➤ BY DR. LAROUX K. GILLESPIE

Cool Quality

Understanding and controlling thermal effects can improve part quality.

Thermal effects have a major influence on machined part accuracy. All materials expand or contract when they are heated or cooled, which changes measured dimensions on parts. Also, expansion and contraction distort the machine tool and its positioning accuracy. Researchers note that thermal distortion can cause 40 to 70 percent of all dimensional errors on precision parts.

Minute temperature changes make a big difference in part quality. For example, an 18"-long steel gage changes 0.000002" with a change of 1⁄50° F. Taking this example a step further, a shop experiencing a 2° F change on an 18"-long steel part will experience a size change of about 0.0002". While this may only be critical on gages, more extreme temperature excursions clearly can take many parts out of tolerance. An aluminum part of the same size will be off by twice as much as the steel part because it has twice the coefficient of thermal expansion (12.8 vs. steel's 6.5 µin./in./° F). When the machine tool experiences an increase of 2° F, the part being produced can be off much more than the expansion caused by the 2° F increase because the heat distorts machine geometry and that mispositions the tool relative to the part.

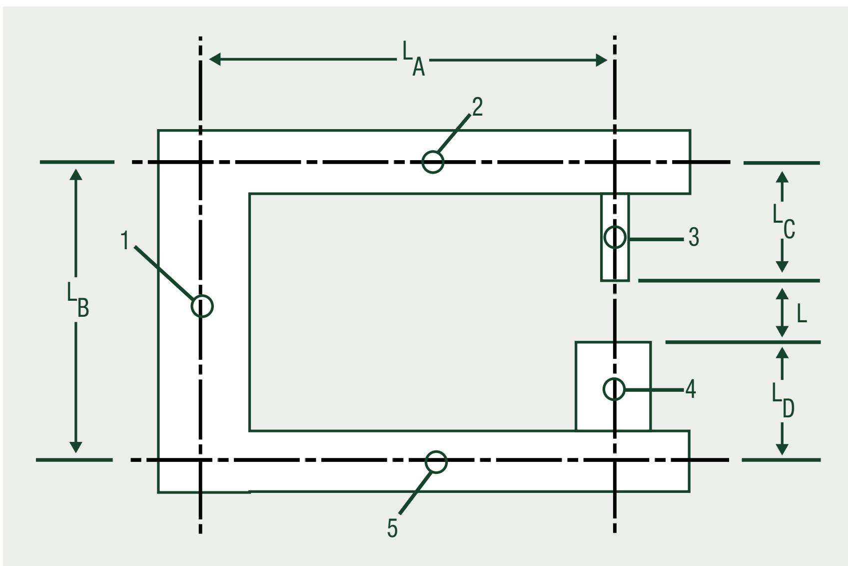
Several studies show that by using relatively simple thermal controls, many shops can increase part accuracy by 50 percent or more. For example, at the National Taiwan University, K.C. Fan and his associates compensated for temperatures on a 3-axis column mill and reduced spindle growth dimensional errors from 53µm to 18µm and errors in X- and Y-axis positions from 40µm to 20µm.

There are two key aspects of thermal control: determining a temperature standard and controlling temperature variations. Part dimension measurements should be made at a temperature that buyer and seller agree on—accurate part measurements depend on knowing part temperature, and the gage should be at the same temperature. In most instances, 68° F is the standard. The second aspect—controlling thermal effects—requires understanding, controlling or compensating for all of the following:

- machine tool temperature,
- part temperature,
- room air temperature,
- floor, ceiling and wall temperatures,
- coolant temperature,
- hot chips, and
- other heat sources in the room, including other machine tools, pumps, windows and personnel.

Thermal control includes steady state control, controlling time-related temperature changes (e.g., day to night) and controlling variations within the room (e.g., temperatures near the ceiling are higher than temperatures near the floor; temperatures near a window can be higher or lower, depending on the season, than on the opposite wall).

Current temperature control research is focused on providing better controls for machine tools to accommodate thermal changes, more targeted coolant delivery and the means to surround machines with stable temperature envelopes.



University of Manchester (England) Institute of Science and Technology

Figure 1: C-frame machine and temperature sensors.

Machine Tool Temperatures

Fan's research has shown that by simply compensating for machine tool temperatures (without controlling them), part accuracy can be improved more than 50 percent. The study measured results on a 3-axis machine and is basically in agreement with several other measurement studies of thermal effects. The key is to measure temperatures at critical areas of the machine and then measure the accuracy of the machine at those temperatures using probes and laser interferometers. Then, by running the machine, which increases temperatures in the machine's materials over time, and repeating the temperature and positioning measurements, the user or machine tool builder can determine how any temperature change affects part accuracy.

Using this data, equations can be developed for predicting required positioning corrections. These equations are then added to the machine tool control or fed directly to machine offsets. The net result is machine positioning that compensates or corrects for thermal effects.

Actual distortion of machine tools as a function of temperature is a rather complicated topic, but developing compensating equations is relatively simple. Figure 1 shows a side view of a typical C-frame machine that has five temperature sensors. As temperatures increase at sensor No. 1, the back of the machine will move up, in direction L_B. The same temperature change at sensor No. 2 will cause that arm to move right in direction L_A. An increase at sensor No. 3 in the spindle will cause the spindle to move down in direction L_C, and the arm carrying sensor No. 5 will move right in direction L_A. An increase at sensor No. 4 will cause the vertical base to move up in direction L_D. For a variety of reasons, temperatures measured simultaneously by each sensor will vary and will also change in different proportions over time. Once the temperature measurements are taken, a computer will make easy work of the many calculations needed so the machine tool can compensate for the temperature changes. A stand-alone computer is used to make the initial statistical analysis; then equations and sensor readings or actual X, Y and Z adjustments can be input to the machine controller.

Positioning changes (Figure 2) can occur on a machine tool due to table motion, according to a study performed by National Taiwan University researchers and reported at a conference in Manchester, England. At startup, the X-axis grew and continued to grow until the machine was stopped after 300 minutes (5 hours) of operation. The movement stopped at that point and, as the machine began to cool down, the X-axis slide position began to shrink until it leveled out after 430 minutes. The same general pattern occurred for the X-axis motor, the X-axis ballscrew nut and the Y-axis slide.

Even after 5 hours of constant workload, the machine never reached steady state temperatures (Figure 3). By adding thermal compensation equations calculated from the measurement study

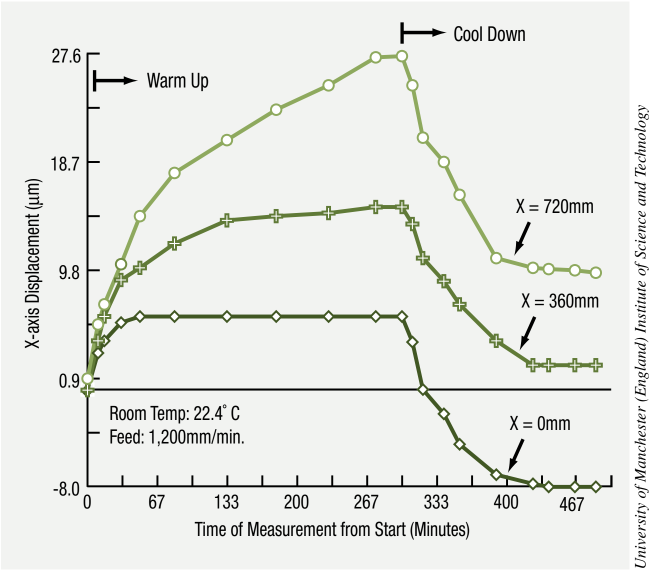


Figure 2: X-axis displacement due to table motion.

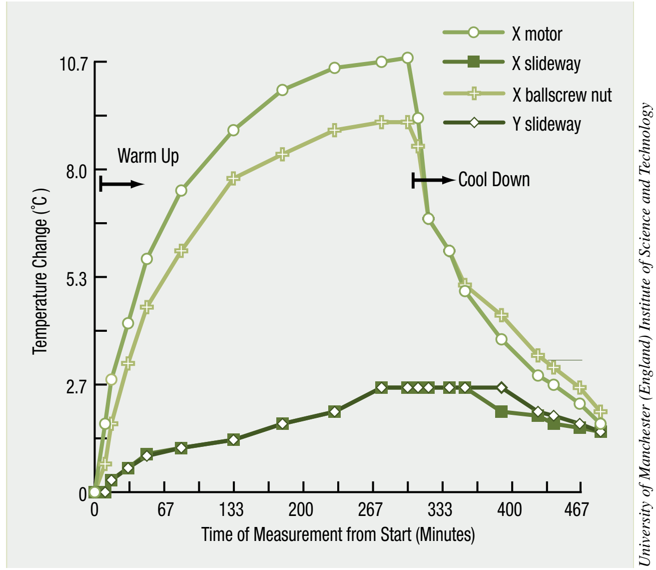


Figure 3: Temperature change due to table motion.

to positioning commands in the controller, the average thermal effects on parts being produced on the machine were eliminated, leaving only variation due to the machine itself. The FANUC 0MA controller took NC commands in block-by-block sequence. Machine tool builders can include these types of compensation as part of their control strategies, and users can do the same on older machine tools.

Critical machine tool areas where temperatures must be monitored include spindles and spindle housings, tables, saddles, main spindle slideways, ballscrew nuts, motors and bearings. Sensors on columns and cross-arms can also be useful, but some researchers have found them to be less critical. Research by C. Brecher of Aachen (Germany) University's Laboratory for Machine Tool and Production Engineering has shown that if sensors are placed where heat is generated and results are measured, positioning errors from thermal effects can be predicted almost as well as from placing sensors throughout the machine structure. Beyond that, motor current and spindle speed can be used as primary indicators of heat because changes in these programmed conditions directly generate heat. Entering readings from temperature sensors into a machine tool's controller makes it possible to adjust for thermal effects in near real time.

Another temperature control approach is preventing heat from reaching key areas of the machine. In one study, Noriyuki Koreta and his associates at Sojo University (Japan) performed a study on "Control of Thermal Deformation of Machine Tool Structure Due to Room Temperature's Change by Use of Thermal Insulating Balancing Boards" (published by the Journal of Japan Society for Precision Engineering). The researchers modified a bridge-style machine tool by adding insulating boards to the back of a column and the cross-ways to prevent thermal imbalances. Those changes improved machine perpendicularity by a factor of three. The vertical column that held the spindle would tilt forward as temperatures rose and tilt backwards when they fell, which meant it was no longer perpendicular to the workpiece on the table. The insulating boards on the back of the vertical column reduced the temperatures being felt by the column and cross-saddle, which held the spindle.

Manufacturers are also redesigning machines and using different materials to make machine tools less sensitive to heat flow and temperature changes. The materials listed in Table 1 can greatly reduce thermal growth and increase the ability to dissipate heat. Designers are attempting to balance geometry and machine materials to reduce distortion and minimize growth.

For example, by controlling the temperature of the spindle bearing oil as it leaves the spindle to within ±1.0° C, and the temperature of the pressurized oil in the inlet tank holding the spindle oil to within ±0.01° C, many thermal effects can be prevented. The consensus view of several studies is that spindle heat is a major issue in accuracy and that it is possible to hold these close temperatures in spindles. Data by Fan and his associates demonstrates that under minimal loads, spindle temperatures can rise 10° C, causing Z-axis errors of over 0.001". The heat generated also distorts the machine in either the X or Y direction, depending upon machine design.

In another study, Jim Bryan and his associates at Lawrence Livermore

Table 1: Thermal factors for materials used in machine tools.

Thermal Factor	Material					
	Carbon steel	Cast iron	Alumina-ceramics (97%*)	Alumina-ceramics (87%*)	Ferrite-resin concrete	Cement concrete
Coef. Thermal Expansion ($\times 10^{-6}$)/° K	12	11.5	4.5	4.2	13	11
Thermal Conductivity [W/(m × ° K)]	53.5	52.5	25.6	16.3	2.8	1.0
Thermal Diffusivity (^{m}/s)	147	163	75	54	-	5.4

* Percentage of alumina contents. Source: Springer-Verlag

National Laboratory noted that by forcing 160 liters per minute of bearing oil through the spaces in tapered roller bearings on a 500mm Monarch lathe and a 750mm LeBlond lathe, axial growth was reduced from 100 microns to 2.5 microns and thermal equilibrium was reached in 1 minute rather than the typical 5 hours. At least one machine tool builder, Enshu (USA) Corp., Schaumburg, Ill., currently cools axis ballscrews to prevent screw elongation.

Approaches for on-machine improvements that can be made by the builder or the user include controlling spindle bearing input oil temperatures more accurately, adding an oil- or water-cooled shell to the spindle just for cooling, reducing friction in the bearings, adding a thermal shroud to keep motor heat from the structure, adding cooling jackets for motors, accelerating air flow over any part of the machine that gets hot, isolating hydraulic units from the machine, quickly removing hot chips, cooling lead screws and ballnuts, installing heat pipes in the machine structure to carry away heat and precision cooling of other hydraulic oils. Developing more capable computer models for machine tool distortion may help to further improve accuracy.

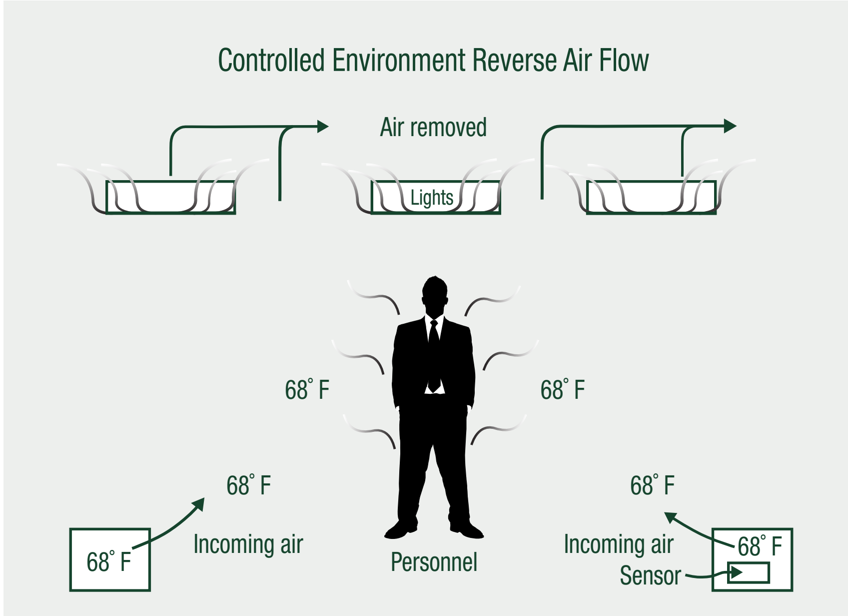
Massachusetts Institute of Technology researchers John H. Lienhard and Alex Slocum are also investigating the use of water as a spindle bearing coolant rather than more viscous spindle oils. Water lowers rotational friction and has a heat capacity 2.5 times greater than many oils. Using water and special pockets to reduce friction in the spindle bearings, Lienhard and Slocum reduced temperature increases to less than 3° C when their spindles were run at 10,000 rpm.

Controlling Part Temperatures

Precision parts are normally "soaked" in air at the desired temperature for several hours to reduce errors that occur when machining causes a part to become hot and later cool (return to room temperature). To save time, some users place parts that have not cooled to the desired temperature in a liquid bath (typically oil) that forces a constant-temperature liquid over the part.

Several years ago, A. Cooper and others from The Timken Co., Canton, Ohio, reduced cooling time from 6 hours to 2 minutes for a large roller bearing cup by using a temperature-controlled liquid, as reported in a 1990 CIRP paper by Jim Bryan. High-velocity (2,000 ft./min.) compressed air will also cool a part, but for the part just mentioned, forced air took 25 minutes to reach the same level of stability. There are also heat exchangers available that help maintain coolant temperatures.

Handbook values of thermal coefficients of expansion are averages for that material. Researchers note that actual coefficients are affected by slight changes in the alloying elements, heat treatment and amount of cold work (the internal deformation of crystal and grain structures) produced when a steel mill rolls the metal to size. This means that published values may be off by as much as 20 percent on some materials. One researcher notes that the expansion of steel may vary from 10.5 to 13.5 µin/in./° F, depending upon the hardness and composition (J. Bryan, 1990). When machines, tools or parts have several materials that come from different lots, it is difficult to predict actual changes.



Moore Special Tool

Figure 4: Controlled environment reverse air flow.

There are several systems that can help control part temperatures. For example, Renishaw plc, Gloucestershire, U.K., a measurement systems builder, was asked by a manufacturer to solve the problem of a large aluminum aerospace component that expanded 0.1" or more in the time it took to manufacture it. Renishaw provided a laser scale thermal compensation feedback system. This system calculates coefficients of thermal expansion that accommodate unusual part shapes and materials whose expansion is not consistent from part to part and not consistent in X, Y and Z directions. The system provided the ability to make thermal corrections to large and unusually shaped parts.

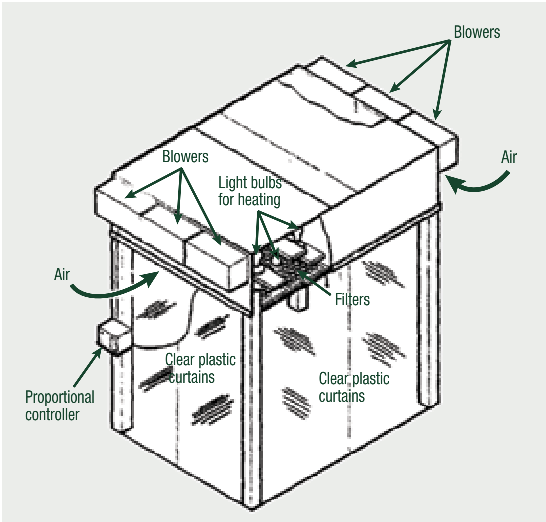
Controlling Room Temperatures

Temperature variations in a machine room can also affect part quality, with hotter temperatures typically found at the ceiling. Even in well-controlled machine rooms, vertical stratification can produce variations of ±2° F. Machine tools, which bend as temperatures increase, will experience variations in this environment. The most efficient room temperature systems introduce 68° F air at floor level and evacuate hot air from the room and lighting fixtures at the ceiling (Figure 4). This reduces stratification effects in normally ventilated rooms by 80 percent and keeps the entire room close to the 68° F target. Gage measuring rooms designed in this manner have been able to maintain ±¼° F.

Because they conduct heat, machine room floors are also a factor. In addition, metrology lab personnel note that even in a room 6' underground, walls change temperature during the day, which affects room temperature.

Some of the most precisely controlled machine rooms maintain air temperatures at ±¼° F. This requires costly design and build considerations, including using false floors and even multiple layers of water-cooled floors. With multiple heat-generating machines, production sites that maintain room temperatures of ±1° F also require expensive systems.

Many shops today use a lower-cost “boxed” approach—building a flexible wall or box around the machine so only the air space around the machine must be controlled. In one application, Lawrence Livermore National Laboratory (LLNL) built an enclosure around a lathe using clear plastic curtains and an overhead enclosure. The overhead unit included a number of 100w light bulbs with a set of blowers at each end (Figure 5). Shop air, which was held to ±2° F, was drawn in above the unit and passed over the light bulbs. In this arrangement, 68° F air, ±2°, was drawn over the warm light bulbs, producing an air temperature of 70° F, ±0.3°. The air temperature prior to passing over the light bulbs was always slightly above the desired 68° F, but it was constant. In 1983, the enclosure cost $5,000. A more elaborate plastic wall enclosure was later built that used the enclosed air rather than shop air and it was able to maintain an air temperature of 68° F, ±0.08°. In another study, Jeff Roblee of Precitech Inc., Keene, N.H., reported being able to control air temperatures in the LLNL enclosure to ±0.004° F for days at a time. The most precise machine tools, used to make glass or metal mirrors, cut to tolerances of 0.000003" and must impart on the mirrors surface finishes that approach 0.1µin. R_a. These machines often use an oil shower rather than air to remove heat and maintain uniform temperatures. The operator just installs parts and removes them. The oil shower has a heat transfer coefficient several hundred times that of air. Oil temperatures can be controlled to within ±0.01° F.



Proceedings of the SPIE

Figure 5: Plastic wall enclosure for thermal control.

Minimizing Heat Sources

Windows and doors are significant heat sources in a shop, and the amount of heat they let in varies throughout the day. Simply blacking out windows that shine directly on machine tools can reduce temperatures on machines by several degrees and eliminate a significant part of the daily heat cycle. Locating machines away from radiators and ventilators can also reduce temperature variations.

Movement of people can produce large thermal changes in a shop. An operator standing in front of a machine adds heat. This may not be a significant factor on high horsepower machines, but people are not typically allowed near low horsepower machines that must cut to tolerances of 0.000001" because people add too much heat to the work envelope and affect thermal stability in uncontrolled ways.

One of the least costly thermal control strategies involves coolant. Flooding the table and cutting area with coolant that never changes temperature will keep machine beds, fixtures and parts at one temperature. Effective flooding will also wash away hot chips that hold 80 percent of cutting energy in the form of heat. Coolant can typically be controlled to ±0.01° F using specially designed heat exchangers just as oil showers can.

Table 2: Identifying sources of thermal error and improvement solutions.

Heat Source	Error allowed for this application	Error estimated to be contributed by this source	Change required	Approach to reduce impact by change amount
Spindle				
Ballscrew nuts				
X-axis motor				
Y-axis motor				
Z-axis motor				
Bearings				
Coolant				
Window				
Overhead vent				
Hot chips				
Room lights				
Personnel				

Temperature Control Strategies

Thermal improvement strategies require consideration of all key issues. Not all of the items must be controlled, but all should be evaluated before allocating resources. Preparing an error budget table, such as the one shown in Table 2, defines the amount of error produced by each source, the amount of error that can be tolerated and how much improvement is needed. Filling out the table helps define areas that must be controlled. Computing a heat load (Table 3) also helps define the most important thermal control areas.

Shops can determine the amount of error caused by thermal effects by using laser interferometers or probes to check positioning accuracy over time at various workloads. For most shops, the lowest cost improvement strategy is to reduce heat coming to the machine from windows, doors, HVAC vents and nearby machines. Soaking large parts in temperature-controlled solutions provides a low-cost method of bringing parts to the temperature they should be at when machining starts. Using large volumes of temperature-controlled coolant on the machine is another effective strategy.

Boxing a machine in a space with temperature-controlled air lowers machine accessibility and can be costly, but it can provide a steady-state operating environment. Modifying spindles to reduce the heat they generate or pass on to the machine requires working with suppliers. Making thermal compensations to machine positioning requires a one-time cost and minimal changes to equipment. Shop owners, however, must determine if the machine manufacturer has already incorporated solutions that account for the temperature changes. If not, users need to research how to control the changes because part accuracy depends on it. △

About the Author

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Table 3: Heat load table example for machining area.

Source	Load Type	Winter			Summer		
		Latent Heat	Non Latent	Total (Btu/hr)	Latent Heat	Non Latent	Total (Btu/hr)
Conduction through south wall	DN	0	-15,092	-15,092	0	14,063	14,063
Conduction through roof	DN	0	-31,040	-31,040	0	69,134	69,134
Conduction through floor	S	0	0	0	0	0	0
From personnel	DN	6,132	3,000	9,132	6,132	3,000	9,132
Air handler	S	0	19,100	19,100	0	19,100	19,100
Infiltration	S	0	-10,780	-10,780	0	0	0
Makeup air	V	0	-332,640	-332,640	0	279,720	279,720
Lighting	S	0	28,700	28,700	0	28,700	28,700
Machine tools	V	0	12,804	12,804	0	12,804	12,804
	S	0	59,633	59,633	0	59,633	59,633
Other		0					
Total		6,132	-266,315	-260,183	6,132	486,154	492,286

DN = day/night load S = steady load V = variable thermal load Source: Proceedings of the SPIE