Effects of Temperature on Gage Repeatability & Reproducibility

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Temperature Induced Dimensional Changes

Temperature causes various materials to change size at different rates, known as their Coefficients of Expansion (COE). The effects of this phenomenon on precision dimensional measurements are continuous and costly to industry. Precautions can be taken to allow parts and gages to temperature stabilize before conducting gage R & R studies, but the fact remains that on the shop floor temperatures vary all the time. The slow pace at which industry has accepted this reality probably has to do with the subtlety of these tiny size variations and our inability to sense gradual, but significant temperature changes.

Table 1 shows how much a steel part of a given dimension will change as its temperature varies from 70°F. The data shows, for example, that a four-inch steel work piece will change size by .001 inch when its temperature changes by 40°F, from 70° to 110°F (Table 1). Aluminum, another commonly used material in the metal working industry, has a COE almost twice that of steel, so that it expands and contracts nearly twice as much.

Depending on the overall dimension and the allowable tolerances, temperature can have a greater or lesser impact on the accuracy of measurements. The larger the work piece, the greater will be its size variation for a given temperature change. More significant, however, the tighter the tolerance spread or total tolerance, the more chance there is of a significant portion of that tolerance being used up by thermal errors.

The ratio of a dimension to its total tolerance may be known as its Tolerance Ratio. For example, if the 4.0000-inch work piece had a tolerance of +/-.0005" (total tolerance of .001") it would have a .25% tolerance ratio. As a rule of thumb, if the tolerance ratio for a specified part is around .05% or less, it is probable that temperature should be taken into account when measurements are made. At this level of precision, even small thermal variations cause dimensional changes which start to consume a significant portion of total tolerance.

Effects of Dimensional Changes on Gages

If, in addition to parts changing temperature between measurements, the gage should also change temperature (through handling or changes in ambient, for example), it will change size too. It is often thought that these changes will offset each other, so that the net effect will be immaterial.

As Tables 2 and 3 demonstrate, however, the net error can be considerable, particularly if the gage and the part are made of different materials. For example, an aluminum gage at 70°F, measuring a 4-inch steel part which is at 105°F, will register an error as large as .0011" (Table 2).

The temperature of the Master or Setting Standard is also a major consideration. These calibration tools are often to be found on the shop floor. But they have been meticulously manufactured to accurate dimensions at 68°F (20°C). A few degrees variance from that international standard temperature will cause this vital reference to be erroneous, so that a conventional measuring instrument that is set to zero on it will necessarily be inaccurately calibrated.

Most gages used in production today were not originally designed for the tighter tolerances required by modern manufacturing. Thermal stability and compensation were not issues when tolerance ratios were greater. Indeed, in general, modern machine tools have reached the point at which their ability to hold to highly accurate settings exceeds the capabilities of most of the gages on shop floors to measure their output. The next shop floor revolution has to be in gaging. One of the principle areas to be addressed has to do with the effects of

Table 1 - VARIATIONS FROM NOMINAL DIMENSION WITH TEMPERATURE CHANGES

70° being reference temperature

TEMPERATURE INDUCED DIMENSIONAL ERRORS: STEEL

Coefficient of Expansion: 6.4000 parts/million/°F

Nominal	30f	40f	50f	60f	70f	80f	90f	100f	110f
1.0000 inch	-0.0003	-0.0002	-0.0001	-0.0001	0.0000	0.0001	0.0001	0.0002	0.0003
2.0000 inch	-0.0005	-0.0004	-0.0003	-0.0001	0.0000	0.0001	0.0003	0.0004	0.0005
3.0000 inch	-0.0008	-0.0006	-0.0004	-0.0002	0.0000	0.0002	0.0004	0.0006	0.0008
4.0000 inch	-0.0010	-0.0008	-0.0005	-0.0003	0.0000	0.0003	0.0005	0.0008	0.0010
5.0000 inch	-0.0013	-0.0010	-0.0006	-0.0003	0.0000	0.0003	0.0006	0.0010	0.0013
6.0000 inch	-0.0015	-0.0012	-0.0008	-0.0004	0.0000	0.0004	0.0008	0.0012	0.0015

Steel - Thermally Induced Variations

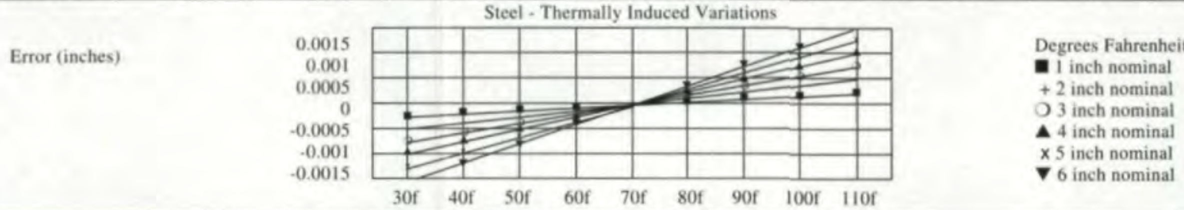


Table 2 - NET EFFECTS OF PART AND GAGE THERMAL ERRORS

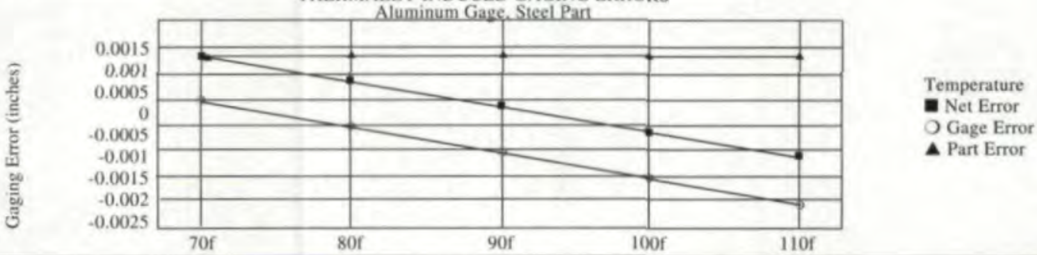
Remaining error after partial cancellation of temperature-induced errors

THERMAL ERROR AS ALUMINUM GAGE TEMPERATURE CHANGES

Steel part dimension, nominal:	4.0000 inches	Part temperature:	105°F
Part dimension at 105°F:	4.0009 inches	COE of gage:	12.4 parts/million/°F
Aluminum gage starting temp:	70°F		

	70f	80f	90f	100f	110f
GAGE ERROR	0.0000	-0.0005	-0.0010	-0.0015	-0.0020
NET ERROR	0.0009	0.0004	-0.0001	-0.0006	-0.0011

THERMALLY INDUCED GAGING ERRORS
Aluminum Gage, Steel Part



temperature on low tolerance ratios.

Effect on Gage R & R

Specifications imply, in accordance with standards such as ANSI Y14.5M-1982, that all dimensions are to be true at 68°F. To quote the Fundamental Rules, section 1.4(k) of that standard: "Unless otherwise specified, all dimensions are applicable at 20°C (68°F). Compensation may be made for measurements made at other temperatures."

Traditional gage Repeatability and Reproducibility (R & R) studies neglect to consider the effects of temperature. Standard procedures for these studies do go out of their way to specify that gage and parts must be normalized at laboratory temperature before commencing. We go to elaborate lengths to evaluate gage performance under strictly controlled conditions, but we then put the gages out on the shop floor where environmental controls are minimal at best.

Gages are continually changing in temperature during use, and even small changes can have a major effect on their R & R. Tables 4 and 5 show the effects of temperature on a gage. Two separate R & R studies were run on the same gage. Table 4 shows the results when the setting standard (master), gage, and work piece were maintained at a constant 68°F. Table 5 shows the results of conducting the same test with the gage increasing in temperature by just 5°F.

The results show that a possibly acceptable 18.5% R & R Tolerance Analysis can deteriorate to 93.8% with just a minor temperature variation. Gage thermal error has consumed the majority of the total tolerance.

Clearly, an R & R study that disregards thermal effects when a gage is to be used in an uncontrolled environment is going to be unreliable. A review of some of the key terms relating to dimensional metrology is revealing.

We probably all remember that the work "accuracy" relates to the ability to measure true size. And that "precision" refers to the fineness of a range of measurements. A precise gage will give highly repeatable, but not necessarily accurate, results. The gage may, for example, indicate a reading of 1.2345"

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TABLE 3 - THERMAL ERROR AS STEEL GAGE TEMPERATURE CHANGES

Steel part dimension, nominal:	4.0000 inches	Part temperature:	105°F
Part dimension at 105°F:	4.0009 inches	COE of gage:	6.4 parts/million/°F
Steel Gage starting temp:	70°F		

	70f	80f	90f	100f	110f
GAGE ERROR	0.0000	-0.0003	-0.0005	-0.0008	-0.0010
NET ERROR	0.0009	0.0006	0.0004	0.0001	-0.0001

THERMALLY INDUCED GAGING ERRORS
Steel Gage, Steel Part

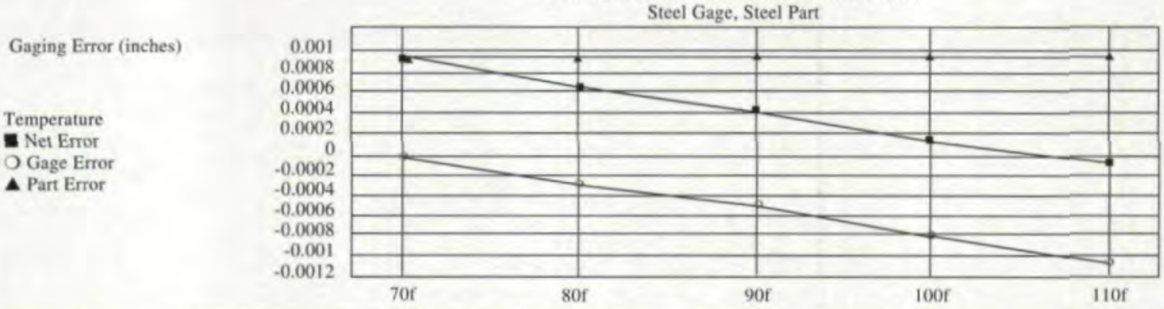

Table 4 - MASTER, GAGE, AND PART ALL AT CONSTANT 68°F (20°C)

GAGE REPEATABILITY AND REPRODUCIBILITY DATA SHEET

Operator	A			B			C		
Sample #	1st Trial	2nd Trial	Range	1st Trial	2nd Trial	Range	1st Trial	2nd Trial	Range
1	0.00025	0.00020	0.00005	0.00025	0.00020	0.00005	0.00020	0.00020	0.00000
2	0.00030	0.00025	0.00005	0.00030	0.00025	0.00005	0.00020	0.00025	0.00005
3	0.00030	0.00015	0.00015	0.00030	0.00020	0.00010	0.00020	0.00030	0.00010
4	0.00025	0.00020	0.00005	0.00025	0.00020	0.00005	0.00020	0.00020	0.00000
5	0.00025	0.00020	0.00005	0.00025	0.00020	0.00005	0.00020	0.00020	0.00000
6	0.00030	0.00025	0.00005	0.00030	0.00025	0.00005	0.00020	0.00020	0.00000
7	0.00020	0.00020	0.00000	0.00020	0.00020	0.00000	0.00020	0.00020	0.00000
8	0.00020	0.00025	0.00005	0.00020	0.00025	0.00005	0.00020	0.00020	0.00000
9	0.00025	0.00025	0.00000	0.00025	0.00025	0.00000	0.00025	0.00025	0.00000
10	0.00025	0.00020	0.00005	0.00025	0.00020	0.00005	0.00025	0.00020	0.00005
Totals	0.00255	0.00215	0.00050	0.00255	0.00220	0.00045	0.00210	0.00220	0.00020
	-->	0.00255	0.00005	-->	0.00255	0.00004	-->	0.00210	0.00002
	Sum	0.00470	$\bar{R}a$	Sum	0.00475	$\bar{R}b$	Sum	0.00430	$\bar{R}c$
	$\bar{X}a$	0.00024		$\bar{X}b$	0.00024		$\bar{X}c$	0.00022	

Sum $\bar{R}a + \bar{R}b + \bar{R}c$: 0.0001

$\bar{R}$: 0.0000

Max $\bar{X}$, Min $\bar{X}$ Diff: 0.00002

GAGE R & R REPORT SUMMARY
Gage Type: Steel Comparator
Nominal Dimension: 5.6910 inches Total Tolerance: 0.00100 inch

	Measurement Unit Anaylsis	Tolerance Analysis
Repeatability - Equipment Variation:	0.1748	17.48%
Reproducibility - Appraiser Variation:	0.0607	6.07%
Repeatability & Reproducibility:	0.1851	18.51%

ten times in ten separate measurement tests, being highly precise and repeatable, although a more accurate measurement may be 1.2300".

A precision measuring instrument without temperature compensation is inaccurate if the master, part, and gage are not all constantly at 68°F (20°C). The precision instrument will repeatedly give the same wrong answer until a temperature varies.

On-Line Temperature Compensation Is A Feasible Solution

One solution is to apply on-line thermal compensation to gages on the floor. Such systems are now readily available and in use in many industrial applications. Attempts to apply this methodology to CMMs are complicated by the three-dimensional aspects of measurements, but most shop floor gaging is concerned with relatively simple, single axis dimensions, such as outside and inside diameters. This discussion is primarily focused on such gaging.

A true temperature compensating system compensates for all three of the most probable causes of thermal distortion: namely, the effects of temperature on: 1) work piece, 2) master, and 3) gage. In some cases it may also be necessary to compensate for temperature-induced electronic drift.

There are a variety of sensors which can be used to monitor the relevant temperatures. Non-contact means for high-speed applications are limited primarily to infrared, with response times measured in hundredths of a second. However, their calibration can be tricky, and they are unreliable unless constant emissivity can be guaranteed. Many contact sensors are available, some of which have fast response times, in the order of one to five seconds, and some of which are suited to slower needs.

It is usually desirable to sense the temperature of a work piece or master rapidly. However, gages tend to change temperature at slower rates, and slower temperature sensing allows a system to ignore brief, local variations.

Table 5 - MASTER AND PART AT CONSTANT 68°F (20°C), GAGE INCREASES BETWEEN 68°F to 73°F BETWEEN 1st AND 2nd TRIAL

GAGE REPEATABILITY AND REPRODUCIBILITY DATA SHEET

Operator	A			B			C		
Sample #	1st Trial	2nd Trial	Range	1st Trial	2nd Trial	Range	1st Trial	2nd Trial	Range
1	0.00025	0.00000	0.00025	0.00025	0.00005	0.00020	0.00020	0.00000	0.00020
2	0.00030	0.00005	0.00025	0.00030	0.00005	0.00025	0.00020	0.00005	0.00015
3	0.00030	0.00005	0.00025	0.00030	0.00005	0.00025	0.00020	0.00010	0.00010
4	0.00025	0.00005	0.00020	0.00025	0.00005	0.00020	0.00020	0.00000	0.00020
5	0.00025	0.00000	0.00025	0.00025	0.00000	0.00025	0.00020	0.00000	0.00020
6	0.00030	0.00010	0.00020	0.00030	0.00010	0.00020	0.00020	0.00000	0.00020
7	0.00020	0.00000	0.00020	0.00020	0.00000	0.00020	0.00020	0.00005	0.00015
8	0.00020	0.00005	0.00015	0.00020	0.00005	0.00015	0.00020	0.00000	0.00020
9	0.00025	0.00005	0.00020	0.00025	0.00005	0.00020	0.00025	0.00005	0.00020
10	0.00025	0.00000	0.00025	0.00025	0.00000	0.00025	0.00025	0.00005	0.00020
Totals	0.00255	0.00035	0.00220	0.00255	0.00040	0.00215	0.00210	0.00030	0.00180
	-->	0.00255	0.00022	-->	0.00255	0.00022	-->	0.00210	0.00018
	Sum	0.00290	$\bar{R}_a$	Sum	0.00295	$\bar{R}_b$	Sum	0.00240	$\bar{R}_c$
	$\bar{X}_a$	0.00015		$\bar{X}_b$	0.00015		$\bar{X}_c$	0.00012	

Sum Ra + Rb + Rc: 0.0006

$\bar{R}$: 0.0002

Max $\bar{X}$, Min $\bar{X}$ Diff: 0.00003

GAGE R & R REPORT SUMMARY

Gage Type: Steel Comparator

Nominal Dimension: 5.6910 inches Total Tolerance: 0.00100 inch

	Measurement Unit Anaylsis	Tolerance Analysis
Repeatability - Equipment Variation:	0.9348	93.48%
Reproducibility - Appraiser Variation:	0.0742	7.42%
Repeatability & Reproducibility:	0.9377	93.77%

Table 6 - PISTON DIAMETERS

Nominal Dimension: 1.75000 inches

	Part at 72°F Gage at 75°F		Part at 82-88°F Gage at 75°F		Part at 77°F Gage at 86-92°F		Ranges	
Part #	No Comp	With Comp	No Comp	With Comp	No Comp	With Comp	No Comp	With Comp
1	-0.00195	-0.00210	-0.00175	-0.00200	-0.00235	-0.00200	0.00060	0.00010
2	-0.00230	-0.00235	-0.00195	-0.00240	-0.00270	-0.00245	0.00075	0.00010
3	-0.00195	-0.00195	-0.00160	-0.00200	-0.00270	-0.00195	0.00110	0.00005
4	-0.00190	-0.00195	-0.00155	-0.00195	-0.00270	-0.00200	0.00115	0.00005
5	-0.00170	-0.00170	-0.00140	-0.00170	-0.00245	-0.00180	0.00105	0.00010
6	-0.00185	-0.00190	-0.00150	-0.00185	-0.00250	-0.00195	0.00100	0.00010
7	-0.00215	-0.00215	-0.00190	-0.00215	-0.00275	-0.00225	0.00085	0.00010
8	-0.00215	-0.00220	-0.00195	-0.00225	-0.00310	-0.00225	0.00115	0.00005
9	-0.00210	-0.00210	-0.00165	-0.00200	-0.00285	-0.00205	0.00120	0.00010
10	-0.00195	-0.00195	-0.00155	-0.00190	-0.00270	-0.00190	0.00115	0.00005
Ave:	-0.00200	-0.00204	-0.00168	-0.00202	-0.00268	-0.00206	0.00100	0.00008
		-0.00200	-->	-0.00168	-->	-0.00268	Range of Ave.	
Ave. Variation:		-0.00004		-0.00034		-0.00062	Variation	0.00096

Microprocessors are used to collect the electronic signals from the sensors and the measuring probe(s) or system. An algorithm applies programmable coefficients of expansion for work piece, master, and gage to nominal dimension and the collected data, and outputs a dimension as if all these components were at a constant 68°F, regardless of their true temperature.

A setup such as this must of necessity assume that the components are all at some stable temperature. It does not matter when that temperature is (within reason), so long as each component is at some constant temperature throughout its body. It would be possible, but overly complex, to use multiple sensors to verify that this were true. In practice, however, it is unusual to find significant variations within any single component.

To illustrate the effectiveness of these systems, a study of ten aluminum pistons was performed. The results appear in Table 6. Using the same gage, with thermal compensation mode first switched off (No Comp) and then turned on (With Comp), the parts were measured while temperatures were varied. At first the gage and part were at roughly the same temperature. Then the parts were heated by about ten to fifteen degrees F. Finally, the gage was heated by approximately fifteen degrees.

The range of non-compensated errors averaged .001", while the average error range of the gage when in temperature compensating mode was less than .0001", representing a greater than ten fold improvement. Clearly, this represents a significant upgrading capability, and demonstrates the significance of considering compensation for thermal effects when specifying shop floor, close tolerance gaging.

Temperature compensation for gaging holds out the real possibility of constantly measuring under uniform conditions, without going to the extreme trouble and expense of providing environmental control. Here is a significant opportunity to substantially improve quality and save costs of scrap, downtime, and rework, that should be considered for all precision gaging and production processes.■