Dimensional measuring of parts as function of temperature variation and FEM study

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Abstract. The components of a structure can be made in many different areas by many suppliers, before being brought together as a single final. Measuring geometry and geometric dimensions of a structure is an essential process in establishing product quality. Dimensional measurement is often affected by several human or physical factors, of which temperature is an essential factor in introducing deviations. Often the expected results are out of specification due to temperature variation. Paper aims to present the effects due to temperature variations in dimensional measurement as well as way to solve problems. One of the problems in the measurement process is the lack of repeatability in measuring tolerated dimensions. The study presents measurements in the conditions of volumetric thermal expansion of AMCs and measured parts, which are directly influenced by temperature. The need to verify the accuracy of measurements and control of equipment is an important step for quality departments in this industry because the quality of production is based on the target of "zero defects" so the need to know about the condition of equipment is extremely important. In specific cases in addition to the normal calibration which is according to international standard ISO 10360-2: 2009 as a mandatory application, the same standard determines the need to perform re-verification tests according to user specifications, looking for deviations that should not occur in systematic errors. Also, the international standard ISO 17025: 2005 which defines the general requirements for testing and calibration components of laboratories, in point 5.5.10 of the technical requirements it is said that intermediate checks are necessary to maintain confidence in the calibration status of equipment, these checks having to be done according to a specific procedure. Three techniques for assessing measurement uncertainty are presented in ISO 15530-; they can be used alone or in combinations. The first of these is known as sensitivity analysis and is described in the ISO Guide for Expressing Uncertainty in Measurement. Modeling and simulation can help evaluate the size of a part as a function of temperature. The article presents in the second part this method which offers values very close to the experimental ones and which may in the future simulate the values of the measurements where the experimental part is difficult to be done.

1. Introduction

Currently there are three techniques for assessing measurement uncertainty are presented in ISO 15530-; they can be used alone or in combinations. The first of these is known as sensitivity analysis and is described in the ISO Guide for Expressing Uncertainty in Measurement. Modeling and simulation can help evaluate the size of a part as a function of temperature. The article presents in the second part this method which offers values very close to the experimental ones and which may in the future simulate the values of the measurements where the experimental part is difficult to be done.
interactions of uncertainty; it is considered rigorous and defensive, although it can be expensive because it is based on the existence of an artifact, the availability of a more capable measurement system and the ability to meet similar conditions. The third technique is to use Monte Carlo-based simulation, known as Uncertainty Assessment Software (UES), and may be the only viable option when there are many measurements to be evaluated and predictions are needed; such as if someone wants to plan the consistency of measurements in a variety throughout the life cycle of the product. The simulation is unlikely to adequately cover all sources of uncertainty, so it is advisable to use it in combination with other techniques. The relative merits of these three techniques are discussed in Baldwin et al, which referred to a previous draft of ISO 15530-1, which mentions that two additional options are discussed - the history of measurements and the judgment of experts. These techniques seem to have been de-emphasized in the latest release, however they may have an important place in a context where historical records and expert opinions could be systematically captured and used. In addition, future revisions are expected to extend the use of the Bayesian approach, supporting the idea of using more uncertainty assessment techniques, as long as they improve the current state of knowledge.

2. Strategies in the field of part measuring

Three working strategies are presented for part measurements. These are briefly presented below.

2.1 Expert strategy

A small number of knowledge-based systems have been designed, which try to capture the knowledge of experts. This may include knowledge of the manufacturing process. However, given the large number of variables involved, doubts have been raised as to whether the information captured may be sufficient.

2.2 Adaptive strategy

The trend is towards strategies that adapt to real geometry. Innovative methods that dynamically change strategy, using previous measurements to determine the choice of the next point, are promising. However there are unresolved technical difficulties, for example in avoiding collisions. A related adaptive approach is to study the manufacturing process and characterize its "signature". The signature is used to develop a model of the actual feature that was produced. The measurement strategies are then designed based on this model of the real characteristic.

2.3 Digital metrology

It provides the opportunity to inject the structure into the task of the metrologist, integrating tools that allow testing strategies for evaluating applications on digital models. If a feature can be synthesized from a detailed measurement, different strategies can be tested depending on the model to determine which of them reaches a target level of uncertainty for the lowest cost (for example, by taking a small number of points).

3. The influence of temperature in the measurement process

Thermal expansion is the physical phenomenon by which the dimensions (volume, surface, length) of a body increase as a result of temperature variation. The opposite phenomenon is called thermal contraction [1]. For most substances, increasing the temperature leads to an increase in size, but there are exceptions. If a bar with length $L_{\text{mm}}$ is heated with $t [{}^\circ\text{C}]$, it will elongate and will have length $L = L_0 (1 + \alpha * \Delta t)$. Here $L_0$ is the part length at temperature $T = 20\, ^\circ\text{C}$, $L$ is the part length at measuring temperature. Possible causes in which measurements errors may occur are:

- Case 1 – temperature difference between the part processing area and the part measurement area. During the measurement performed on the mechanical processing machine, the part has a temperature $T_1 [{}^\circ\text{C}]$, and when the final processing has been performed, the part is removed from the M.U., being moved to the area where the last adjustments and the final dimensional
inspection are made. The temperature is different, hence it results that there is no repeatability in the measurements (temperature $T_2 \neq T_1$).

- **Case 2** – Temperature difference between the temperature of the AMCs and the temperature of the parts. In general, micrometers are stored in specially designed places where the temperature is controlled and maintained at $T = 20 \, ^\circ C \pm 2$, unlike the measured parts which are located in the machining section where the temperature reaches $\sim 5 \, ^\circ C$ in the cold season and $\sim 35 \, ^\circ C$ in the warm season. Depending on the season, there are large differences between the temperature of the measured part and the temperature of the measuring instrument. Because the shops where mechanical processing is performed are large, it is difficult to ensure a constant temperature of $\sim 20 \, ^\circ C$ depending on the season.

Due to temperature variations, the measurement results in the different stages of processing and control have different values.

**4. Applicable procedure in the case of dimensional measuring at different temperatures**

**4.1 Generalities**

In order to improve the results obtained after the measurements, a procedure for measuring large parts in different measuring thermal conditions was drawn up. This procedure contains detailed steps for obtaining the results as close to reality as possible. This procedure was also applied in the case of the Crusher Roller part, presented in figure 1.

![Figure 1: Roll crusher metal machining.](image)

The optimal measuring conditions are represented by the constant temperature of $20 \, ^\circ C$ of the AMCs and of the measured parts. In general, these conditions are difficult to obtain, due to the conditions in the production halls and the size of the parts. It is often difficult for these parts to be moved to a temperature controlled area. According to the SR EN1090-1 standard, it is known that a 1000mm steel bar has the dimension of 1000.00 mm at $20 \, ^\circ C$, where this temperature is the 0 reference point for dimensional tests. The deviation 1000mm for every 1°C is about 0.0125 lower or higher. Example: A piece measured at $30 \, ^\circ C$ with an inner diameter of 1000 mm and a temperature of the measuring instrument of $20 \, ^\circ C$. There is a possibility that during the measurements performed on the processing machine, the operator performing the measurement will not realize the 10°C deviation. In these conditions the piece will be made at dimension 1000.00 mm. The actual value resulting in these conditions will be 1000.125 mm. A deviation of $+ 0.125mm$ will be more than enough for the part to be declared rejected when the tolerance allowed for it is $+ 0.06/0.08 \, mm$. Under these conditions, the inspector performing the measurement must ensure that the part and the measuring instruments have the same temperature, namely the ambient temperature and the temperature of the part must be the same. To ensure that the two elements are at the same temperature, they must be stored for a few days, depending on the dimensions of the workpiece and the initial temperature after final machining. The duration of the measurements can be long if the same measuring equipment is used and therefore the inspector performing the measurement must know that a long use of the measuring equipment risks transferring heat from his hands to the equipment and dimensional deviations may result. To avoid heat transfer from the operator's hands which may have an adverse effect on the measurements, after each measurement it is recommended that the meter be left near the
workpiece and avoid contact with the operator's hands so as not to heat the measuring instrument. It is recommended that there be a 10-minute break between measuring each size (figure 2).

Figure 2. Crush roller dimensional measuring.

4.2 Calibration procedure
An annual verification of CMD in a metrology institute that includes a metrological verification certificate is not sufficient to ensure that the measuring device is in optimal condition. The calibration made in a metrology institute only verifies that the current equipment is maintained in the parameters at a temperature of 20 °C (figure 3.). A metrology certificate cannot provide real values during use in measurements and does not certify the correct calibration. Note: the measuring equipment needs to be calibrated before use.

Figure 3. Checking the interior micrometer on a static machine in laboratory conditions.

4.3 Calibration on stationary devices
- If the calibration of the equipment is necessary on a stationary measuring device, then it is very important that the equipment is acclimatized in the same conditions in which they were checked in the laboratory conditions;
- After acclimatization of the equipment, calibration can be done;
- After calibration the measuring equipment must be acclimatized in the same conditions as the part to be measured. Again, leave the equipment near to the measuring part. Ensure that the measuring equipment is 100% acclimatized before use;
- After the final acclimatization the measurement can start, ensuring at the same time that there is no heat transfer between the operator's hands and measuring instruments. Checking the temperature of the measuring equipment during the measurements is recommended.

4.4 Checking the calibration with the gauge of the measuring equipment
- If the gauge belongs to the measuring equipment and can be brought with it before calibration it is necessary to have the same temperature;
- Acclimatization of the calliper and the measuring instrument so the calibration can be done (figure 4).

5. Finite element modelling of the parts expansion process during the metal machining
In order to show the change of dimensions that takes place with the increase of the temperature due to the processing by cutting and to put in correlation with the analytical calculations, the modelling with finite elements was performed.
Figure 4. Measuring equipment acclimatization; a – part temperature measuring $T = 23^\circ\text{C}$; b – acclimatization of the measuring instrument

- After calibration the measurement can start (figure 5).

Figure 5. Indoor micrometer calibration.

This makes the connection between thermal and mechanical phenomena that include the increase of its dimensions. In the case of modeling with finite elements of the process of expansion of a part, the following steps are presented [2]:

- Following the cutting by machining of the inner surface of the part, the temperature in this area had the value $T = 25^\circ\text{C}$. The FEM analysis was performed in which the ambient temperature $T = 20^\circ\text{C}$ was considered (figure 6 (a)).

Figure 6. Dimensional variation at measuring temperature $T = 25^\circ\text{C}$.

As a result of the expansion process, the dimensions of the part will change. Following a structural analysis based on the results of the thermal problem, in figure 6(b) is presented the modification of the linear dimensions along the OY axis. From the image analysis it can be seen how in the area of yellow colour the change of dimensions is of the order of hundreds of millimeters, values very close to the real ones. These values represents the correction that must be taken into account when measuring the inside diameter. In the case of storing a part at a temperature $T = 30^\circ\text{C}$ (figure 7(a)) and measuring the inner diameter, an increase in diameter can be observed as can be seen in figure 7(b). Under these conditions the piece will be made at 1000.00 mm. The measured actual value resulting in these conditions will be 1000.125 mm. Using modeling and simulation, a very close value of the size variation was found due to the measurement at temperature $T = 30^\circ\text{C}$, namely $l = 1000.14$ mm.
In order to correct the variation of the dimensions that often appears in the situation in which the measuring instruments are not at the same temperature with the parts that will be measured, it is necessary to apply some dimensional corrections. Depending on the measured dimensions and the temperatures at which the measurements are made, the following dimensional correction table has been created (table 1).

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Table 1. Dimensional correction table.

| mm/temp. | 17  | 18  | 19  | 20   | 21   | 22   | 23   | 24   | 25   | 26   | 27   | 28   | 29   | 30   |
|----------|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|------|
| 200      | 0.007 | 0.005 | 0.002 | 0 | 0.002 | 0.005 | 0.007 | 0.009 | 0.012 | 0.014 | 0.016 | 0.018 | 0.021 | 0.023 |
| 300      | -0.010 | -0.007 | -0.003 | 0 | 0.003 | 0.007 | 0.010 | 0.014 | 0.014 | 0.021 | 0.024 | 0.028 | 0.031 | 0.035 |
| 400      | -0.014 | -0.009 | -0.005 | 0 | 0.005 | 0.009 | 0.014 | 0.018 | 0.018 | 0.028 | 0.032 | 0.037 | 0.041 | 0.046 |
| 500      | -0.017 | -0.012 | -0.006 | 0 | 0.006 | 0.012 | 0.017 | 0.023 | 0.023 | 0.035 | 0.040 | 0.046 | 0.052 | 0.058 |
| 600      | -0.021 | -0.014 | -0.007 | 0 | 0.007 | 0.014 | 0.021 | 0.028 | 0.035 | 0.041 | 0.048 | 0.055 | 0.062 | 0.069 |
| 700      | -0.024 | -0.016 | -0.008 | 0 | 0.008 | 0.016 | 0.024 | 0.032 | 0.040 | 0.048 | 0.056 | 0.064 | 0.072 | 0.081 |
| 800      | -0.028 | -0.018 | -0.009 | 0 | 0.009 | 0.018 | 0.028 | 0.037 | 0.046 | 0.055 | 0.064 | 0.074 | 0.083 | 0.092 |
| 900      | -0.031 | -0.021 | -0.010 | 0 | 0.010 | 0.021 | 0.031 | 0.041 | 0.052 | 0.052 | 0.072 | 0.083 | 0.093 | 0.104 |
| 1000     | -0.035 | -0.023 | -0.012 | 0 | 0.012 | 0.023 | 0.035 | 0.046 | 0.058 | 0.069 | 0.081 | 0.092 | 0.104 | 0.115 |

6. Conclusions
The process of measuring the parts is a very complex one that must take into account a series of factors that often overlap. The paper studied the influence of temperature in the process of measuring parts in the situation of storing the piece in an area with a temperature higher than 20 °C and in the case of inner diameter metal machining by turning. In order to obtain correct results when measuring the parts made in different thermal conditions, the article presents working procedures based on real processing situation. To correct the measurements, a table of correction values was created that takes into account the temperature and the value of the measured dimensions. To verify these values, an analysis was performed based on the finite elements that came and verified with great precision the values in the tables.

7. References
[1] https://www.machinedesign.com/archive/article/21818680/correcting-for-thermal-measurement-errors, accessed date 05.02.2019.
[2] Nițoi Dan Florin, 2020, Optimizarea proceselor tehnologice prin metoda elementelor finite – Noțiuni teoretice și exemple, Bren Publishing House, Bucharest.