United States Department of Commerce
National Institute of Standards and Technology

NIST Technical Note 1271

Thermal Effects of Handling Ball Bars

Jianying Shi, Ted Doiron, and Bruce Borchardt

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October 1989

U.S. Department of Commerce
Robert A. Mosbacher, Secretary

National Institute of Standards and Technology
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National Institute of Standards
and Technology
Technical Note 1271
Natl. Inst. Stand. Technol.
Tech. Note 1271
15 pages (Oct. 1989)
CODEN: NTNOEF

U.S. Government Printing Office
Washington: 1989

For sale by the Superintendent
of Documents
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Washington, DC 20402

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Ball bars are a primary method of testing coordinate measuring machines. The accuracy of the method depends critically on the stability of the length of the bar. This study shows the primary thermal relaxation time for ball bars to be near 15 minutes and explores the size and duration of thermal effects for two bars of different materials.

Keywords: ball bar, coordinate measuring machine, CMM, dimensional metrology, thermal effects

1. Introduction

The current techniques to substantiate the accuracy of three-dimensional coordinate measuring machines are documented in ANSI standard B89.1.12M. One option calls for the use of a ball bar system, like that shown in figure 1, to generate a very precise spherical motion for the measuring machine. The bar consists of a center rod, two end pieces with precision balls, and two magnetic sockets which have spherical bearings matched to the balls.

The rod has threaded holes in each end and usually a plastic handle in the middle to insulate the bar thermally from the operator's hand. The ball bar set has three or more center bars of different lengths. The end pieces, which have the precision balls attached, are screwed into the center bar. The magnetic sockets are mated to the balls to provide angular motion with less than 125 nanometers of runout. One socket is mounted on the CMM table, and the other in the probe holder. The magnets are strong enough that the machine can be moved by hand in any path on the spherical section allowed by the length of the bar. On computer driven machines the bar is used without one or both of the sockets. The ball is repeatedly positioned in the measurement volume and the CMM probe is used to measure positions of the free ball/balls.

Using this system the operator can generate spherical motions which are uniform in radius to better than 1 micrometer (μm). By recording the apparent positions given by the CMM the geometry errors will appear as deviations from a sphere. The accuracy of this test depends only on the repeatability of the motion of the bar in the socket, measured as the runout, and the constancy of the bar length. Since the runout depends primarily on the original manufactured geometry, it is not likely to change during the measurement. The length of the bar, however, is dependent on its temperature.

When the ball bar is assembled, some heat from the operator will transfer into the ball bar, setting up a gradient both within the bar and with respect to the measuring machine environment. As the bar cools it will change length in proportion to the temperature change. This work is an exploration of the size and duration of these effects for two geometrically similar ball bars, one made of steel and one made of invar[1].

2. Heat Transport for Ball Bars

The geometric response to temperature changes in the ball bar is given by the thermal expansion equation[2]:

$$\Delta L = \alpha_t \, \Delta T \qquad \begin{aligned} \alpha_t &= 11.5 \times 10^{-6} \text{ /°C for steel} \\ &= 1.2 \times 10^{-6} \text{ /°C for invar} \end{aligned}$$

where α_t is the thermal expansion coefficient.

Once heat is added to the bar, at the ends from the operator's hands during assembly for example, the heat has two paths. First, the heat will flow in the bar, reducing the gradient but maintaining the same average temperature. Second, the heat will be transferred to the environment via radiation, conduction and convection. Since this second transfer to the environment depends directly on the area of contact between the environment and the bar, if the heat from the end of the bar disperses quickly throughout the bar, the added exposed warm surface will increase the heat transport and bring the bar to the environmental temperature more quickly.

The heat transport inside the bar is governed by the gradient and the thermal diffusivity. The general one dimensional heat transport equation can be written as:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha_d}\frac{\partial T}{\partial t} \qquad \begin{aligned} \alpha_d &= 0.13 \times 10^{-4} \text{ m}^2\text{/s for steel} \\ &= 0.30 \times 10^{-4} \text{ m}^2\text{/s for invar.} \end{aligned}$$

This shows that for a given spatial thermal gradient, the higher the thermal diffusivity the faster the gradient will equilibrate. Thus the response of the invar will be faster than the steel by a factor of 2. Since assembling the bar causes heat transfer mainly at the ends this factor may be significant depending on the relative magnitudes of the conduction to the radiation/convection into the environment.

In summary, the relative values of the thermal expansion coefficients of the metals imply that the dimensional effects of handling the invar bar will be smaller by a factor of about 10. The differences in the thermal diffusivity imply that the thermal gradients along the bar, caused by handling the ends during assembly, should dissipate more quickly in the invar bar.

The actual heat transfer between the air and the bar is a combination of radiation and convection. Simple calculations show that both transfer channels are of the same magnitude. The use of a fan near the measuring machine is not recommended, however, since altering the thermal environment of the machine may produce changes in the CMM geometry. For small temperature differences the heat flow is proportional to the temperature difference between the bar and the air. If a small fan is used to produce forced convection the cooling rate would be expected to be considerably enhanced. This implies that the bar-air temperature difference will exhibit an exponential decay with a characteristic time τ:

$$(T_{bar}-T_{air}) = \Delta T\ e^{-t/\tau}$$

All of the data was analyzed to obtain this decay time τ.

3. Experiments

The two ball bars were tested for changes in length and temperature under two different initial conditions. Each bar had six calibrated thermistors attached in the positions shown in figure 1. The thermistors were placed on the bar, covered by a layer of insulation, and held in place by tape.

3.1 Experiment 1

The first tests were to measure the basic thermal time constant, τ, for the bar to decay to ambient temperature. Each of the bars in turn were placed in a refrigerator and cooled to near 10°C. The experiment proceeded as follows. A bar was removed from the refrigerator and placed on a stand. The stand was on the table of a coordinate measuring machine (CMM). The temperature of each of the thermistors was recorded every minute. At the same time the CMM was used to measure the overall length of the bar.

Typical measurements of both bar temperatures are shown in figure 2; they are very similar. All of the thermistors show basically the same response, except those near the center. The bar has a plastic handle in the center to carry and manipulate the bar during setup. The thermistors near the handle show that the combination of heat conduction through the handle and radiation from the operator's hand caused the center of the bar to heat up preferentially, although when the heat sources were removed the decay constant to the ambient conditions was the same as the other parts of the bar.

A semi-log plot of the same data is shown in figure 3. All of the thermistors show nearly the same relaxation time. The lines which vary the most are those closest to the handle, i.e., those which had thermal interaction with the technician setting up the test. These data are not useful for the relaxation time calculation because of the stray heat.

The thermal response of the two bars in this test was expected to be very similar. The important dimension for this test is the diameter of the bar because the air surrounds the bar on all sides. Both bars have the same diameter, less than 2 cm. The thermal diffusivity difference in the bars, which is their only significant difference, is not important because the thermal gradient across the bar diameter is too small to cause detectible differences in the response of the bars.

The characteristic time τ found for the bars is 16 minutes. Since most metrology equipment is not kept in refrigerators, a more realistic example is as follows. Suppose the bar is taken from the gage lab at 20°C, and brought out to a metrology area in the shop which is 23°C. The initial gradient between the bar and the atmosphere is 3°C. After 16 minutes the gradient will be reduced by a factor of 1/e, to 1.1°C. The temperature of the bar at different times is given in table 1.

TABLE 1

Time	Temperature
0	20
15	21.82
30	22.54
45	22.82
60	22.93
75	22.97

These temperatures would be roughly the same for the invar and steel bars. The length of the bars would be very different, however. The length of each bar was measured at the same time the temperature data were taken. The lengths of the invar and steel bars are shown in figure 4. The change in length of the steel was found to be about 10 times greater than the change in the invar bar, as expected from their thermal expansion coefficients.

Using the thermal expansion coefficients of each bar, the lengths of the bars at the given times in our example are shown in table 2.

TABLE 2

		Length (mm)	
Time	Temperature	Invar	Steel
0	20	900	900
15	21.82	900.002	900.019
30	22.54	900.003	900.026
45	22.82	900.003	900.029
60	22.93	900.003	900.030
75	22.97	900.003	900.031
equilibrium	23.00	900.003	900.031

In using a ball bar, according to the ANSI B89.1.12M standard, the absolute length is not important. What is important is that the length be constant during the measurement. According to this example, a steel ball bar must be allowed to stand in its new environment about 1 hour before it will be in equilibrium at the 1 micrometer level. For the invar bar the time is roughly 15 minutes. For larger temperature differences the times would be somewhat larger, although since the response is exponential, any reasonable difference would not be much larger than those in the example.

3.2 Experiment 2

The second experiment was to measure the thermal and dimensional response to the assembly of the bar by a technician. The bar was mounted as in experiment 1 and the data taking computer was started. The ball on one end was then removed and then replaced as it would be in actual use. The thermal response was found to vary considerably depending on the type of gloves used and the time involved in the assembly. A typical data run for the invar bar is shown in figure 5.

The six lines are the temperature responses of the six thermistors. At time=10 minutes one of the ball holders was unscrewed from the bar and replaced. The thermistors lines are in the order they were placed on the bar, with the manipulated ball the top plot. Both the thermistors nearest the joint show 1°C rises in temperature. The next thermistor from the end shows less effect, and the thermistors on the other end of the bar show negligible effects. Essentially there are two heat transfers going on, the transfer into the air via radiation and convection, and conduction down the bar. Since there are more heat paths in this experiment than in experiment 1, the thermal relaxation time is smaller.

Figure 6 shows semi-log plots of the response of thermistors on the steel and invar bars. The size of the temperature change and the details of the relaxation depend on the time the bar is handled and how the bar is held. In general, the relaxation times for both bars were between 10 and 14 minutes, slightly less than the 16 minutes found in experiment 1. This is, of course, due to the conduction of some of the heat down the bar to the undisturbed volume. When both ends are manipulated, the major part of the center of the bar is still undisturbed and forms a heat sink only slightly less efficient than when only one end is manipulated.

When the bar is assembled, inserting the balls on both ends, the largest temperature change is only about 1-2 degrees over less than 1/2 of the bar volume. Using the larger number, the average temperature of the bar rises 1°C and then returns to ambient conditions exponentially with a characteristic time of 12 minutes. Under these conditions the steel bar would expand 10 micrometers and would return to within 1 micrometer of its original size in about 30 minutes. The invar bar, with a change in temperature of 1°C expands only 1 micrometer, so no waiting period is necessary.

4. Summary

The temperature response of both invar and steel are very similar. The relaxation to ambient conditions from both small and large perturbations are nearly identical. The characteristic relaxation time for both bars under a homogeneous change in temperature was found to be about 16 minutes. When the bar is assembled, it was found that the ends can rise in temperature a few degrees, but due to the unchanged temperature of the middle of the bar the relaxation time is reduced to about 12 minutes.

The length of the invar ball bar, due to its lower thermal expansion coefficient is much less sensitive to changes in temperature. In most cases the invar bar can be assembled and used immediately. The steel bar will need 30 minutes to equilibrate in air, and somewhat less if put in contact with a thermal sink at ambient conditions. Since the bar and its ends are round, the contact area with the sink will be small and the 30 minutes will not be reduced dramatically.

When the bar is brought into a different thermal environment, both bars will take some time to equilibrate. For a 3°C change the invar bar will be within 1 micrometer of its equilibrium length in about 15 minutes. The corresponding time for the steel bar is 60 minutes.

In summary, the invar bar will be ready to use some 15 to 45 minutes faster than the steel bar, depending on the thermal changes imposed on the bar by travel and assembly. The significance of these differences in waiting times for the different bars depends on the setup and test procedures of the user.

5. References

1. The authors thank Sheffield Measurements Inc. for the loan of an invar ball-bar for these tests.

2. "The Heat Transfer Problem Solver," Staff of Research and Education Association, Research and Education Association, 1984.

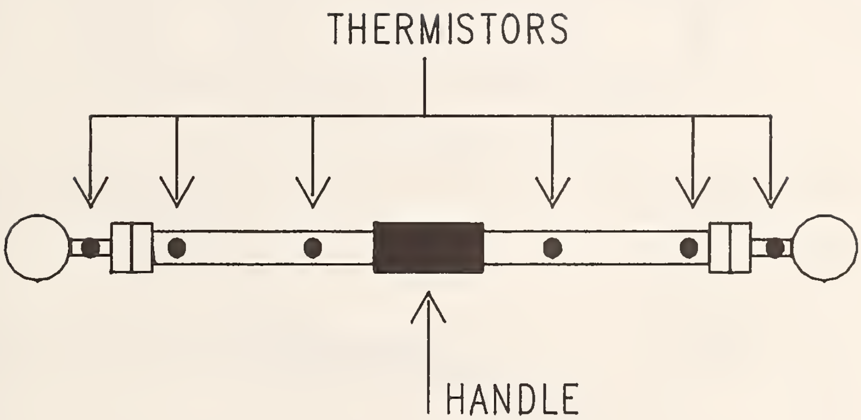

Figure 1. Ball bar with the relative positions of the six thermistors used to monitor the bar temperature.

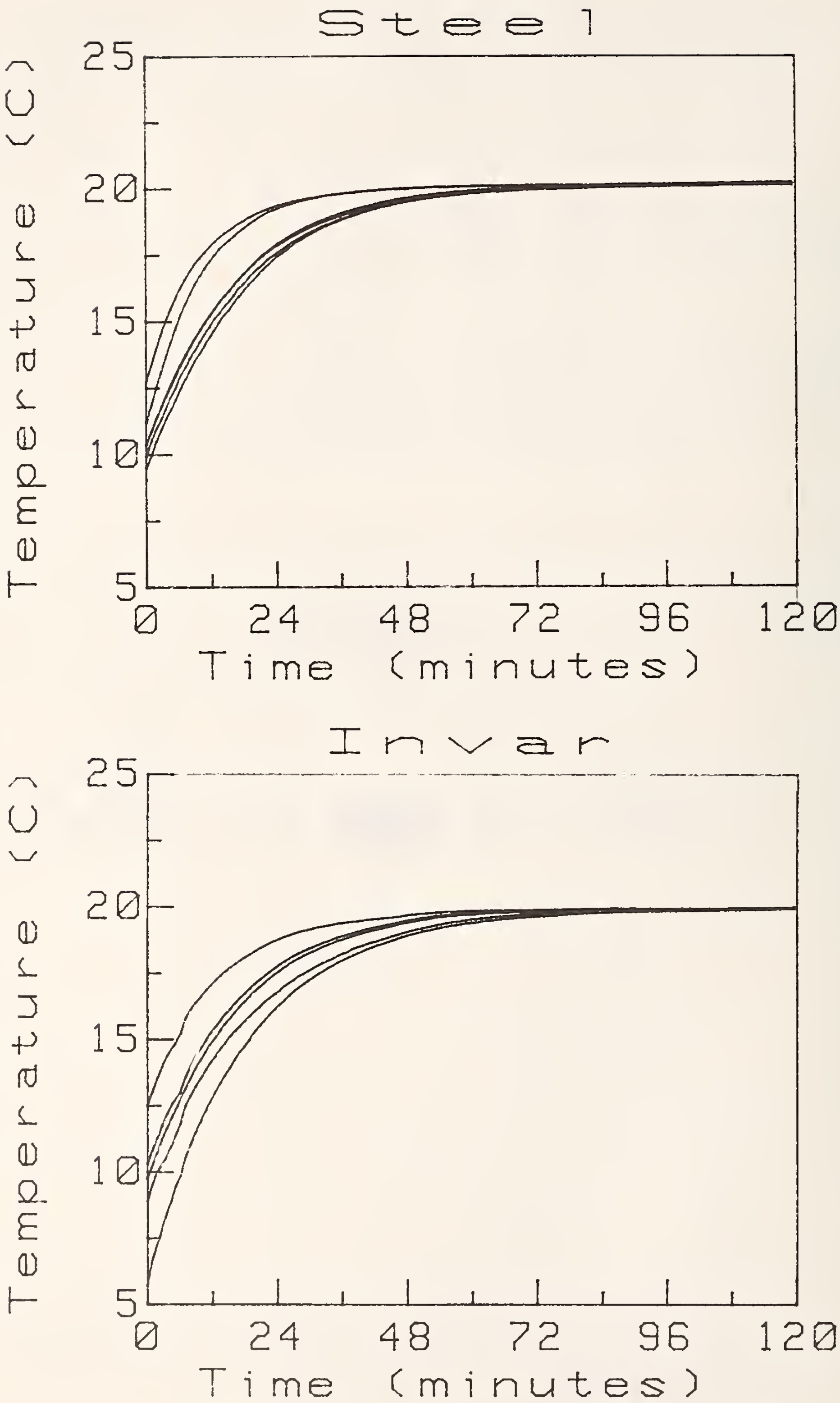

Figure 2. Response of steel and invar bar temperatures when initial temperature was 5°C.

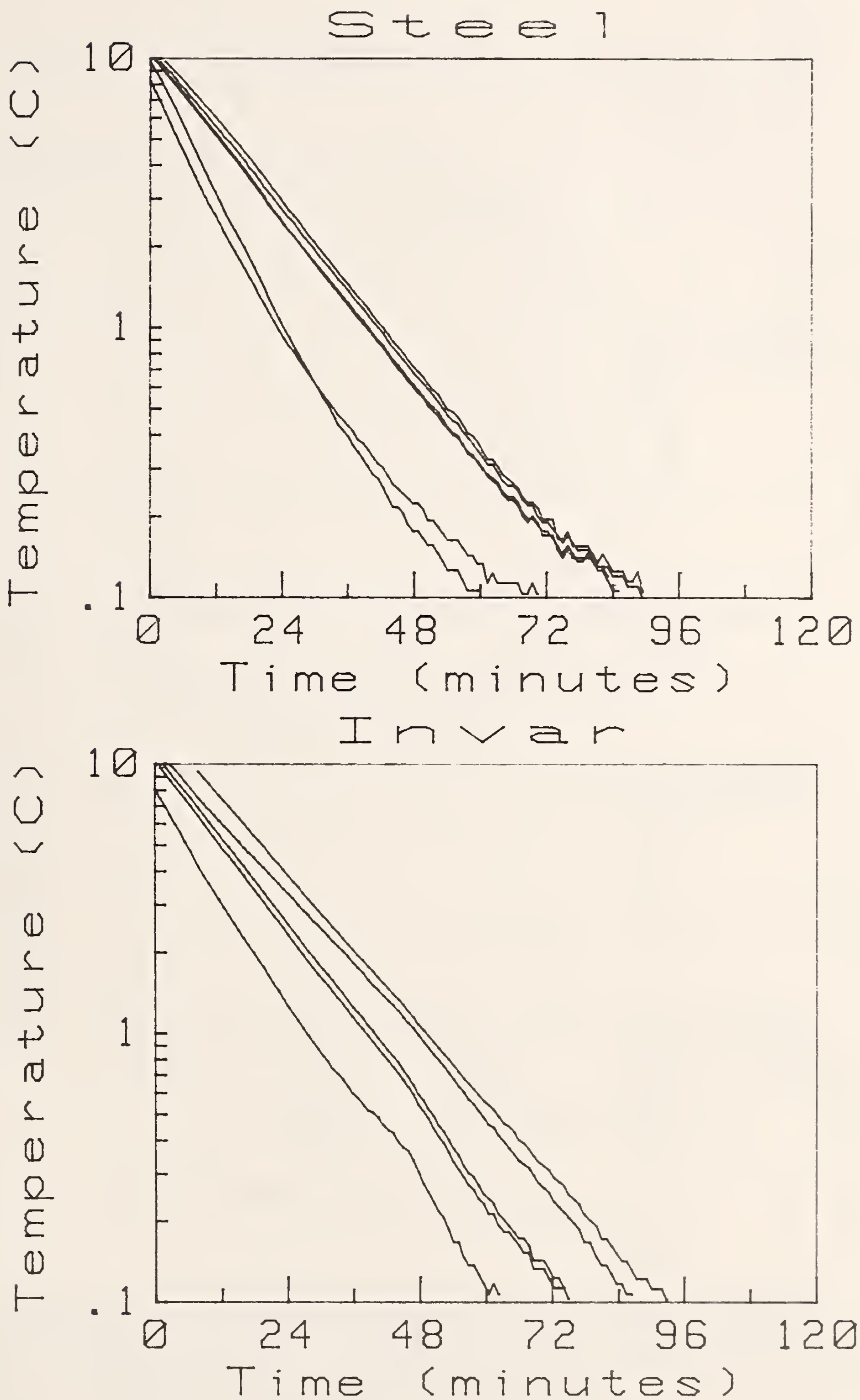

Figure 3. Semi-log plot of the data in figure 2, showing exponential decay of temperature difference between the bar and the air.

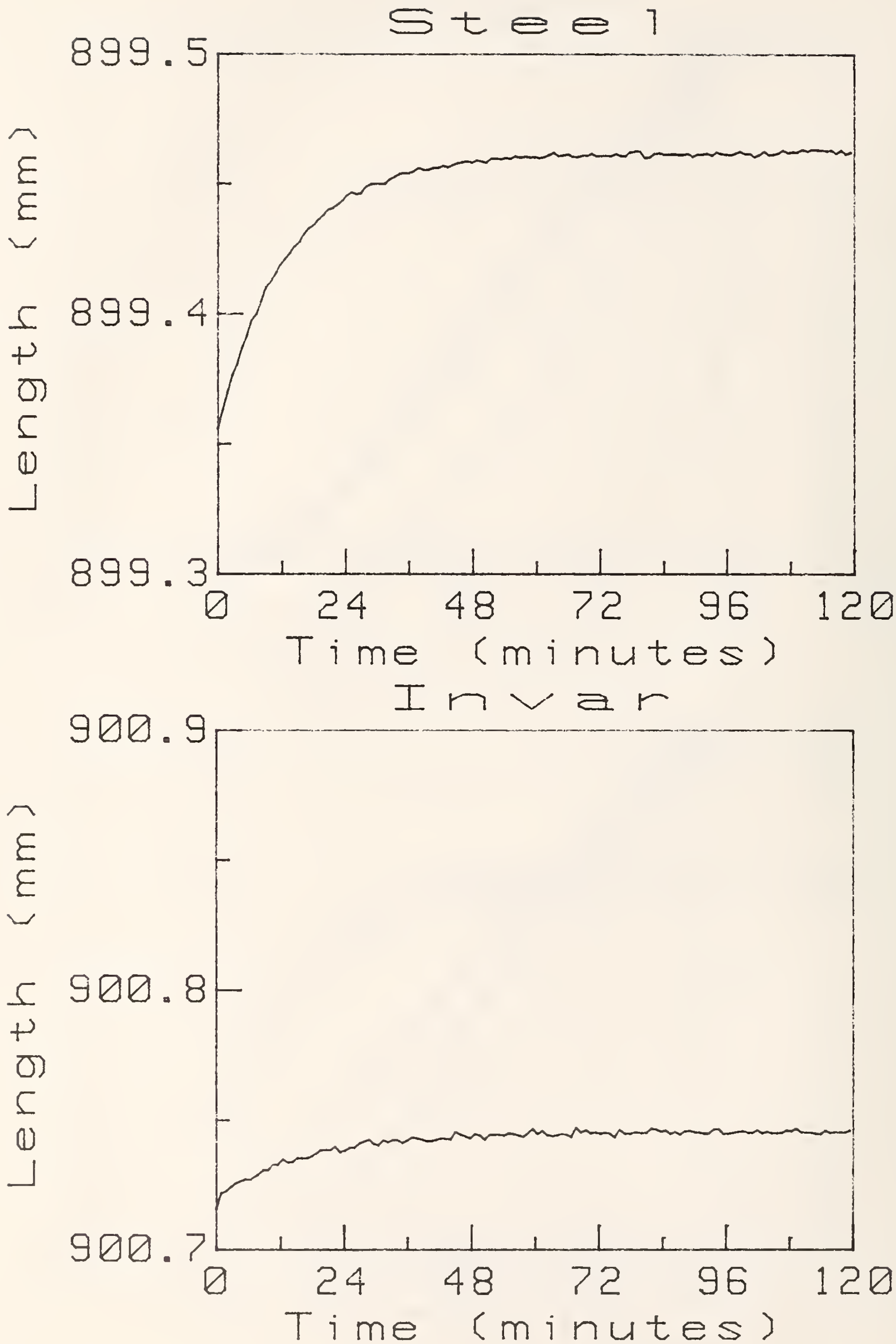

Figure 4. The length of each of the bars during the temperature changes shown in figure 2.

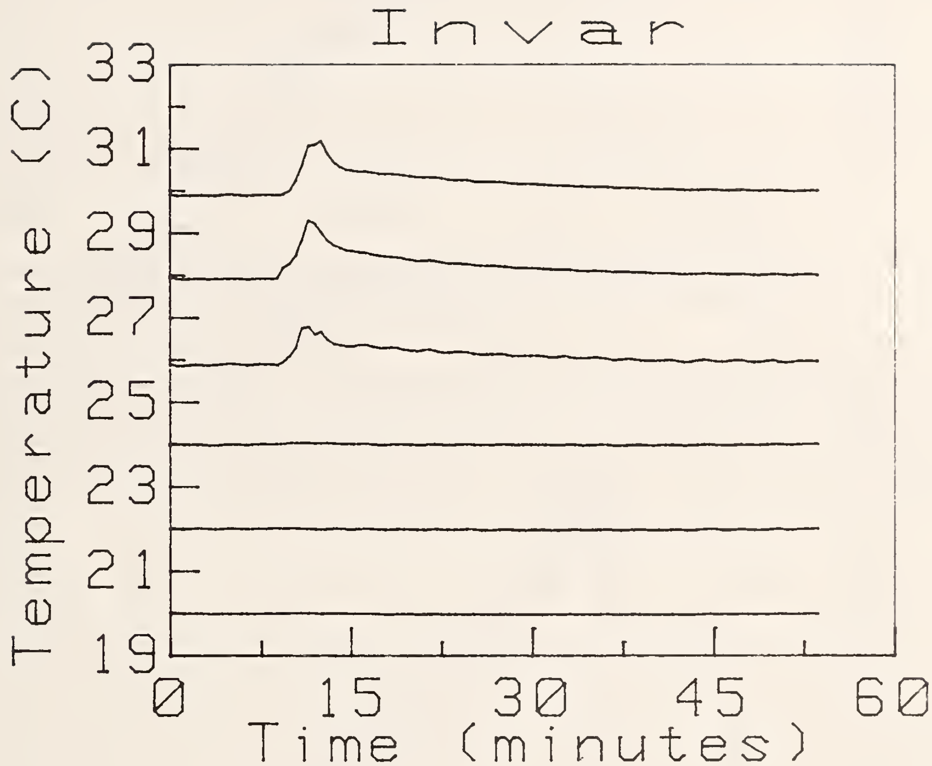

Figure 5. Temperature response of the invar bar to removing and replacing one of the balls. The top line shows the thermal response of the thermometer on the assembled end of the bar. The thermometers in the graph are in the same order as those on the bar, with the top line closest and the bottom furthest away from the handling point.

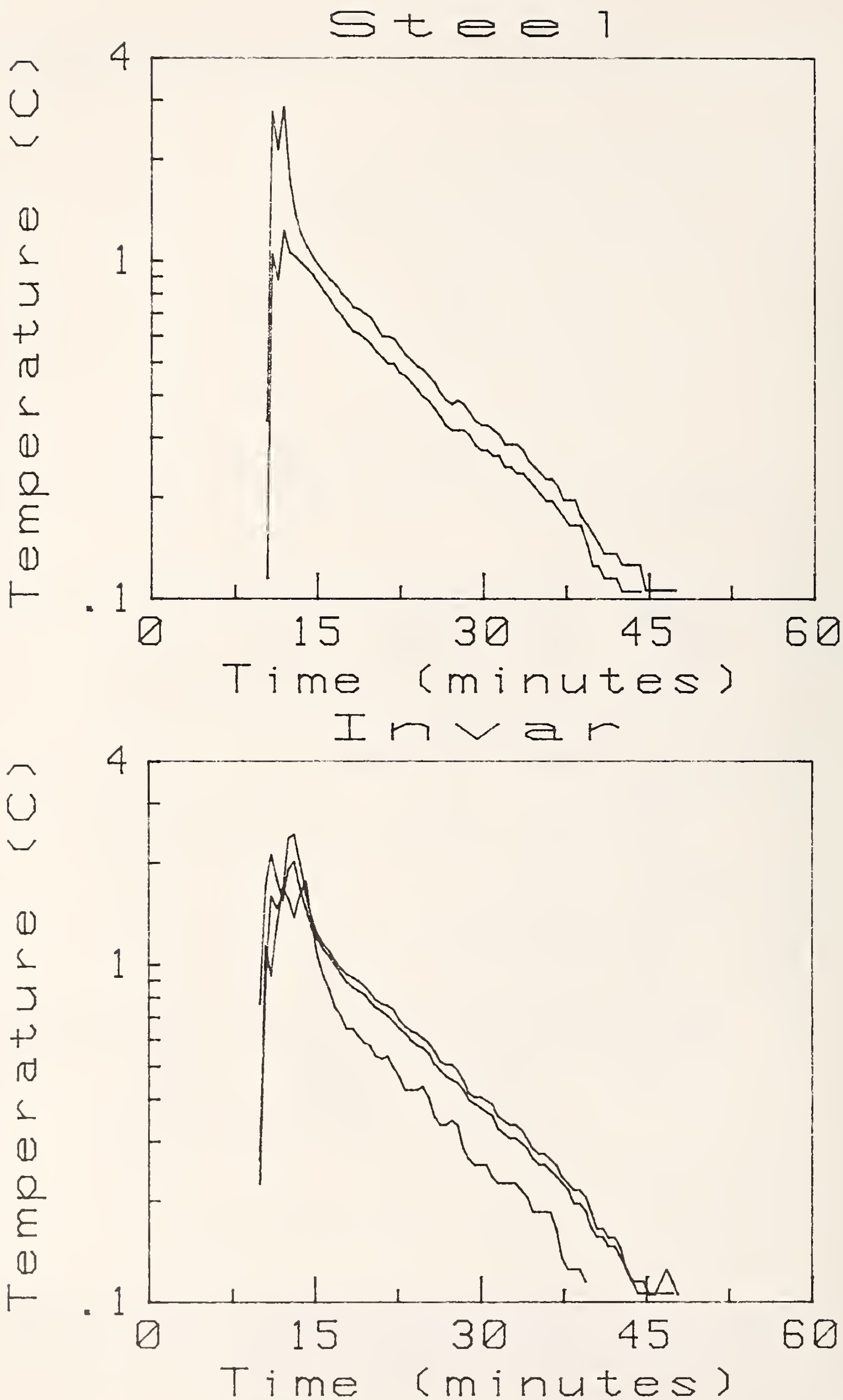

Figure 6. Semi-log plot of the thermal response of both the steel and invar bars to the heat input during hand assembly.

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** *(See instructions)*	1. PUBLICATION OR REPORT NO. NIST/TN-1271	2. Performing Organ. Report No.	3. Publication Date October 1989

4. TITLE AND SUBTITLE

Thermal Effects of Handling Ball Bars

5. AUTHOR(S)

Jianying Shi, Ted Doiron, Bruce Borchardt

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
(formerly NATIONAL BUREAU OF STANDARDS)
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Same as item # 6

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Ball bars are a primary method of testing coordinate measuring machines. The accuracy of the method depends critically on the stability of the length of the bar. This study shows the primary thermal relaxation time for ball bars to be near 15 minutes and explores the size and duration of thermal effects for two bars of different materials.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

ball bar; coordinate measuring machine; CMM; dimensional metrology; thermal effects

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14. NO. OF PRINTED PAGES

15

15. Price

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