerned with taps than with dies, as the latter are ordinarily adjustable on diameter, whereas, the former can be made adjustable only on the larger sizes. It is, accordingly, more difficult to secure a given degree of accuracy in the thread produced by a tap than in one produced by a die. The greatest difficulty encountered in maintaining the accuracy of the dimensions of taps, particularly of the lead, is the distortion of the steel in hardening.

(a). The Problem of Distortion on Hardening

The distortion of steel on hardening, as it affects the manufacture of taps, may be either a symmetrical volume change, affecting both the diameter and length by proportional amounts and introducing a progressive lead error, or an unsymmetrical change, known as warpage, which affects not only the values of the length and diameter, but their uniformity, that is, the straightness and roundness of the tap, introducing local lead errors.

In the case of a symmetrical volume change, if its amount is uniform for a steel of given composition and treatment, it can be compensated by machining the tap or chaser to dimensions differing from standard by amounts corresponding to the dimensional changes on hardening. Devices known as lead variators may be readily attached to lathes which retard or advance the motion imparted by the lead screw to the cutting tool by any desired amount within certain limits, and the accuracy of the lead is thus controlled.

If, however, the volume change is unsymmetrical, a number of factors enter into the problem, including the size and shape of the piece to be hardened. Ovbiously the only way out of the difficulty is to reduce such distortion to a minimum, unless it can be confined to one direction. As this problem is essentially one of metallurgy, and, as has been pointed out, (1)[6] an adequate explanation of the phenomena related to it presents extraordinary difficulties, only a brief analysis of it can be here presented. Sources of information supporting statements made in this analysis are listed in the appended bibliography.

Three primary factors determine the properties of a steel, namely, its chemical composition, thermal treatment, and mechanical treatment. These together determine the structure of the material, to which its physical properties are most closely related. Upon heating a steel to certain definite temperatures, depending upon its composition, pronounced changes in structure occur which are to be ascribed to phase changes or transformations within the material. The condition of solution normally existing only at a temperature slightly above that at which a given transformation occurs can be caused to persist at room temperature, to a large extent, by extremely rapid cooling or quenching. The hardening of steel by heat treatment depends upon this fact, (2); a number of explanations of the phenomenon of the hardening of steel and other alloys have been advanced, (3), (4), (5).

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[6]Numbers in parenthesis refer to the papers listed in the bibliography given in the appendix, and indicate the source of the information given in the statement preceding each number.

The suppression of allotropic or phase changes by quenching depends upon a number of factors. It is important that the piece to be hardened be maintained at the quenching temperature for a sufficient length of time to permit it to become uniform in temperature. In quenching, the temperature, and the heat absorbing qualities of the quenching medium as determined by its specific heat, heat of evaporation, and viscosity, together with the speed of immersion and amount of agitation, determine the rate of cooling. This in turn determines the degree to which transformation and phase changes are suppressed. The differing rates of cooling of the exterior and interior of the piece, as affected by its size and shape and its thermal conductivity, then determine the degree of uniformity or variation of its structure from the interior to the exterior, (6).

It has been shown that such heat treatment sets up internal stresses within the piece (7) which are to be ascribed to: (a), differing rates of cooling and consequent differing rates of volume change, and (b), volume changes incident to transformations which are not suppressed. Stresses resulting only from differential thermal contraction disappear when the piece again becomes uniform in temperature, provided that the range of temperature through which it is quenched is entirely within the range in which the material is elastic, unless they are of sufficient magnitude to deform the material beyond its elastic limit. On the other hand, if a part of the rapid cooling is in the plastic range, so that equalization of strain by flow takes place in the interior but not near the surface, a residual strain remains when the piece again becomes uniform in temperature, which tends to distort it in such a way that it assumes a more nearly spherical shape. (8), (13).

Stresses resulting from volume changes accompanying transformations not suppressed in quenching, that is, differences in specific volume between structures whose transformation was suppressed and transformation structures, may be of more serious consequence in their effect on the mechanical properties and on the distortion of the piece than purely thermal stresses, (9). These effects are of a very complex nature, the composition of the steel being a predominating factor. Special studies have been made of steels of specific composition, in which the effect of stresses resulting from volume changes, on the properties of the steel, are given consideration. Among these may be mentioned a research by Scott on high-carbon steels (10), another by Andrew, Rippon, Miller and Wragg on carbon, nickel, chrome, and nickel-chrome steels (11), and a third by Greenwood on various tool steels

(12), in which reference is made to similar important work by Matsushita. These papers do not, however, deal specifically with the control of dimensional changes, but, at the present time, an extensive investigation along such lines is being carried on at this Bureau, under the supervision of the Gage Steel Committee, to determine the composition and treatment of an alloy steel most suitable for limit gages, the results of which when available may also be of use to tap makers.

Another research which should be especially valuable in the manufacture of taps is that by Lineham (13), in which the quenching media most suitable for securing minimum distortion of mild steel thread gages cased in cyanide were determined. Accurate temperature control, such as that secured by means of the methods and apparatus described by Colvin (14), is essential in such operations.

The release of strains resulting from the hardening operation either by spontaneous action, artificial seasoning, or tempering, constitutes another phase of this subject. Whether the piece is restored to its original dimensions or still further distorted by such release of strain again depends upon its composition and on the temperature to which it is reheated. These matters are touched upon in the references cited; an additional source of information, giving results of preliminary experiments on artificial seasoning, is an article by French (15).

Aside from the heat treatment of a steel piece after machining, its treatment previous to the hardening operation is equally as important as the method of conducting the hardening operation. Conditions which are likely to cause error in taps are uneven rolling or uneven annealing of the steel; also if the tap blank is not straight before it is turned, the surface is cut away to different depths below the surface skin, which may cause distortion.

There are, of course, other sources of error in taps, and in the threads produced by taps, due to several minor defects in workmanship in chamfering and relieving, and to conditions under which taps are used, such as improper alinement of the axis of the tap with that of the hole. These do not properly come within the scope of this paper and, therefore, require no consideration here.

(b). The Available Accuracy in Taps

Large errors in the thread elements of a tap, which are introduced either by inaccurate cutting of the thread or by distortion in hardening, can only be removed by grinding the thread, an operation which increases the cost of production. If a tap is made of a highly wear-resisting material, this

expense can be justified in ordinary commercial work, as the wearing life of a tap is considerably increased by grinding because of the more uniform distribution of wear. Taps which are available commercially fall, then, into two categories, - ordinary commercial taps and ground taps.

The improvement in accuracy in lead and angle effected by grinding is illustrated by measurements made at this Bureau of three ordinary commercial and one ground 1/2 inch, 13 threads per inch, taps, listed in Table 2. Each of the three ordinary commercial taps is by a different representative maker, and was selected at random from stock on hand. The ground tap by no means represents the highest commercially attainable accuracy, as in this instance there was an insufficient grinding allowance so that a deeper cut was taken on one side of the thread than on the other. This would unquestionably introduce lead errors.

Ordinary commercial taps can be and are produced within Class 2, Free Fit tolerances; and the fractional sizes of ground taps within Class 4, Close Fit tolerances. However, practice has not, up to this time, advanced to the point where ground taps of the numbered sizes can be economically manufactured within Class 4, Close Fit tolerances. Accordingly, as it is not practicable to undertake the production of taps for all classes of fit, taps may be graded, and tapped holes of each class of fit may be produced as follows:

Class 4, Close Fit - by the use of ground taps.

Class 3, Medium Fit - by the use of ground taps or of carefully selected ordinary commercial taps, some of which, as produced, are within Medium Fit tolerances.

Class 2, Free Fit - by the use of ordinary commercial taps.

Class 1, Loose Fit - by the use of ordinary commercial taps. Those found outside of Free Fit but within Loose Fit tolerances may be used for this purpose.

2. Recommended Lead, Angle, and Pitch Diameter Tolerances For Taps

According, then, to the relative difficulty of securing accuracy in lead, angle, and pitch diameter of a solid tap

TABLE 2. -- Measurements of Lead Errors and Angle Errors of 1/2 in.-13 Taps Produced by Different Makers

1	2	3	4	5	
Tap No.	Progresside lead error		Local lead errors	Angle error	
	per inch	per diameter			
	inch	inch	inch	Deg.	Min.
		Ground tap			
1	+0.00025	+0.00012	±0.00015	+0	17
		Ordinary commercial taps			
2	+0.0020	+0.0010	±0.0003	+0	40
3	- .0008	- .0004	± .0007	-0	50
4	+ .0017	+ .0009	± .0004	-0	35

the following distribution of the tolerance on effective size or so-called pitch diameter tolerance, to each of these thread elements is believed to be the most desirable;

Lead, - one half of the tolerance
Pitch Diameter, - one third,
Angle, - one sixth.

The zone within the tolerance on effective size which the tolerance on the pitch diameter itself, of the tap, should occupy, is the next most important consideration, inasmuch as angle error and progressive lead error in the tap decreases the effective size of the tapped hole; whereas, a given local lead error increases the pitch diameter of the tapped hold above that of the tap by a definite amount, but the resultant effective size of the tapped hole is less than its pitch diameter by an indefinite amount, as has been previously stated.

The mechanical properties of the material to be tapped also affect the diameter of the tapped hole. In a material inclined to tear, the average pitch diameter of the tapped hole produced by a tap of a given size may be greater than in a clean-cutting material; on the other hand its effective size may be less as a result of the roughness of the thread surface. Conditions of lubrication likewise affect the character of the surface and, consequently, the effective size. As the manufacturer of taps can have little or no control over the material in which, or conditions under which, a tap is to be used, the fixing of the pitch diameter tolerance zone for commercial taps must be based, in this discussion, on the assumption that taps are to be used under normal operating conditions and in a clean-cutting material.

Assuming such a basis, let:

A represent the lower limit on effective size of the tapped hole,
B represent the upper limit, and
T represent the total tolerance on effective size.

From a careful consideration of the factors involved, it is adduced that the most desirable position of the pitch diameter tolerance zone of the tap be:

From $A + \frac{1}{2}T$ to $A + \frac{5}{6}T$.

The upper limit, $A + \frac{5}{6}T$, is selected, taking into account that although the local lead errors will tend to make the effective size of the tapped hole larger, this effect will be counterbalanced by the effects of any angle error, and by the

effects of progressive lead errors which may be as large as the equivalent of $\frac{T}{2}$.

A tap made to the lower limit on pitch diameter, $A + \frac{1}{2} T$, may cut a hole whose effective size is $\frac{1}{2} T$ smaller when the maximum progressive lead error is present in the tap. It is safe to assume, however, that a tap with maximum progressive lead error will also have appreciable local lead errors increasing the effective size of the hole, and that these local lead errors will counterbalance the effects of angle errors decreasing the effective size of the hole below the minimum limit, A, when the maximum progressive lead error is present.

This distribution of tolerances then insures that, in practically all cases, the effective size of the tapped hole produced by a new tap will be within the tolerances specified, and it provides a generous margin for wear of the tap on pitch diameter. It is, therefore, recommended as being the best for all practical purposes. An exception, however, to this distribution of tolerances is necessary in the case of ground taps of the smaller sizes, since the resulting tolerances on pitch diameter are too small to be commercially practicable; whereas the tolerance on lead, as applied to progressive lead error, is larger than necessary because of the short length of engagement commonly used for such sizes. The tolerance on pitch diameter is, therefore, set at the minimum of 0.0005 inch, and the pitch diameter tolerance zone at from $A + \frac{1}{2} T$ to $A + \frac{1}{2} T + .0005$. The tolerance on thread angle is allowed to remain at the equivalent of $\frac{1}{6} T$, and the equivalent of the remainder, namely, $\frac{T - .0005 - \frac{T}{6}}{1.73205}$, is the tolerance on lead. These resulting lead tolerances are sufficiently large to cover either progressive or local lead errors. As previously mentioned, however, the manufacture of these sizes of ground taps to Class 4 Close Fit tolerances on effective size is, as yet, very difficult.

The following general formula, adopted by the National Screw Thread Commission, was used as the basis for determining the angle error equivalents of one-sixth of the respective tolerances on effective size:

$$\cot a' = \frac{h}{E'' \sin a \cos a},$$

which, for one-sixth of the tolerance on National threads reduces to:

$$\tan a' = \frac{n E''}{9}$$

in which,

h = basic thread depth
a' = 1/2 of tolerance of thread angle
n = number of threads per inch
E" = tolerance on effective size.

The numerical values corresponding to the above recommended distribution of tolerances for National Coarse and National Fine Threads are given in Tables 3, 4, 5, and 6. For purposes of comparison, the tolerances on the pitch diameters of taps and the maximum and minimum pitch diameters adopted in 1922 for commercial taps by the Tap and Die Institute,[7] together with those recommended herein and listed in Tables 3, 4, 5, and 6, are given in Tables 7 and 8, and it will be noted that the comparison is favorable. The Tap and Die Institute Standards were based on the actual measurements of several thousand taps obtained from various tap manufacturers. Also, referring to Table 2, in which measured lead and angle errors of specimen taps are given, it will be noted that the progressive lead errors are well within the recommended lead tolerances for a length of engagement of one diameter; and that the local lead errors and angle errors are also within the recommended tolerances.

3. Recommended Lead and Angle Tolerances for Chasers in Adjustable Taps and Dies

A division, similar to the above, of the tolerances on the effective size of the screw, or so-called pitch diameter tolerance, may be made to cover separately the lead, angle, and pitch diameter variations of threading dies. It is believed that the two sets of lead and angle tolerances for taps, given in Tables 3, 4, 5, and 6, should likewise be applied to die chasers, and that, as in the case of taps, these two sets are sufficient to cover all classes of fit, the larger being applied to the Loose and Free Fit classes, and the smaller to the Medium and Close Fit classes. As the diameter of the thread produced by a die is affected by factors other than the diameter of the die, it is not practicable to specify pitch diameter tolerances for the die. The die must be so adjusted that the effective size of the thread produced under given conditions, as determined by gaging, is within the tolerance specified for the class of fit for which the product is intended.

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[7] See "Commercial Standards as Adopted by the Tap and Die Institute." Address, The Tap and Die Institute, Cuyler Building, 116-120 West 32nd Street, New York City.

Table 3. - Recommended Tolerances on Commercial Taps, National Coarse Thread Series

1	2	3	4	5	6	7	8	
Sizes	Threads per inch	Basic pitch diameter	Minimum pitch diameter	Maximum pitch diameter	Tolerance on pitch diameter	Tolerance on lead*	Tolerance on angle	
		Inches	Inches	Inches	Inch	Inch	Deg.	Min. ±
1	64	0.0639	0.0639	0.0645	0.0006	0.0005	1	33
2	56	.0744	.0754	.0761	.0007	.0006	1	26
3	48	.0855	.0866	.0873	.0007	.0006	1	21
4	40	.0958	.0970	.0978	.0008	.0007	1	13
5	40	.1088	.1100	.1108	.0008	.0007	1	13
6	32	.1177	.1191	.1200	.0009	.0008	1	06
8	32	.1437	.1451	.1460	.0009	.0008	1	06
10	24	.1629	.1646	.1657	.0011	.0010	1	01
12	24	.1889	.1906	.1917	.0011	.0010	1	01
1/4	20	.2175	.2193	.2205	.0012	.0010	0	55
5/16	18	.2764	.2784	.2798	.0014	.0012	0	56
3/8	16	.3344	.3367	.3382	.0015	.0013	0	55
7/16	14	.3911	.3936	.3952	.0016	.0014	0	52
1/2	13	.4500	.4526	.4543	.0017	.0015	0	52
9/16	12	.5084	.5112	.5131	.0019	.0016	0	52
5/8	11	.5660	.5689	.5709	.0020	.0017	0	50
3/4	10	.6850	.6882	.6903	.0021	.0018	0	49
7/8	9	.8028	.8063	.8086	.0023	.0020	0	48
1	8	.9188	.9226	.9251	.0025	.0022	0	46
1 1/8	7	1.0322	1.0365	1.0393	.0028	.0025	0	45
1 1/4	7	1.1572	1.1615	1.1643	.0028	.0025	0	45
1 1/2	6	1.3917	1.3967	1.4001	.0034	.0029	0	46
1 3/4	5	1.6201	1.6259	1.6298	.0039	.0033	0	44
2	4 1/2	1.8557	1.8621	1.8663	.0042	.0037	0	44
2 1/4	4 1/2	2.1057	1.1121	2.1163	.0042	.0037	0	44
2 1/2	4	2.3376	2.3446	2.3493	.0047	.0040	0	43
2 3/4	4	2.5876	2.5946	2.5993	.0047	.0040	0	43
3	4	2.8376	2.8446	2.8493	.0047	.0040	0	43

* Between any two threads within the length of engagement. When the length of engagement is equal to one times the diameter, the permissible progressive lead errors per inch may be determined by dividing these lead tolerances by the corresponding diameters.

Table 4. - Recommended Tolerances on Commercial Taps, National Fine Thread Series

1	2	3	4	5	6	7	8	
Sizes	Threads per inch	Basic pitch diameter	Minimum pitch diameter	Maximum pitch diameter	Tolerance on pitch diameter	Tolerance on lead*	Tolerance on angle	
		Inches	Inches	Inches	Inch	Inch ±	Deg.	Min. ±
0	80	0.0519	0.0527	0.0533	0.0006	0.0005	1	44
1	72	.0640	.0649	.0655	.0006	.0005	1	39
2	64	.0759	.0769	.0775	.0006	.0005	1	33
3	56	.0874	.0884	.0891	.0007	.0006	1	26
4	48	.0985	.0996	.1003	.0007	.0006	1	21
5	44	.1102	.1113	.1121	.0008	.0007	1	17
6	40	.1218	.1230	.1238	.0008	.0007	1	13
8	36	.1460	.1473	.1481	.0008	.0007	1	09
10	32	.1697	.1711	.1720	.0009	.0008	1	06
12	28	.1928	.1944	.1954	.0010	.0009	1	06
1/4	28	.2268	.2284	.2294	.0010	.0009	1	06
5/16	24	.2854	.2871	.2882	.0011	.0010	1	01
3/8	24	.3479	.3496	.3507	.0011	.0010	1	01
7/16	20	.4050	.4068	.4080	.0012	.0010	0	55
1/2	20	.4675	.4693	.4705	.0012	.0010	0	55
9/16	18	.5264	.5284	.5298	.0014	.0012	0	56
5/8	18	.5889	.5909	.5923	.0014	.0012	0	56
3/4	16	.7094	.7117	.7132	.0015	.0013	0	55
7/8	14	.8286	.8311	.8327	.0016	.0014	0	52
1	14	.9536	.9561	.9577	.0016	.0014	0	52
1 1/8	12	1.0709	1.0737	1.0756	.0019	.0016	0	51
1 1/4	12	1.1959	1.1987	1.2006	.0019	.0016	0	51
1 1/2	12	1.4459	1.4487	1.4506	.0019	.0016	0	51
1 3/4	12	1.6959	1.6987	1.7006	.0019	.0016	0	51
2	12	1.9459	1.9487	1.9506	.0019	.0016	0	51
2 1/4	12	2.1959	2.1987	2.2006	.0019	.0016	0	51
2 1/2	12	2.4459	2.4487	2.4506	.0019	.0016	0	51
2 3/4	12	2.6959	2.6987	2.7006	.0019	.0016	0	51
3	10	2.9350	2.9382	2.9403	.0021	.0018	0	49

*Between any two threads within the length of engagement. When the length of engagement is equal to one times the diameter, the permissible progressive lead errors per inch may be determined by dividing these lead tolerances by the corresponding diameters.

Table 5. - Recommended Tolerances on Ground Taps, National Coarse Thread Series

1	2	3	4	5	6	7	8	
Sizes	Threads per inch	Basic pitch diameter	Minimum pitch diameter	Maximum pitch diameter	Tolerance on pitch diameter	Tolerance on lead*	Tolerance on angle	
		Inches	Inches	Inches	Inch	Inch ±	Deg. ±	Min.
5	40	0.1008	0 1092	0.1097	0.0005	0.00015	0	28
6	32	.1177	.1182	.1187	.0005	.0002	0	24
8	32	.1437	.1442	.1447	.0005	.0002	0	24
10	24	.1629	.1635	.1640	.0005	.0003	0	22
12	24	.1889	.1895	.1900	.0005	.0003	0	22
1/4	20	.2175	.2182	.2187	.0005	.0003	0	20
5/16	18	.2764	.2772	.2777	.0005	.0004	0	21
3/8	16	.3344	.3352	.3357	.0005	.0005	0	20
7/16	14	.3911	.3920	.3926	.0006	.0005	0	19
1/2	13	.4500	.4510	.4516	.0006	.0005	0	18
9/16	12	.5084	.5094	.5101	.0007	.0006	0	18
5/8	11	.5660	.5670	.5677	.0007	.0006	0	18
3/4	10	.6850	.6861	.6869	.0008	.0007	0	18
7/8	9	.8028	.8040	.8048	.0008	.0007	0	17
1	8	.9188	.9202	.9211	.0009	.0008	0	17
1 1/8	7	1.0322	1.0337	1.0347	.0010	.0009	0	16
1 1/4	7	1.1572	1.1587	1.1597	.0010	.0009	0	16
1 1/2	6	1.3917	1.3935	1.3947	.0012	.0010	0	17
1 3/4	5	1.6201	1.6221	1.6235	.0014	.0012	0	16
2	4 1/2	1.8557	1.8579	1.8594	.0015	.0013	0	15
2 1/4	4 1/2	2.1057	2.1079	2.1094	.0015	.0013	0	15
2 1/2	4	2.3376	2.3400	2.3516	.0016	.0014	0	15
2 3/4	4	2.5876	2.5900	2.6016	.0016	.0014	0	15
3	4	2.8376	2.8400	2.8516	.0016	.0014	0	15

*Between any two threads within the length of engagement. When the length of engagement is equal to one times the diameter, the permissible progressive lead errors per inch may be determined by dividing these lead tolerances by the corresponding diameters.

Table 6. - Recommended Tolerances on Ground Taps, National Fine Thread Series

1	2	3	4	5	6	7	8	
Sizes	Threads per inch	Basic pitch diameter	Minimum pitch diameter	Maximum pitch diameter	Tolerance on pitch diameter	Tolerance on lead*	Tolerance on angle	
		Inches	Inches	Inches	Inch	Inch ±	Deg. ±	Min.
5	44	0.1102	0.1106	0.1111	0.0005	0.0001	0	27
6	40	.1218	.1223	.1228	.0005	.0001	0	28
8	36	.1460	.1465	.1470	.0005	.0001	0	25
10	32	.1697	.1702	.1707	.0005	.0002	0	24
12	28	.1928	.1933	.1938	.0005	.0002	0	24
1/4	28	.2268	.2273	.2278	.0005	.0002	0	24
5/16	24	.2854	.2860	.2865	.0005	.0003	0	22
3/8	24	.3479	.3485	.3490	.0005	.0003	0	22
7/16	20	.4050	.4057	.4062	.0005	.0003	0	20
1/2	20	.4675	.4682	.4687	.0005	.0003	0	20
9/16	18	.5264	.5272	.5277	.0005	.0004	0	21
5/8	18	.5889	.5897	.5902	.0005	.0004	0	21
3/4	16	.7094	.7102	.7107	.0005	.0005	0	20
7/8	14	.8296	.8295	.8301	.0006	.0005	0	19
1	14	.9536	.9545	.9551	.0006	.0005	0	19
1 1/8	12	1.0709	1.0719	1.0726	.0007	.0006	0	18
1 1/4	12	1.1959	1.1969	1.1976	.0007	.0006	0	18
1 1/2	12	1.4459	1.4469	1.4476	.0007	.0006	0	18
1 3/4	12	1.6959	1.6969	1.6976	.0007	.0006	0	18
2	12	1.9459	1.9469	1.9476	.0007	.0006	0	18
2 1/4	12	2.1959	2.1969	2.1976	.0007	.0006	0	18
2 1/2	12	2.4459	2.4469	2.4476	.0007	.0006	0	18
2 3/4	12	2.6959	2.6969	2.6976	.0007	.0006	0	18
3	10	2.9350	2.9361	2.9369	.0008	.0007	0	18

*Between any two threads within the length of engagement. When the length of engagement is equal to one times the diameter, the permissible progressive lead errors per inch may be determined by dividing these lead tolerances by the corresponding diameters.

Table 7. - Comparison of Maximum and Minimum Pitch Diameters and Tolerances for Commercial Taps Given in Table 3 with Tap and Die Institute Standards, - National Coarse Thread Series

1	2	3	4	5	6	7	8
		Table 3, columns 4, 5, and 6			Tap and Die Machine screw, hand, and pulley taps		
Sizes	Threads per inch	Maximum pitch diameter	Minimum pitch diameter	Tolerance on pitch diameter	Maximum pitch diameter	Minimum pitch diameter	Tolerance on pitch diameter
		Inches	Inches	Inch	Inches	Inches	Inch
1	64	0.0645	0.0639	0.0006	0.0644	0.0634	0.0010
2	56	.0761	.0754	.0007	.0759	.0749	.0010
3	48	.0873	.0866	.0007	.0870	.0860	.0010
4	40	.0978	.0970	.0008	.0978	.0963	.0015
5	40	.1108	.1100	.0008	.1108	.1093	.0015
6	32	.1200	.1191	.0009	.1197	.1182	.0015
8	32	.1460	.1451	.0009	.1457	.1442	.0015
10	24	.1657	.1646	.0011	.1649	.1634	.0015
12	24	.1917	.1906	.0011	.1909	.1894	.0015
1/4	20	.2205	.2193	.0012	.2200	.2180	.0020
5/16	18	.2788	.2784	.0014	.2789	.2769	.0020
3/8	16	.3382	.3367	.0015	.3369	.3349	.0020
7/16	14	.3952	.3936	.0016	.3941	.3916	.0025
1/2	13	.4543	.4526	.0017	.4530	.4505	.0025
9/16	12	.5131	.5112	.0019	.5114	.5089	.0025
5/8	11	.5709	.5689	.0020	.5690	.5665	.0025
3/4	10	.6903	.6882	.0021	.6885	.6855	.0030
7/8	9	.8086	.8063	.0023	.8063	.8033	.0030
1	8	.9251	.9226	.0025	.9223	.9193	.0030
1 1/8	7	1.0393	1.0365	.0028	1.0362	1.0327	.0035
1 1/4	7	1.1643	1.1615	.0028	1.1612	1.1577	.0035
1 1/2	6	1.4001	1.3967	.0034	1.3957	1.3922	.0035
1 3/4	5	1.6298	1.6259	.0039	1.6251	1.6211	.0040
2	4 1/2	1.8663	1.8621	.0042	1.8607	1.8567	.0040
2 1/4	4 1/2	2.1163	2.1121	.0042	2.1112	2.1067	.0045
2 1/2	4	2.3493	2.3446	.0047	2.3431	2.3386	.0045
2 3/4	4	2.5993	2.5946	.0047	2.5936	2.5886	.0050
3	4	2.8493	2.8446	.0047	2.8436	2.8386	.0050*

*Specified for 3 inch, 3 1/2 threads per inch.

Table 7. - Comparison of Maximum and Minimum Pitch Diameters and Tolerances for Commercial Taps Given in Table 3 with Tap and Die Institute Standards, - National Coarse Thread Series

1	2	3	4	5	6	7	8	9	10	11
		Table 3, columns 4, 5, and 6			Tap and Die Machine screw, hand, and pulley taps			Institute Standards Nut and tapper taps		
Sizes	Threads per inch	Maximum pitch diameter	Minimum pitch diameter	Tolerance on pitch diameter	Maximum pitch diameter	Minimum pitch diameter	Tolerance on pitch diameter	Maximum pitch diameter	Minimum pitch diameter	Tolerance on pitch diameter
		Inches	Inches	Inch	Inches	Inches	Inch	Inches	Inches	Inch
1	64	0.0645	0.0639	0.0006	0.0644	0.0634	0.0010			
2	56	.0761	.0754	.0007	.0759	.0749	.0010			
3	48	.0873	.0866	.0007	.0870	.0860	.0010			
4	40	.0978	.0970	.0008	.0978	.0963	.0015			
5	40	.1108	.1100	.0008	.1108	.1093	.0015			
6	32	.1200	.1191	.0009	.1197	.1182	.0015			
8	32	.1460	.1451	.0009	.1457	.1442	.0015			
10	24	.1657	.1646	.0011	.1649	.1634	.0015			
12	24	.1917	.1906	.0011	.1909	.1894	.0015			
1/4	20	.2205	.2193	.0012	.2200	.2180	.0020	0.2215	0.2190	0.0025
5/16	18	.2788	.2784	.0014	.2789	.2769	.0020	.2804	.2779	.0025
3/8	16	.3382	.3367	.0015	.3369	.3349	.0020	.3384	.3359	.0025
7/16	14	.3952	.3936	.0016	.3941	.3916	.0025	.3956	.3926	.0030
1/2	13	.4543	.4526	.0017	.4530	.4505	.0025	.4545	.4515	.0030
9/16	12	.5131	.5112	.0019	.5114	.5089	.0025	.5134	.5104	.0030
5/8	11	.5709	.5689	.0020	.5690	.5665	.0025	.5710	.5680	.0030
3/4	10	.6903	.6882	.0021	.6885	.6855	.0030	.6905	.6870	.0035
7/8	9	.8086	.8063	.0023	.8063	.8033	.0030	.8083	.8048	.0035
1	8	.9251	.9226	.0025	.9223	.9193	.0030	.9243	.9208	.0035
1 1/8	7	1.0393	1.0365	.0028	1.0362	1.0327	.0035	1.0387	1.0347	.0040
1 1/4	7	1.1643	1.1615	.0028	1.1612	1.1577	.0035	1.1637	1.1597	.0040
1 1/2	6	1.4001	1.3967	.0034	1.3957	1.3922	.0035	1.3982	1.3942	.0040
1 3/4	5	1.6298	1.6259	.0039	1.6251	1.6211	.0040	1.6271	1.6226	.0045
2	4 1/2	1.8663	1.8621	.0042	1.8607	1.8567	.0040	1.8627	1.8582	.0045
2 1/4	4 1/2	2.1163	2.1121	.0042	2.1112	2.1067	.0045	2.1137	2.1087	.0050
2 1/2	4	2.3493	2.3446	.0047	2.3431	2.3386	.0045	2.3456	2.3406	.0050
2 3/4	4	2.5993	2.5946	.0047	2.5936	2.5886	.0050	2.5961	2.5906	.0055
3	4	2.8493	2.8446	.0047	2.8436	2.8386	.0050*	2.8461	2.8406	.0055*

*Specified for 3 inch, 3 1/2 threads per inch.

Table 8. - Comparison of Maximum and Minimum Pitch Diameters and Tolerances for Commercial Taps Given in Table 4 with Tap and Die Institute Standards, - National Fine Thread Series

1	2	3	4	5	6	7	8	9	10	11
		Table 4, columns 4,5,and 6			Tap and Die Institute Standards					
					Machine screw, hand, and pulley taps			Nut and tapper taps		
Sizes	Threads per inch	Maximum pitch diameter	Minimum pitch diameter	Tolerance on pitch diameter	Maximum pitch diameter	Minimum pitch diameter	Tolerance on pitch diameter	Maximum pitch diameter	Minimum pitch diameter	Tolerance on pitch diameter
		Inches	Inches	Inch	Inches	Inches	Inch	Inches	Inches	Inch
0	80	0.0533	0.0527	0.0006	0.0534	0.0524	0.0010			
1	72	.0655	.0649	.0006	.0655	.0645	.0010			
2	64	.0775	.0769	.0006	.0774	.0764	.0010			
3	56	.0891	.0884	.0007	.0889	.0879	.0010			
4	48	.1003	.0996	.0007	.1005	.0990	.0015			
5	44	.1121	.1113	.0008	.1122	.1107	.0015			
6	40	.1238	.1230	.0008	.1238	.1223	.0015			
8	36	.1481	.1473	.0008	.1480	.1465	.0015			
10	32	.1720	.1711	.0009	.1717	.1702	.0015			
12	28	.1954	.1944	.0010	.1948	.1933	.0015			
1/4	28	.2294	.2284	.0010	.2288	.2273	.0015	0.2298	0.2278	0.0020
5/16	24	.2882	.2871	.0011	.2874	.2859	.0015	.2884	.2864	.0020
3/8	24	.3507	.3496	.0011	.3499	.3484	.0015	.3509	.3489	.0020
7/16	20	.4080	.4068	.0012	.4075	.4055	.0020	.4985	.4060	.0025
1/2	20	.4705	.4693	.0012	.4700	.4680	.0020	.4710	.4865	.0025
9/16	18	.5298	.5284	.0014	.5289	.5269	.0020	.5304	.5279	.0025
5/8	18	.5923	.5909	.0014	.5914	.5894	.0020	.5929	.5904	.0025
3/4	16	.7132	.7117	.0015	.7124	.7099	.0025	.7139	.7109	.0030
7/8	14	.8327	.8311	.0016	.8316	.8291	.0025	.8331	.8301	.0030
1	14	.9577	.9561	.0016	.9566	.9541	.0025	.9581	.9551	.0030
1 1/8	12	1.0756	1.0737	.0019	1.0744	1.0714	.0030	1.0764	1.0729	.0035
1 1/4	12	1.2006	1.1987	.0019	1.1994	1.1964	.0030	1.2014	1.1979	.0035
1 1/2	12	1.4506	1.4487	.0019	1.4494	1.4464	.0030	1.4514	1.4479	.0035
1 3/4	12	1.7006	1.6987	.0019						
2	12	1.9506	1.9487	.0019						
2 1/4	12	2.2006	2.1987	.0019						
2 1/2	12	2.4506	2.4487	.0019						
2 3/4	12	2.7006	2.6987	.0019						
3	10	2.9403	2.9382	.0021						

V. A Practical Method of Inspecting the Thread of a Tap

Although the tap manufacturer cannot be responsible for inaccuracy in the dimensions of a tapped hole caused by the mechanical properties of the material into which the hole is tapped, or by conditions under which the tap is to be used, nevertheless there should be some standard of performance by which a tap may be judged, since defects in chamfering and relieving, as well as errors in thread dimensions of the tap, determine the dimensions of the tapped thread, and it is the latter in which the tap user is interested.

The following performance test is, therefore, proposed as the basis for agreement between the manufacturer and user of taps:

(1). For taps intended for Class 3, Medium Fit, or Class 4, Close Fit work, cast brass shall be used as the material into which the hole is to be tapped. For taps intended for Class 1, Loose Fit or Class 2, Free Fit, soft carbon steel may be used instead of brass.

(2). The thickness of the material shall be such that a through hole may be tapped, whose depth is from one to one and one-half times the diameter of the tap.

(3). The diameter of the blank hole shall be within the minor diameter limits on the nut established in the report of the National Screw Thread Commission, as determined by means of "Go" and "Not Go" plain plug gages.

(4). The hole shall be machine-tapped at a moderate speed, without lubricant when in brass, and with lard oil as a lubricant when in steel. The spindle of the machine shall be close-running and the tap shall be set to revolve concentrically.

(5). For ordinary commercial taps the tapped hole shall be inspected by means of the following gages, made to the dimensions specified. within the master gage tolerances specified for Free Fit in the report of the National Screw Thread Commission:

(a). A "Go" thread plug gage, three threads in length, whose pitch diameter is that specified in column 4 of Tables 3 or 4 herein.

(b). A "Not Go" thread plug gage whose pitch diameter is that specified in column 5 of Tables 3 or 4 herein.[8]

(c). A "Go" thread plug gage, one diameter in length, whose pitch diameter is basic; that is, the minimum pitch diameter for all tapped holes specified in the report of the National Screw Thread Commission, and given in column 3 of Tables 3 or 4 herein.

For ground taps the tapped hole shall be inspected by means of the following gages, made to the dimensions specified to within the master gage tolerances specified for Close Fit in the report of the National Screw Thread Commission:

(a). A "Go" thread plug gage, one diameter in length, whose pitch diameter is basic; that is, the minimum pitch diameter for all tapped holes specified in the report of the National Screw Thread Commission, and given in column 3 of Tables 5 or 6 herein.

(b). A "Not Go" thread plug gage whose pitch diameter is that specified in column 5 of Tables 5 or 6 herein.[8]

To pass inspection, a tap shall produce a tapped hole under the conditions specified which will pass the above gages. In addition, the lead error between any two threads of a ground tap not further apart than one times the diameter, as measured by means of a reliable lead testing device, shall not exceed the tolerance specified in column 7 of Tables 5 or 6 herein.

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[8]The figures in this column are one-sixth of the tolerance on effective size less than the maximum permissible pitch diameter of the tapped hole in the product, and this margin was intended to provide for local lead errors in the tap which would cause it to cut large. In this case, however, these same figures are chosen as the maximum limit on pitch diameter to provide some margin for variations in the cutting action of the tap in various materials and under various conditions when in actual use.

VI. Summary

The control of the accuracy of the lead of commercial threaded product within definite limits is necessary in order to secure a specified class of fit and to insure that the assembled thread shall have sufficient strength. Errors in lead are of three types, namely, uniformly progressive, local, and periodic; and each of these types of lead error is caused by certain inaccuracies in machine tools used in threading, or in self-leading threading tools such as taps and dies.

The National Screw Thread Commission has standardized tolerance specifications for screw threads in which variations of lead, angle, and pitch diameter are all included in tolerances on effective size, designated as pitch diameter tolerances. Lead error bears a definite relation to effective size, and equivalent lead errors which consume one-half of the specified tolerances for each of the four classes of fit are tabulated.

The accuracy of the lead, as well as of the other thread elements, of commercial threaded product is controlled by gaging the product and by inspecting the thread forming tools. The control of the accuracy of lead when threaded product is gaged by means of "Go" and "Not Go" thread plug and ring gages, snap gages of special form, indicating gages, and the projection comparator are discussed. Methods of inspecting thread forming tools are mentioned. The control of lead errors of taps and dies presents special problems, the most serious of which is distortion in hardening. This problem is essentially one of metallurgy, and an analysis of the problem is presented which is based on information given in the papers listed in the appended bibliography.

Taps which are available commercially may be classified, as to accuracy, as ordinary commercial taps and ground taps. Recommendations are made as to tolerances on pitch diameter, lead, and angle, for each of these classes of taps for National Coarse and Fine Threads, which provide for producing tapped holes within the tolerances on effective size for each class of fit. These recommendations are based on considerations pertaining to the effective size of the tapped hole produced by a tap in which the maximum permissible errors in each of these thread elements are present. On a similar basis, lead and angle tolerances on die chasers are recommended. There is also outlined a practical performance test of a tap, to determine whether it will produce a tapped hole, under suitable conditions, within the required tolerances on effective size.

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