Erciyes Üniversitesi
Fen Bilimleri Enstitusu Dergisi
Cilt 38, Sayı 3, 2022

Erciyes University
Journal of Institue Of Science and Technology
Volume 38, Issue 3, 2022

Correction and Compensation of Thermally-Induced Errors in CNC Milling via Integrated CAD / CAM and Finite Element Analysis for AL 7075(T6)

Saban Murat UNLU[1*], Eyup Sabri TOPAL[2], Omer Faruk ERGIN[1], Mustafa GUL[1]

[1] Erciyes Üniversitesi Mühendislik Fakültesi Makine Mühendisliği, KAYSERİ
[2] Akdeniz Üniversitesi Mühendislik Fakültesi Makine Mühendisliği, ANTALYA

(Alınış / Received: 19.08.2022, Kabul / Accepted: 02.12.2022, Online Yayınlanma / Published Online: 30.12.2022)

Keywords
Milling, Thermal Error Compensation, Finite Element Analysis(FEA), Computer Aided Design (CAD)/ Computer Aided Manufacturing (CAM)

Abstract: In this study, examining and correction thermal expantion induced errors on CNC milling machine is aimed. In this scope, workpiece thermal expansion attitude will be analysed with finite elements method on the CAD Model, and workpiece will be revised according to the results of analysis. For revision process, an interface software is developed, making a relation between computer aided analysis modul and CAD modul. Thanks to CAM process implemented on new CAD Model, a CNC part program that will correct the error is created. The reproducibility of the performance of the correction process was investigated by processing identical samples at different manufacturing environment temperatures. As a result of studies machining errors reduced with a success rate of 84% for Al 7075(T6). By the method developed, the workpiece's dimensional error which thermally induced can be minimized at any temperature without using climatised to ideal temperature and isolated machining shops.

AL 7075(T6) Malzemenin CNC Frezeleme İşleminde Oluşan Isıl Hataların CAD/CAM ve Sonlu Elemanlar Analizi ile Düzeltilerek İyileştirilmesi

Anahtar Kelimeler
Frezeleme, Isıl Hata İndirgeme, Sonlu Eleman Analizi(FEA), Bilgisayar Destekli Tasarım(CAD), Bilgisayar Destekli İmalat (CAM)

Öz: Bu çalışmada CNC frezeleme işleminde ısıl değişimlerden kaynaklanan işleme hatasının incelenmesi ve düzeltilmesi hedeflenmiştir. Bu amaçla iş parçası CAD modelinin ısıl genleşme/büzülme davranışı sonlu eleman analizi (SEA) yöntemiyle analiz edilmiş ve iş parçası CAD modeli bu analiz sonuçlarına göre "imalat ortamı hangi sıcaklıkta olursa olsun işparçası tam boyutlarında işlenecek şekilde" revize edilmiştir. Revizyon işlemi için bilgisayar destekli analiz modülü ile CAD modülünü entegre eden yeni bir yazılım geliştirilmiştir. Bu yazılım ile ısıl analiz sonuçları dikkate alınarak işparçası CAD modeli yeniden yapılandırılmıştır. Revize edilmiş yeni CAD modeli üzerinde gerçekleştirilen CAM uygulaması ile hatayı düzeltecek alternatif CNC işleme kodları elde edilmiştir. Özdeş numuneler farklı imalat ortamı sıcaklıklarında işlenerek düzeltme stratejisinin performansının tekrarlanabilirliği araştırılmıştır. Yapılan çalışma sonucunda Al 7075(T6) malzeme için %84 oranında başarı ile işleme hataları indirgenmiştir. Geliştirilen yöntemle talaşlı imalat sektöründe yüksek boyutsal kalitede parça üretebilmek için halen kullanılmakta olan, ortamın sürekli ideal sıcaklıkta (22^{o}C) kalması için klimatize edilmiş ve yalıtılmış atölyeler oluşturulmasına ihtiyaç kalmayacaktır. İmalat ortamları hangi sıcaklıkta bulunursa bulunsun yüksek boyutsal tamlıkta ürünlerin üretimi ek maliyetlere katlanmaksızın mümkün olacaktır.

*Corresponding Author, email: smunlu@erciyes.edu.tr

1. Introduction

Machining has an essential place among production techniques. The machining technique is used for the-finished products, such as rolling and casting products which are brought into full production or brought to their final dimensions. Commonly used machining methods are milling, turning, grinding, drilling, and planing machine operations. Computerized Numerical Control (CNC) machine tools have been widely used in many industries including molding, automotive, marine, aviation, biomechanical systems, defense, and space industry since it increases the production speed and reduces the production costs. The CNC milling process has attracted researchers due to its common usage. Tolerances and production speed are related to each other. Therefore, it is very crucial to understand the relationship between these factors on product quality, production speed, and productiveness.

In modern manufacturing conditions, lowering production costs and developing methods in order to increase the dimensional accuracy of the workpiece are related to the machine tool errors [1]. The machine tool errors can be classified as geometric errors, kinematic errors, dynamic errors, and thermal errors. The machine components lead to the geometric errors. The relative movement of the machine components and mechanical or inertia moment of the components of the machine may cause the kinematic and dynamic errors [2]. Thermal errors occur because of deformation and expansion caused by the relative movement of the tool and the workpiece. There are several methods used to increase machining precision and quality. Using high precision machining is a successful way of high-quality machining but the main disadvantage of this method is to increase production costs. There are some techniques such as a quality control to fix the errors on the continuous measurement. This process is also an expensive way of production due to the processing time, raw material usage, and tool costs. Therefore, the error compensation methods (ECM) are used to minimize the manufacturing errors arising from the structure of the machine tool, processing conditions, and temperature differences [3].

Thermal errors, one of the most important sources of processing errors, make up 40% - 70% of the total error [4-6]. In recent years, researchers have resorted to optimization methods, thermally optimized structures to minimize thermal effects, place heat sources separately from the system, and use improved cooling techniques [7]. Three ways are used to improve the thermal performance of the machine tool; firstly, the structural improvement for the thermal characteristic is to be made. In their process, symmetric constructions with simple coefficients of thermal expansion must be constructed, and complex structures must be avoided [8]. The second is temperature control. By controlling the temperature values and distributions of specific points, the resulting thermal deformation of the working shaft is reduced. Temperature control can be done by installing a heating or cooling system on the machine bench. Both systems reduce the thermal deformation in the intended machine tool and compensate for the temperature distribution. A common method is to remove the heat generated by the spindle and the various coolants. The third is the modelling and compensation processes of thermal deformation. This method is used to increase machine accuracy during machining after completion of machine tool design and production. In the initial stage, the temperature distribution and thermal deformations of the machine tool are obtained by forming mathematical methods and thermal deformation model from experimental studies.

There are six sources of thermal effects: These are the heat released as a result of the cutting operation, the heat generated by the machine, cooling and warming caused by the cooling system, changes in ambient temperature, human interaction, the temperature of the previous process so all these effects described above make it difficult to achieve a perfect error model [3, 6]. Due to the non-homogeneous temperature distribution in the machine structure, thermal errors show a time-dependent nonlinear characteristic. The interaction between the location, intensity, thermal expansion coefficient of the heat source and the configuration of the machine system causes a complex thermal behavior to occur [9]. The most critical factor affecting the processing accuracy is the cutting operation. The accuracy is affected by the chip depth. While heat production is low in finishing operations, intensive heat production takes place as a result of course processing. This factor is more effective when the high volume of the chip is removed than any other heat generating source. To solve the problem, the use of coolant in high volume chip removal should be increased. Recently, high-speed machining and grinding techniques have been used to remove chips by transferring chips instead of heat. One of the methods used to solve thermal error problems is to use temperature-controlled chambers. However, keeping the temperature constant with this method is both challenging and costly [9].

In modern manufacturing conditions, lowering production costs and developing methods in order to increase the dimensional accuracy of the workpiece have great prospects. The various factors are geometrical and dimensional errors, tool deformation and workpiece errors, thermal distortions, tool wear, and tool errors. Two main approaches to improve workpiece metrology are used; modelling of workpiece-tool movements and interpolation of the cutting tool position to reduce dimensional errors or alternative tool path generation approach [1]. The limited amount of improvements in these methods has significantly increased production costs. Therefore, the error compensation technique at low cost is of great importance in increasing the processing accuracy of CNC [7]. The math model dependent error compensation software is widely used. Although mathematical model seems successful, it may not be practical for every machining requirement. In other words, it is very difficult to construct a high-accuracy mathematical model that overcomes the deficiencies of thermal error correction techniques commonly used with these methods [3].

There are two limiting factors in error compensation operations; first, the thermal error model cannot provide sufficient accuracy between temperature changes. The correctness of the generated thermal error model is affected if high values of temperature changes are detected. These values must be eliminated. Significant temperature changes may also be perceived incorrectly. Second, non-linear thermal deformations arise in a continuously working machine tool, depending on the time, as processing conditions and environmental effects vary. This mechanism makes machine tool deformations very complex and therefore, makes it difficult to predict thermal source errors. As a result, the thermal improvement model is successful with the best indication of the relationship between key temperature changes and thermal imperfections, which vary according to the location of the heat source (such as motors, bearings, hydraulic system, ambient temperature) [10, 11]. Even though there are two thermal error modes as expansion and bending, the presence of many different structural elements in the machine tool and the different behaviors of these elements make it difficult to determine the thermal error mode of the system. The most important problems encountered in thermal error compensation processes are; the detection of the optimal temperature sensor position and the change in processing conditions can protect the accuracy of the resulting thermal error model [12].

In error compensation exercises, the shifts in the components of the machine tool are mostly examined. Factors affecting the accuracy of this process are the measurement of all relevant geometric error parameters, taking into account the working time, taking precise measurements sufficiently, the effect of temperature changes taking place within a short period [13].

Many researchers are mostly concentrated on real-time correction techniques because of the complexity of the processing conditions. Real-time measurement and instant real-time correction (or compensation) must be carried out for the detailed modelling of system behavior by the modification of G codes [14]. Most research including error compensation methods has not yet gone beyond the laboratory conditions since they require expensive hardware/software and the difficulty in adapting the methods to machine tool operating systems [15]. The disadvantage of real-time (direct) error compensation systems is the difficulty of taking and evaluating fast and frequent measurements to catch sudden temperature changes. Delay in intervention to the system reduces the accuracy of follow-up and correction of errors [16].

The existence and the continuous increase of many different types of CNC, with developing technology has resulted in a large number of error models, and consequently, the error compensation processes are complex and costly [17]. Alternatively, the climatization method reduces the influence of thermal errors to keep the environment at 22℃ continuously by using various heating/cooling equipment such as air conditioning [16]. The climatization processes face with difficulties when a sudden increase occurs in temperature for cutting forces, machine tool, and components. Jianguo et al. [18] conducted thermal error compensation studies by using the CNC package optimization model to detect temperature-sensitive points in the error model by dividing the temperatures into two changing temperatures. The interactions of the errors during processing (heat source, thermal expansion coefficient, the shape of the machine's system, and changing ambient conditions) complicate machining process, which makes it challenging to estimate errors with mathematical models [19]. Zhang et al. [20] developed a simulation model of the vertical machining center by obtaining the temperature map and thermal deformation model of the machine tool to increase the accuracy of the machine tools by thermal simulation. After comparing the simulation and the experimental results, the validity of the finite element model has been proven. Wang et al. [5] examined the reduction of the geometrical and thermal errors on different types of workpieces. They also experimentally investigated the positioning errors in the three-axis machining center under different temperatures by means of Newton's interpolation method. Eksandrai et al. [14] investigated thermal errors by using linear regression, Artificial Neural Network (ANN), and Fuzzy Logic methods. In order to reduce the thermal error, the required data were obtained via laser interferometer. They calculated volumetric errors by considering rigid body kinematics and modification of G codes. They observed that the thermal errors were reduced by 41% on the workpieces. Miao et al. [21] identified the critical thermal points and measured the thermal errors in the z-direction of the workpiece. The critical thermal points were determined by employing the Fuzzy Logic and Gray Correlation methods. They experimentally measured the thermal errors at the critical thermal points at different ambient temperature and spindle speed. Ma et al. [22] minimized the thermal error of linear axis with fixed-fixed installation. They formulated the thermal error by considering the temperature of screw shaft and a trigonometric function with horizontal position as its independent variable. Based on their results, they were able to reduce the repetitive positioning error by more than 45%. Fu et al.[23] proposed one K-means clustering and correlation analysis-based selection method to acquire the optimal temperature-sensitive point combination for thermal error modeling of machine tool spindle with the effects of different heat sources. They demonstrated that the the prediction performance and the robustness of the thermal error model can be improved with in the consideration of the optimal temperature-sensitive point combination.

Despite many different points of view in error compensation operations, the work is usually designed for specific working conditions. Practical mathematical expressions are difficult to achieve in high-precision machining conditions [5]. The internal and external heating/cooling sources on the machine tool and the elements that make up the machine structure have different thermal expansion coefficients, causing thermal distortions [24]. The underlying reason for the difficulty in thermal error compensation is that thermal errors are complex and not linear [25]. In the offline model, which is commonly used in thermal error compensation processes, the relationship between thermal deformation and several experimental temperatures is considered. It exhibits substantial differences in thermal deformation due to temperature distribution and changing processing conditions. Being able to create a correct and robust thermal error forecasting model is the most crucial part of the compensation system [26]. Therefore, these errors should be modelled and reduced accordingly. Geometrical and positional errors are often modelled by kinematic modelling and transformation matrix methods, but modelling thermal errors is difficult [14]. The dimensional accuracy of a processed part depends on the accuracy of the machine tool that processes it. No matter how new a machine tool is, it does not guarantee that dimensional accuracy can be achieved over long runs. Positioning errors are dynamically dependent on factors such as operating conditions, cutting forces, ambient temperature, tool wear, record carrier wear, vibration. The extension of the processing time is changing these factors, and it is difficult to control the processing operations [27]. Establishing a correct mathematical model for the theoretical analyzes made to create the thermal error model in the CNC machine is very difficult because the factors in processing are in excess and continuous change. The thermal expansion coefficient of the machine elements and workpiece must be well known to reduce the thermal errors due to the ambient temperature. Choosing an appropriate measuring system for the error source is important. From external factors, the ambient temperature of the workbench changes slowly but this change completely affects volumetric performance. The local deformations caused by the slides and beds in the workbench partially affect the volumetric performance. It is difficult to estimate displacements resulting from internal heat sources, and they change much more rapidly than environmental conditions [13]. In order to eliminate the aforementioned issues above, a new approach must be developed to minimize the temperature change in the CNC milling process. In this study, it is aimed to improve the dimensional accuracy of the CNC milling process without using any additional equipment and decreasing the manufacturing speed. Also, the thermal expansion/contraction behaviour of the workpiece CAD model is analyzed by means of the finite element method (FEA). Moreover, the workpiece CAD model is modified based on the results acquired from the finite element analysis. Therefore, the manufacturing environment can be processed at a high precision of the workpiece at any temperature. A new software is developed to integrate the CAD module with the FEA module for the revision process. This software reconfigures the workpiece CAD model taking into account the thermal analysis results. The CAM application on the revised CAD model provides alternative CNC machining M-G codes to correct the error. Reproducibility performance of the compensation strategy is investigated by machining identical samples at different ambient temperatures. By using the recommended method, climatized and isolated workshops are not needed for a standard CNC machine to produce parts with high accuracy. Grinding and finishing operations are no longer required. Thus, the production speed is increased, and the production costs are reduced. The proposed method reduces dimensional errors depending on variable ambient temperature.

2. Material and Method

The total thermal expansion value at the work piece is calculated based on the temperature distrubition along the beam as shown in Figure 1.

$$\Delta L = \int_0^L \alpha(\Delta T)\, dx \qquad (1)$$

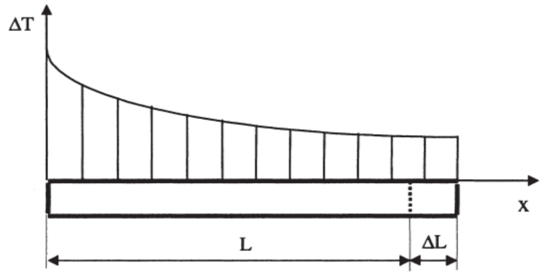


Figure 1. Thermal extension mode of a beam [12]

Air-conditioned(climatized) production environments are used to bring the operating temperature to the ideal temperature . As a result, the workpiece is manufactured which is larger or smaller than the required dimensions. In this work, an approach has been developed in the error correction method to ensure that the manufactured workpiece is at full dimensions regardless of the manufacturing ambient temperature. The first step is the thermal expansion/shrinkage analysis to be performed on the CAD model of the workpiece by the finite element analysis (FEA). This analysis determine whether the workpiece exhibits expansion or contraction behavior under the current temperature conditions in the environment. In the second stage, the CAD model of the workpiece is revised according to the FEA results. This revision is arranged on the new CAD model in a way that ensures that the workpiece is at the ideal temperature and in the desired dimensions at the end of the CAM application. Figure 2 shows the flowchart for the error correction method. FEA is performed at eight different ambient temperatures, except for the ideal temperature. FEA analysis is carried out by using ANSYS software, and the new workpiece model is obtained after the analysis. The new workpiece achieved from the FEA is converted into a solid model in the form of a point cloud with the help of Solidworks CAD program.

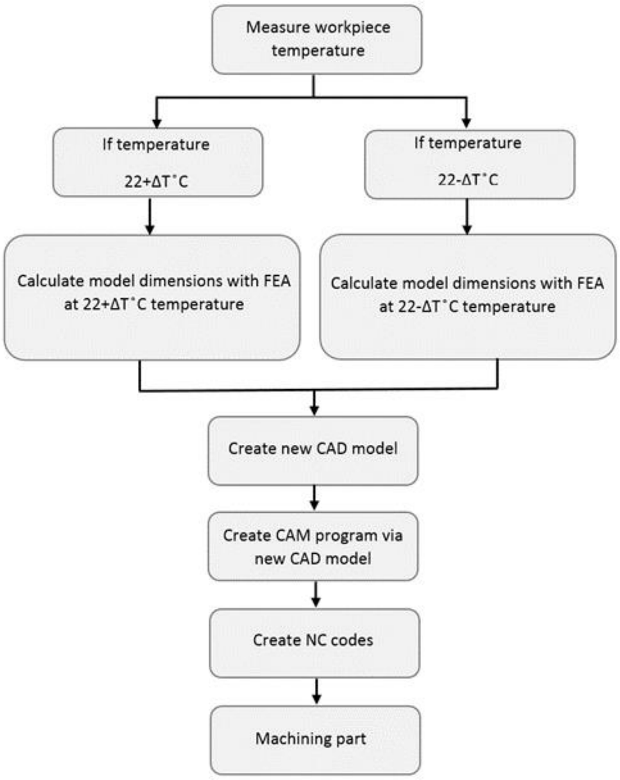


Figure 2. Error correction method

2.1. Finite Element Method (FEM)

The displacement fields of the workpiece are determined by using ANSYS, commercially available FE software. The workpiece is modelled by using a three dimensional 20-node SOLID 186 element (Fig. 3.)

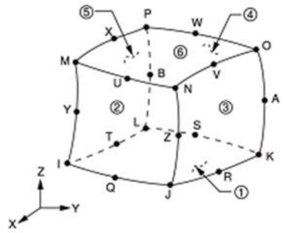
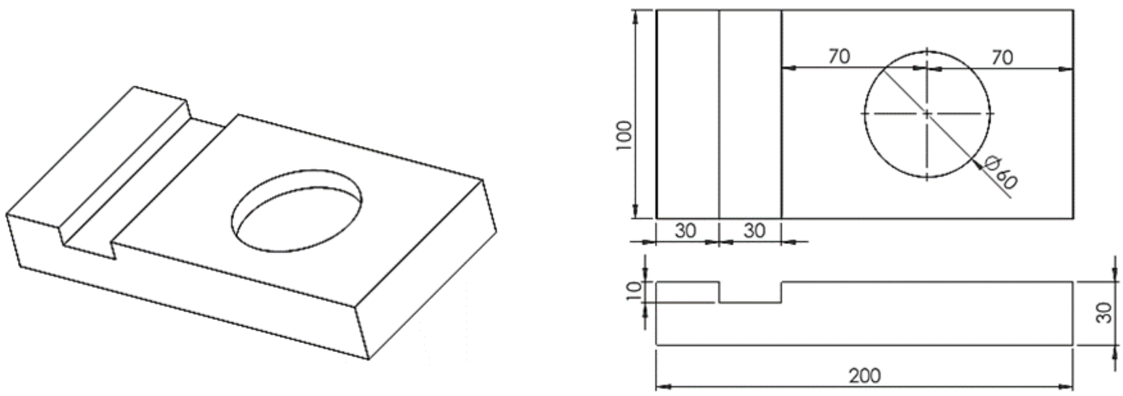


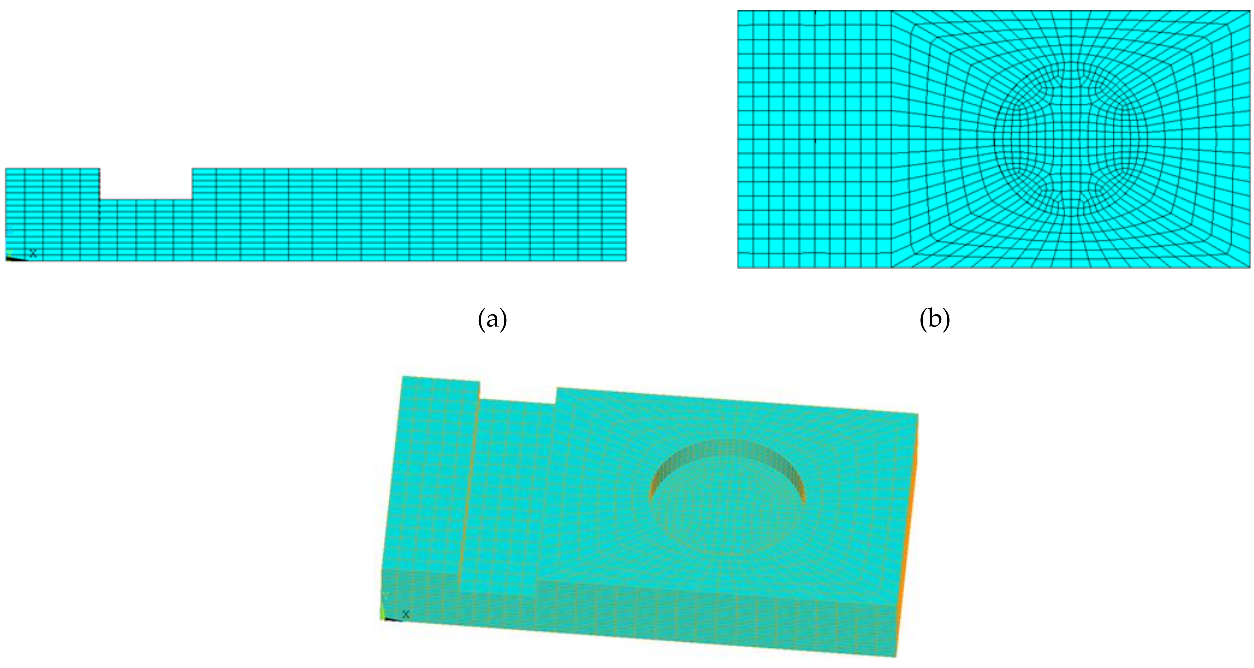
Figure 3. Element type SOLID186 used in FEM analyzes.

The geometrical description and finite element model of the workpiece are presented in Figures 4. and 5. The workpiece is fixed along its left edge while the remaining edges are free of traction. The entire part of the workpiece is subjected to a uniform temperature of varying from 2 to 42 °C. A smooth mesh structure was obtained for the model part. The model is divided into 28 elements in the X direction, 15 elements in the Z direction and 18 elements in the Y direction. Figure 5 shows the FE model of the workpiece which is constructed based on the convergence studies. Thus, the FE model of the work piece consists of 12,450 elements and 52,178 nodes.



(a) (b)

Figure 4. Model Part dimensions (a) full model (b)side and top view



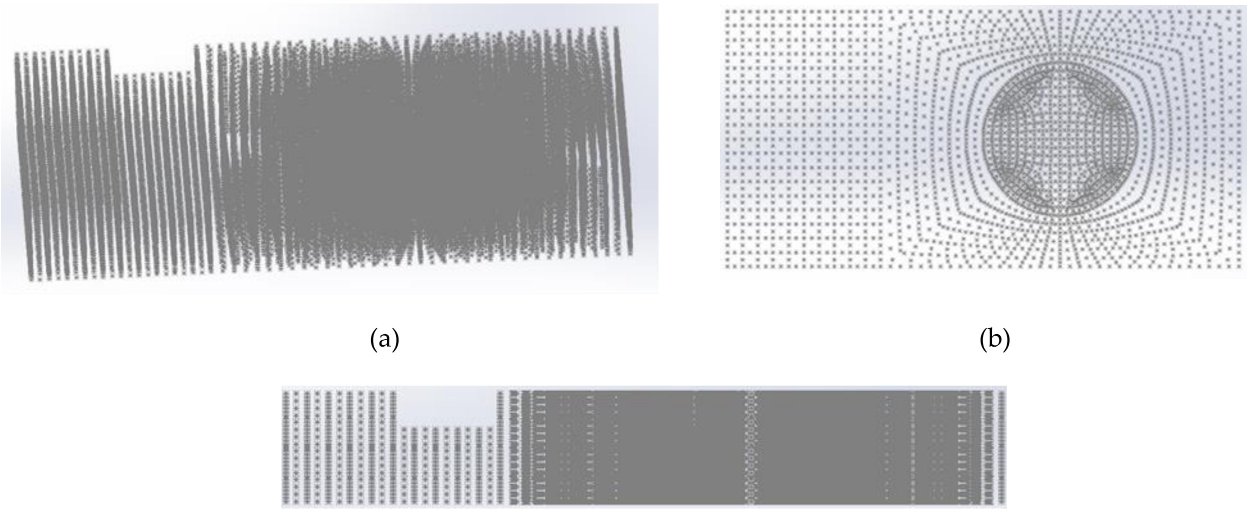
(a) (b)

(c)

Figure 5. Model part mesh structure (a) side-view (b) top-view and (c) full model

2.2. The transition of Solid Model from Finite Element Analysis

The results of the thermal expansion/shrinkage deformation of the test sample deformed by the heat effect at the end of the thermal analyzes made in the ANSYS which are shown in Figure 6. The process to be performed after this step is to transfer the results of the finite element analysis to solid or shell models to produce CAM codes. This part establishes the most difficult phase of the developed method. For this reason, none of the commonly used analysis programs (ANSYS, ABAQUS, etc.) can output in the format of dwg, prt, sldprt as the analysis result. This problem has been solved using the Solidworks package program Scan to 3D and Prep Mesh Wizard. The thermal analysis results from the ANSYS program were obtained as nodal points (point cloud) in the form of "igs" (Figure 6).



(a) (b)

(c)

Figure 6. Temperature output of nodal point in igs format

It is crucial that there is no loss of data while switching to a solid model regarding error compensation in micron levels. While solid model programs cover node points, they form a shell by combining a node point with its closest neighbour. This method gives inaccurate results when working with the importance of dimensional accuracy. The problem mentioned in this study was solved by manually selecting the interior of the point cloud set (Figure 7.)

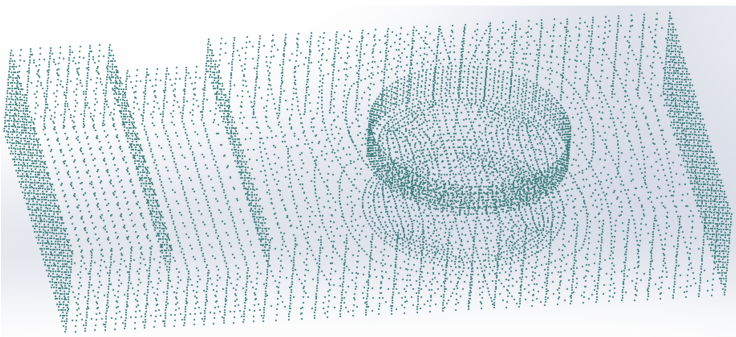


Figure 7. Obtained shell point cloud from the node points

In the next step, the final solid model is obtained without losing data by knitting through the obtained shell point cloud surfaces (Figure 8.). With the help of CAM session performed on this final solid model, the CNC part program to process the part in its full dimensions is obtained.

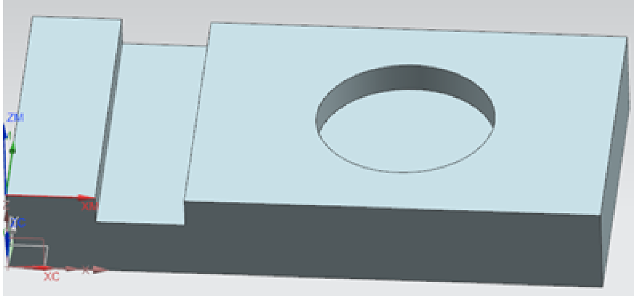


Figure 8. Final solid model for machining,

3. Experimental method and Results
3.1. Experimental equipment and application method

In experimental work, Fanuc O-M type control machine Taksan TMC-500V model CNC vertical machining center is used to milling the workpieces. To increase the efficiency of the experimental study, the length and diameter of the cutting tool are precisely measured with the Renishaw TS27R tool measuring probe on the CNC vertical machining work table. Tool dimension measurement is performed several times for each tool. The aim here is to capture the value of the tool received from the magazine with the least error. Workpieces are made of Al7075(T6) which is used widely in the aviation and automobile industry and has excellent surface quality. The general characteristics are given in Table 1.

Table 1. Material properties of the sample

Material properties of Al 7075(T6)	
Density	2.81 g/cm^3
Yield Strength	503 MPa
Poison Ratio	0.33
Young's Modulus	72 GPa
Thermal Expansion Coefficient	22.2×10^{-6}/°C

For the roughing of the test specimens, a Ø 18 mm cutting tool with two cutting edges were used (MBC tool holder and H490 E90AX-12 ISCAR double sided rectangular inserts with four helical cutting edges). For finish milling, the Al7075(T6) is machined with 3 flute carbide end mills to prevent tool-chip bonding and chip evacuation for the material (ECA-B-3 10-22C10-72 Model). Gewefa hydraulic tool holder is preferred to minimize misfire as a tool holder in finish milling. Machine tool and workpiece temperatures precisely measured with the Fluke 568 IR thermometer (Figure 9). This device can measure the temperature of materials with different emissivity properties. First, rough machining is applied to the workpiece (leaving 1mm chip margin on the side surfaces). Then the finishing process is done(once the appropriate temperature values are reached). Workpieces obtained as a result of roughing and finishing machining are shown in the Figure 10.

Figure 9. Infrared temperature gauge

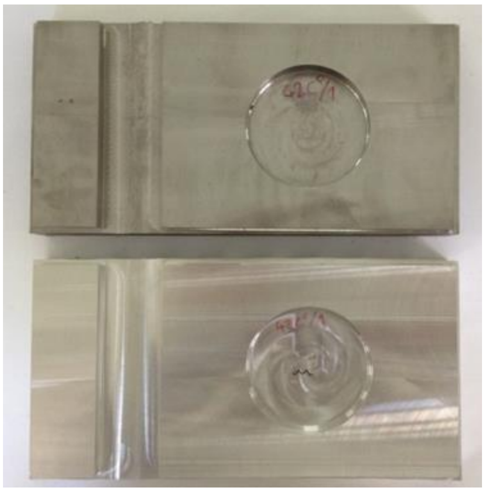


Figure 10. Manufactured sample work parts

3.2. Experimental studies

Aluminium 7075, which gives good surface quality after machining, is used as workpiece material in the experiments. The FEA analyzes for nine different temperature values have been rearranged, and the workpieces have been processed with these generated codes depending on the ambient temperature. The dimensions of the machined workpieces are measured precisely by the CMM (Coordinate Measuring Machine). Figure 11. The measurements are made for five selected critical points, and the results are evaluated. Success rate is presented by "%" taking the absolute value of the average of the three measurements performed under the same conditions.

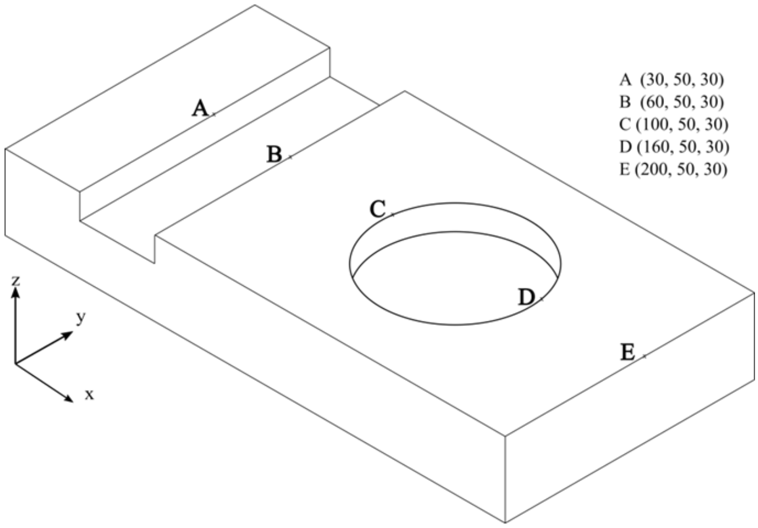


Figure 11. CMM measurement points (A, B, C, D, E)

3.3. Error measurement due to temperature

The temperature-dependent error values for Al7075(T6) at measurement point A are shown in Figure 12. The mean error for the Al7075(T6) at the ideal temperature is measured as 7.5μm. The most successful error correction for Al7075(T6) is 10μm in 12°C test and 21μm in 2°C worst-case error correction.

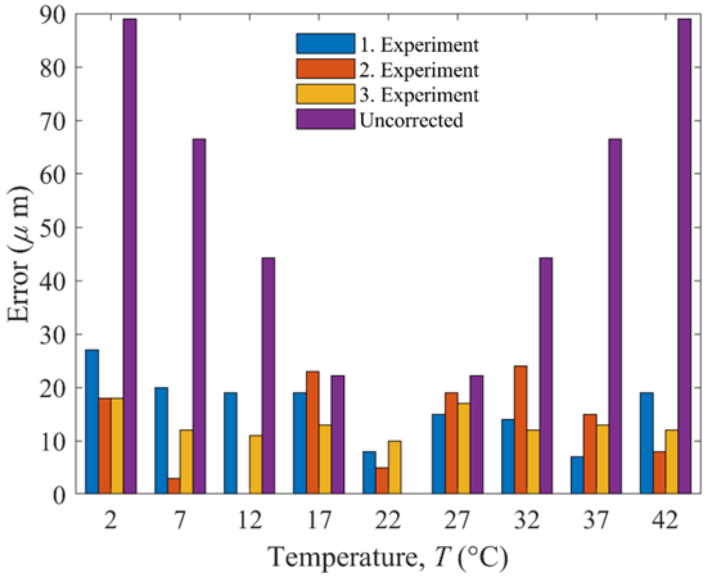


Figure 12. Error measurement due to Al7075(T6) temperature for x=30mm

The temperature-dependent error values for Al7075(T6) at measuring point B (60mm) are shown in Figure 13. The average error for the Al7075(T6) at the ideal temperature was measured at 9μm. The most successful error correction for the Al7075(T6) is 5.5μm in 7°C and 11.7μm in 2°C.

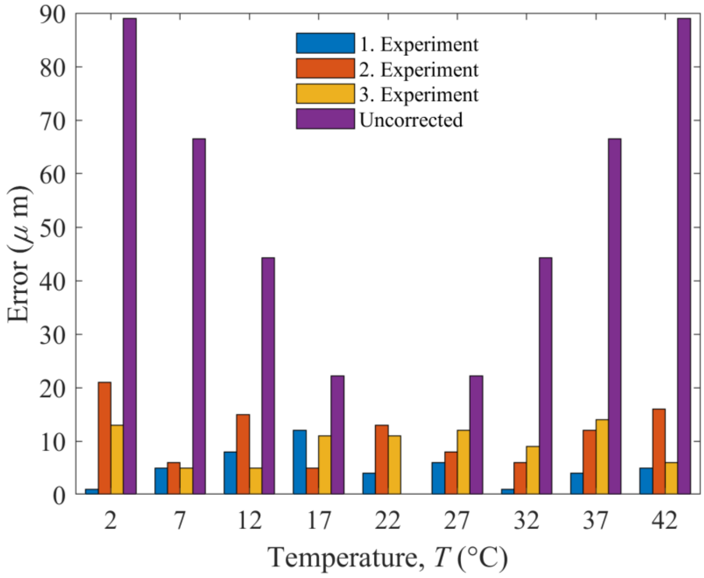


Figure 13. Al7075(T6) temperature-dependent error measurement for x=60mm

The temperature-related error values for Al7075(T6) at measuring point C are shown in Figure 14. The mean error for Al7075(T6) at the ideal temperature is measured to be 10.6μm. The most successful error correction for the Al7075(T6) is measured 4μm at 7 °C, the worst error correction at 32°C, 37°C and 42°C at 14μm.

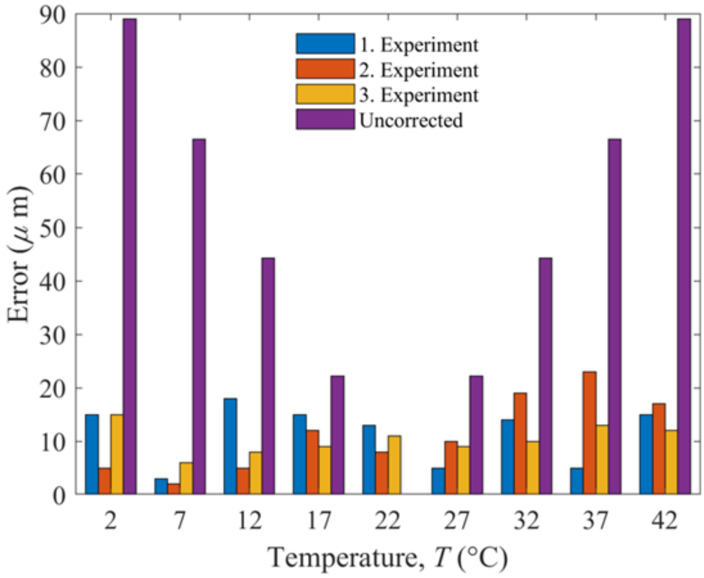


Figure 14. Al7075(T6) temperature-dependent error measurement for x=100mm

The temperature-dependent error values for Al7075(T6) at point D are shown in Figure 15. The mean error for the Al7075(T6) at the ideal temperature is measured to be 10μm. The most successful error correction for Al7075(T6) is 11.6μm at 27°C and the worst is 18.6μm at 7°C.

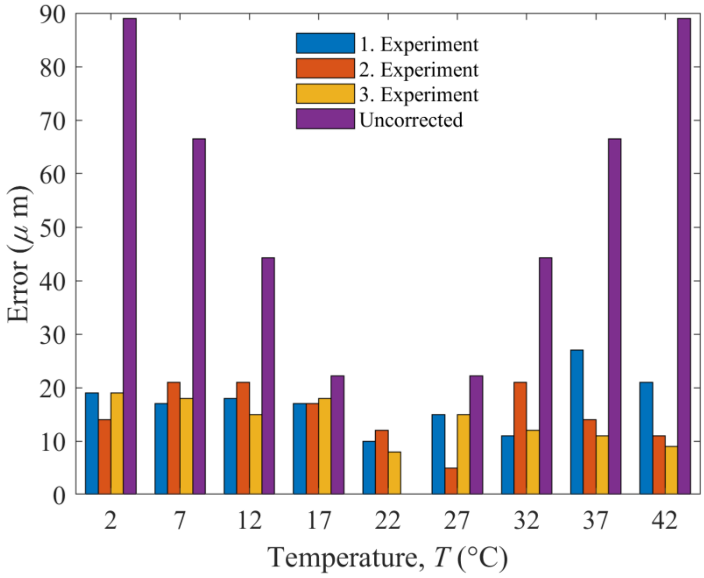


Figure 15. Error measurement due to Al7075(T6) temperature for x=160mm

The temperature-dependent error values for Al7075(T6) at measuring point E are shown in Figure 16. The average error for the Al7075 at the ideal temperature is 9.6μm. The most successful error correction for the Al7075(T6) is 4.3μm in the experiments at 27°C and 6.3μm at 32°C, and the worst error correction is measured at 12.6μm at 42°C.

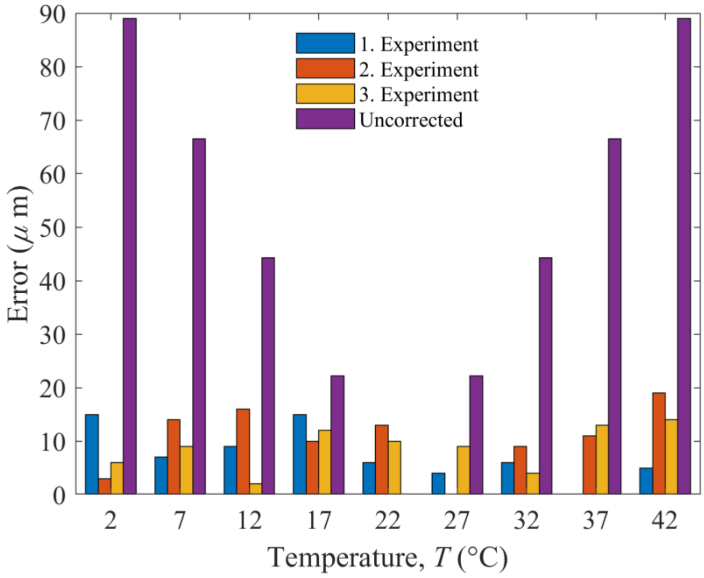


Figure 16. Error measurement due to Al7075(T6) temperature for x=200mm

4. Discussion and Conclusion

The thermal effects on the work piece during the manufacturing process have been investigated by using various devices and tools such as infrared cameras and computer software and hardware. In order to mitigate the influence of the temperature changes, the thermal expansion coefficients of the machine components should be calculated precisely a priori. The production of machine tools having different and complex geometries may be challenging since the use of distinct thermal expansion coefficients and the thermal deformations of these elements. Advanced microprocessors, various space systems, microscopes, and medical equipments play a major role to increase the machining precision and combustion efficiency as well as to reduce the friction. Recently, modern machine tools use advanced material technology to achieve approximately 0.005 mm precision. There are always limitations on the improvement of the machine accuracy regardless of the quality of the machine tools. Therefore, it is crucial to understand the error compensation process for the enhancement of the machine accuracy. For this process, the machine tool should be placed in the air-conditioned room to be able to control the ambient temperature at the desired levels.

In this study, G codes are modified by considering the ambiante temperature at which the work piece is processed. The results show that the present approach for the thermal error measurement is in good correlation with the experimental predictions. The temperature of the workpiece can increase by 100°C or higher depending on the rough machining conditions in the milling operations, the cooling system, and the tool. This situation may lead to undesired expansions in the workpiece and reduce the dimensional accuracy. In addition to minimization of the machining errors, the present approach improves the dimensional accuracy of the workpiece by modifying the G codes based on the desired temperature levels during rough milling process. As a result of the experimental studies, the machining error is reduced from 88μm to 14μm with the success of 84% for Al7075(T6) material at 42°C. It is also noticed that the residual errors around 10-12μm are present for all experiments. This indicates that positioning errors in the machine axes are constant errors due to the servo motor errors and erosions in the slide system. The error is measured at different temperature levels between 2 and 42°C. It is observed that the mean error range was around 11μm. The maxium error (13.93 μm) is monitored at 2°C whereas the minimum error (9.46 μm) levels are noted at the temperature level of 22°C

The major advantage of this offline method is that it can be applied to all other milling machines without using any additional equipment while other special milling machines need sophisticate sensor and high-end software. Thus, it is obvious that the efficiency can be increased by applying the present approach to the milling machines.

Acknowledgment

The authors would like to acknowledge Erciyes University Scientific Research Projects Coordination Unit (Grant No: FBD-12-4062) for their support.

References

[1] Sortino, M., Belfio, S., Motyl, B., Totis, G., 2014. Compensation of geometrical errors of CAM/CNC machined parts by means of 3D workpiece model adaptation. Computer-Aided Design, 48, 28-38.

[2] Bosetti, P., Bruschi, S., 2011. Enhancing positioning accuracy of CNC machine tools by means of direct measurement of deformation. The International Journal of Advanced Manufacturing Technology, 58, (5-8), 651-662.

[3] Bryan, J.,1990. International Status of Thermal Error Research. CIRP Annals-Manufacturing Technology, 1 39 (2), 645-656.

[4] Ni, J., 1997. CNC Machine Accuracy Enhancement Through Real-Time Error Compensation. Journal of Manufacturing Science and Engineering, 119 (4B), 717-725.

[5] Wang, W., Zhang, Y., Yang, J., Zhang, Y., Yuan, F., 2012. Geometric and thermal error compensation for CNC milling machines based on the Newton interpolation method. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 227 (4), 771-778.

[6] Weck, M., McKeown, P., Bonse, R., Herbst, U., 1995. Reduction and Compensation of Thermal Errors in Machine Tools. CIRP Annals-Manufacturing Technology, 44 (2), 589-598.

[7] Wang, W., Zhang, Y., Fan, K., Yang, J., 2015. A Fourier Series-Neural Network Based Real-Time Compensation Approach for Geometric and Thermal Errors of CNC Milling Machines. Advances in Mechanical Engineering, 5 (0), 357920-357920.

[8] Zhang, J., Feng, P., Chen, C., Yu, D., Wu, Z., 2013. A method for thermal performance modelling and simulation of machine tools. The International Journal of Advanced Manufacturing Technology 68 (5-8), 1517-1527.

[9] Ramesh, R., Mannan, M. A., Poo, A. N., 2000. Error compensation in machine tools - a review Part II: thermal errors. International Journal of Machine Tools & Manufacture, 40 (9), 1257-1284.

[10] Kang, Y., Chang, C.-W., Huang, Y., Hsu, C.-L., Nieh, I. F., 2007. Modification of a neural network utilizing hybrid filters for the compensation of thermal deformation in machine tools. International Journal of Machine Tools and Manufacture, 47 (2), 376-387.

[11] Yuan, J., Ni, J., 1998. The real-time error compensation technique for CNC machining systems. Mechatronics, 8 (4), 359-380.

[12] Yang, J., Yuan, J., Ni, J., 1999. Thermal error mode analysis and robust modeling for error compensation on a CNC turning center. International Journal of Machine Tools and Manufacture, 39 (9), 1367-1381.

[13] Mayr, J., Jedrzejewski, J., Uhlmann, E., Alkan Donmez, M., Knapp, W., Härtig, F., Wendt, K., Moriwaki, T., Shore, P., Schmitt, R., Brecher, C., Würz, T., Wegener, K., 2012. Thermal issues in machine tools. CIRP Annals-Manufacturing Technology, 61 (2), 771-791.

[14] Eskandari, S., Arezoo, B., Abdullah, A., 2012. Positional, geometrical, and thermal errors compensation by tool path modification using three methods of regression, neural networks, and fuzzy logic. The International Journal of Advanced Manufacturing Technology, 65 (9-12), 1635-1649.

[15] Tseng, P.-C., Chen, S.-L., 2002. The neural-fuzzy thermal error compensation controller on CNC machining center. JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing, 45 (2), 470-478.

[16] Abdulshahed, A. M., Longstaff, A. P., Fletcher, S., 2015. The application of ANFIS prediction models for thermal error compensation on CNC machine tools. Applied Soft Computing, 27, 158-168.

[17] Fan, K., Yang, J., Yang, L., 2015. Unified error model based spatial error compensation for four types of CNC machining center: Part I—Singular function based unified error model. Mechanical Systems and Signal Processing, 60–61 (0), 656-667.

[18] Qianjian, G., Jianguo, Y., Application of projection pursuit regression to thermal error modeling of a CNC machine tool. The International Journal of Advanced Manufacturing Technology, 2010, 55: (5-8): 623-629.

[19] Yao, X., Fu, J., Xu, Y., He, Y., 2013. Synthetic Error Modeling for NC Machine Tools based on Intelligent Technology. Procedia CIRP, 10, 91-97.

[20] Zhang, J. F., Feng, P. F., Chen, C., Yu, D. W., Wu, Z. J., 2013. A method for thermal performance modeling and simulation of machine tools. International Journal of Advanced Manufacturing Technology, 68 (5-8), 1517-1527.

[21] Miao, E.-M., Gong, Y.-Y., Niu, P.-C., Ji, C.-Z., Chen, H.-D., 2013. Robustness of thermal error compensation modeling models of CNC machine tools. The International Journal of Advanced Manufacturing Technology, 69 (9-12), 2593-2603.

[22] Ma,C., Liu, J. Wang, S., 2020. Thermal error compensation of linear axis with fixed-fixed installation. International Journal of Mechanical Sciences, 175,105531.

[23] Fu, G., Tao, C. Xie, Y., Lu, C. Gao, H., 2021. Temperature-sensitive point selection for thermal error modeling of machine tool spindle by considering heat source regions. The International Journal of Advanced Manufacturing Technology, 112, 2447–2460.

[24] Schwenke, H., Knapp, W., Haitjema, H., Weckenmann, A., Schmitt, R., Delbressine, F., 2008. Geometric error measurement and compensation of machines—An update. CIRP Annals-Manufacturing Technology, 57 (2), 660-675.

[25] Chen, B., Zhang, X., Zhang, H., He, X., Xu, M., 2014. Investigation of error separation for three-dimensional profile rotary measuring system. Measurement, 47, 627-632.

[26] Yang, Z., Sun, M., Li, W., Liang, W., 2010. Modified Elman network for thermal deformation compensation modeling in machine tools. The International Journal of Advanced Manufacturing Technology, 54 (5-8), 669-676.

[27] Fan, K.-C., Chen, H.-M., Kuo, T.-H., 2012. Prediction of machining accuracy degradation of machine tools. Precision Engineering, 36 (2), 288-298.