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MACHINE TOOL DISTORTION ESTIMATION DUE TO ENVIRONMENTAL THERMAL FLUCTUATIONS – A FOCUS ON HEAT TRANSFER COEFFICIENT

Thermally induced errors have been approached in multiple ways due to the influence these have over the positional accuracy of a machine tool. Here, approaches regarding environmental thermal fluctuations surrounding a machine tool remain to be explored in detail. These fluctuations have been explored in terms of the heat transfer coefficient and thermal radiation of the machine shop walls, as well as in terms of seasonality and varying thermal gradients. This paper presents additional considerations regarding environmental temperature perturbations, as heat transfer coefficient fluctuations in the machine shop were thought to play a significant role in machine tool thermal deformation a broader term for these phenomena, environmental thermal fluctuations, was defined and evaluated. Specifically, an environmental thermal data survey of a machine shop was explored. This data was then applied to a NC milling machine and a CNC jig borer FEM analyses and compared to experimental data. FEM simulations were then used to demonstrate that convection regimes and heat transfer coefficient values at a machine shop have a significant influence over machining precision. Here, under maximum and minimum heat transfer coefficient values, the NC milling machine and CNC jig borer simulations results showed an error of cut difference up to 36.5 μm and 18.17 μm, respectively. In addition, as the importance of the heat transfer coefficient was highlighted, considerations regarding machine tool surface color were deemed relevant and were described.

1. INTRODUCTION

Thermally induced errors have been approached in multiple ways due to the influence these have over the positional accuracy of a machine tool. Here, comprehensive compilations regarding the status of thermal error researches that cover a wide range of topics, from error compensation to thermo-mechanical error analysis, are currently available [1]. Nevertheless, while thermal issues have been a subject of study since the 1960s [2], these issues still

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represent around 70% − 75% of the overall geometrical errors during machining [1, 3]. As the modern industry is continuously evolving and increasingly demanding a high precision and superior quality machining, researches have been focusing on designs that simultaneously approach thermal, stiffness and durability issues [4], as well as presenting designs that model and actively decrease thermal deformation through comprehensive temperature control systems [5, 6].

In the same way, current technology trends have allowed the development of promising thermal error behavior prediction methods based on the finite element method (FEM) [7, 8] and neural networks [9]. Here, thermal deformation prediction models have also incorporated transfer functions between defined surface temperatures and the relative displacement over the machining area [10]. FEM analyses have also shown considerable results in terms of thermal error prediction and reduced time scales that represent shorter machine downtimes [7, 11]. Nevertheless, the lack of comprehensive machine tool testing due to the industry reluctance to compromise machine availability has meant that many of the aforementioned methods will not see the implementation phase [7]. This because most machine tool builders have shifted the responsibility to test and manage thermal errors to the users by setting environmental thermal requirements or procedures such as unproductive warm-up times [1].

Here, approaches regarding environmental thermal fluctuations, a broader term that was selected to refer to temperature and heat transfer perturbations, surrounding a machine tool remain to be explored in detail. It must be noted that while the heat transfer coefficient is a variable that cannot be directly measured, empirical approaches have been explored [12]. The coefficient influencing factors (i.e. temperature distribution of the structure, surface orientation, ambient temperature and temperature-dependent material properties) have been approached in order to determine an iterative method that constantly actualizes heat transfer coefficient measurements to generate better FEM simulations [12]. Environmental thermal fluctuations have been explored in terms of the heat transfer coefficient and thermal radiation of the machine shop walls [13], as well as in terms of seasonality and varying thermal gradients [14]. The concept of varying thermal gradients in the shape of environmental temperature perturbations is not new but it has been observed that the heat transfer coefficient is often regarded as a constant that is not dependent of seasonality [7, 13, 14]. In addition, the determination of thermally sensitive points of a machine tool was considered as relevant for a future comprehensive monitoring of thermal fluctuations in machine tools [15].

This paper presents an improved approach to environmental thermal fluctuations by analyzing heat transfer coefficient variation in detail. Here, said variation was thought to influence machine tool thermal deformation in a machine shop environment. Specifically, a yearlong environmental thermal data survey of a conventional machine shop was explored. The machine shop temperature was measured using conventional thermocouples and the heat transfer coefficient was measured using a device developed in previous researches that consisted in a silicone rubber heater and two aluminum plates surrounding it [16, 17]. This data was then applied to a NC milling machine and a CNC jig borer FEM analyses and compared to experimental data. FEM simulations were then used to demonstrate that convection regimes at a machine shop have a significant influence over machining precision. Here, previously registered maximum and minimum heat transfer coefficient values were applied to the NC milling machine and CNC jig borer simulations in order to calculate the difference that exists between the machining error under a minimum heat transfer coefficient constraint and a maximum heat transfer coefficient constraint. Finally, as the importance of the heat transfer coefficient was highlighted and given that the heat transfer coefficient is influenced by temperature-dependent material properties [12], considerations regarding the machine tool surface color in terms of thermal radiation influence were deemed as relevant.

2. TEMPERATURE AND HEAT TRANSFER COEFFICIENT SURVEY

Temperature and heat transfer coefficient values at a conventional machine shop were surveyed throughout a yearlong period and under different weather regimes (Spring 2014 – Winter 2015). This machine shop, shown in Fig. 1, was located at the Nagaoka University of Technology in Northern Japan, an area which is known for its well defined seasons. The details of this concrete structure are shown in Table 1. Here, it is relevant to mention that the heating devices and fans were not positioned within a 5 m range of the machine tools. As mentioned in Chapter 1, the temperature fluctuations shown in Fig. 2 were obtained by positioning Type T thermocouples at the center of the machine shop at a height of 1000 mm and 1800 mm. In the same way, the heat transfer coefficients in Fig. 3 were measured by vertically positioning a previously developed device at a height of 1000 mm and 1800 mm.

Table 1. Specifications of the surveyed machine shop

Dimensions	Surface area: 26 × 14 m Height: 7 m
Total machine tools (Machine tool occupied area rate)	52 (54 %)
Average factory users	20/day
East wall dimensions (Area occupied by windows)	28 m × 7 m (23 %)
South wall dimensions (Shutter dimensions)	14 m × 7 m (3.6 m × 3.6 m)
West wall dimensions (Entrance dimensions)	28 m × 7 m (2.4 m × 2.5 m)
North wall dimensions (Amount of ventilation units)	14 m × 7 m (2)
– Spring: windows are closed. – Summer: windows are opened; five fans are used. – Autumn: windows are opened. – Winter: windows are closed; central heating and 4 heaters are used.	

Even though heat transfer coefficient cannot be directly measured, empirical approaches have been explored; here, surface element orientation is known to affect this coefficient [12]. Particularly, this device consisted in a silicone rubber heater (120 V, 500 W) measuring 127 mm × 127 mm × 1 mm, two aluminum plates attached to the heater sides (two surface element orientations) measuring 127 mm × 127 mm × 2.5 mm, T type thermocouples measuring the temperatures of the plates and T type thermocouples positioned at a 50 mm perpendicular distance from the plates center. Here, heat transfer coefficients surrounding the device can be calculated as the device area, a temperature differential and the heat flux are known [16, 17].

During winter, weather regimes were deemed to be hard to satisfy and measurements were set as days of the week. As machine shop operation throughout the year was constrained to weekdays, resting periods would imply a building cooling period, representative evaluation days were selected. In Fig. 2, it was observed that weather regimes had a small impact (max. 4°C range), ventilation caused greater variability and the winter regime simply accumulated temperature throughout the week. In Fig. 3, it was observed that regimes with convection factors (e.g. heating systems, open windows, fans) generated heat transfer coefficient values with a maximum difference of up to almost 3 W/(m^{2}K) as opposed to the closed windows regime that observed a maximum heat transfer coefficient difference of about 1.5 W/(m^{2}K). Here, winter and summer exhibited the largest thermal environmental fluctuations.

Fig. 1. Machine shop at Nagaoka University of Technology, Niigata, Japan

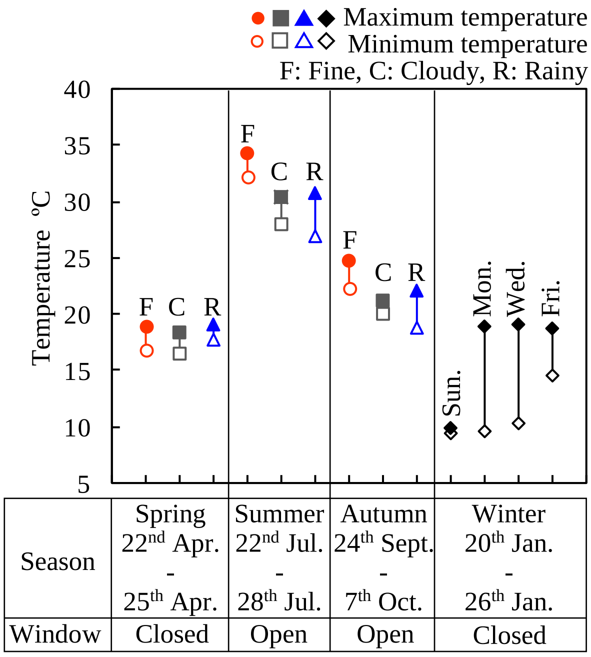

Fig. 2. Temperature fluctuation in machine shop in a yearlong period

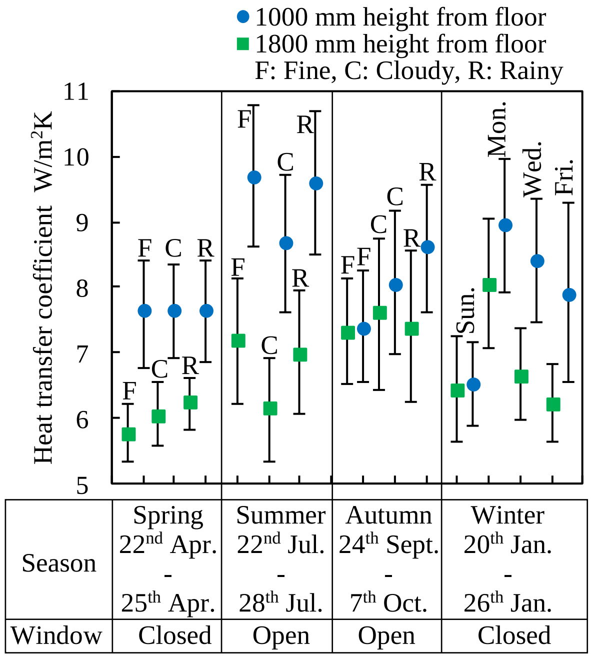

Fig. 3. Heat transfer coefficients of the surveyed machine shop in a yearlong period

3. FEM MODELLING SETUP

In this research two different machine tools, a NC milling machine and a CNC jig borer machine, were used to estimate the influence of environmental thermal fluctuations both through FEM simulations and experimentation. The specifications of the aforementioned machines are shown in Table 2. In this chapter, modelling, meshing, boundary conditions, and considerations regarding simulation evaluation were covered. Here, in order to achieve a smooth and optimized set of analysis, idealized models of both the NC milling machine and the CNC jig borer were created. Similar to literature that explores environmental temperature perturbations [7,14], relevant structural elements such as the carrier, front and rear bearings, spindle, table and tool were generated in detail in a SolidWorks company software platform.

Table 2. Specifications regarding the NC milling machine and the CNC jig borer

Parameters			NC milling machine	CNC jig borer
Table working surface		mm	610 × 381	620 × 320
Table loading weight		kg	250	150
Total table travel	X-axis Y-axis Z-axis	mm	510 381 460	510 310 385
Distance from the table top face to the surface of the spindle nose		mm	100 – 560	110 – 495
Spindle speed		min^{-1}	180 – 7000	200 – 10000
Feed speed		mm/min	0 – 5000	1 – 3600
Motor output		kW	5	1.5
Machine weight		kg	2600	4500

Nodes: 3121
Elements: 2523
Heat source:
- Front bearing: 28 W
- Rear bearing: 14 W

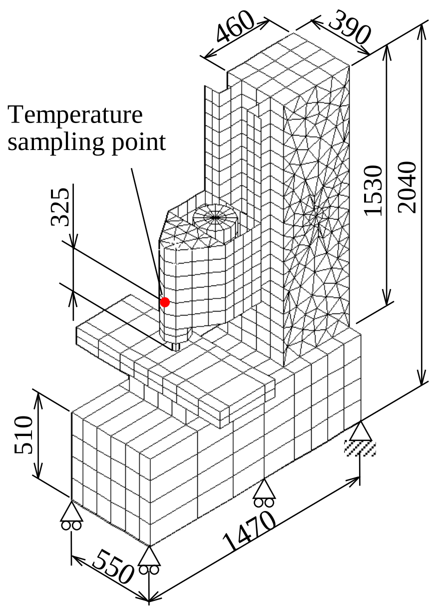

Fig. 4. Meshed FEM model of the NC milling machine

A simplified model of the NC milling is shown in Fig. 4. The meshing utilized for the FEM simulation of the NC milling machine relied on the software default meshing technique and generated 3121 nodes and 2523 elements. Here, the boundary conditions utilized were two heat sources in terms of the front bearing (28 W) and the rear bearing (14 W) as well as the environmental thermal fluctuations measured in the previous chapter, temperatures and heat transfer coefficients, were applied to the whole machine tool surface. Here, as it is common practice to utilize experimental temperature measurements as input to calculate heat transfer coefficient values through the inverse analysis method, FEM simulations were utilized as a tool to obtain the heat source values shown through a heat inverse analysis problem procedure. Moreover, it must be considered that for the FEM simulations the temperature variation of the machine tool was measured based on a representative temperature sampling point near the machine tool carrier as shown in Fig. 4. In the same way, the relative displacement, result of thermal deformations, between the spindle top surface and the table center was defined as "error of cut" during the simulation stage as this was considered to emulate the thermally induced error during machining experimentation. Here, different definitions exist as current environmental temperature perturbations researches utilize displacements in the X-plane, Y-plane and Z- plane as error measurements [7, 14].

A simplified model of the CNC jig borer is shown in Fig. 5. The meshing utilized for the FEM simulation of the CNC jig borer relied on the software default meshing technique and generated 9990 nodes and 5827 elements. The boundary conditions for this simulation were the two heat sources, obtained through heat inverse analysis, at the front bearing (25 W) and the rear bearing (32 W), and the application of previously presented temperatures and heat transfer coefficients over the machine tool surface. The FEM simulations used a sampling point near the machine tool carrier as shown in Fig. 5. Similar to the NC milling machine, the simulated relative displacement between the spindle top surface and the table center was defined as "error of cut" as this emulates the thermal error during machining operations.

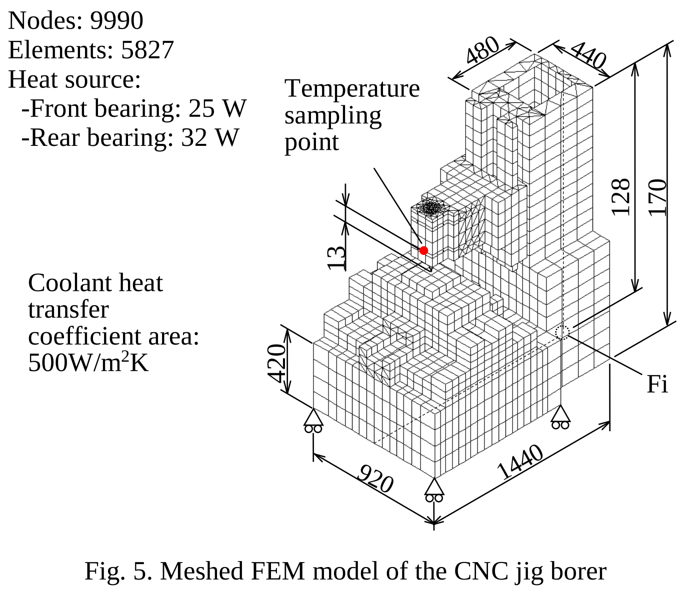

Fig. 5. Meshed FEM model of the CNC jig borer

In addition, as the NC jig borer utilized a ball screw (Temperature: Room temperature ±0°C) and a cooling lubricant (Temperature: Room temperature –1°C) with defined temperatures during experimentation, the cooling lubricant thermal effects over the machine tool deformation behavior were deemed as necessary. In order to approximate the cooling lubricant thermal effects during the FEM simulations, an area surrounding the machine tool table was defined to have a heat transfer coefficient of 500 W/m^2K specific to the cooling lubricant, which was obtained through a thermal inverse analysis procedure.

4. EXPERIMENTAL AND SIMULATED RESULTS VALIDATION

In order to validate the precision of the FEM simulations, a series of experiments were carried out to increase reliability. These experiments consisted in grooving machining of S55C (JIS) (Width 40 mm × Length 85 mm × Thickness 20 mm) and the tool used was an end-mill with a 6 mm diameter. The machining strategy consisted in machining several grooves over the workpiece at different subsequent times in order to appreciate thermally induced machining errors. The defined times for the machining of grooves were the following: 0, 0.5, 1, 1.5, 2.0, 3.0, 4.0, 6.0, 8.0 (hours). Here, the interval between machining times was defined as "idle mode" and the spindle was kept running. The machining parameters were the following; Spindle speed: 4700 rpm (2000 rpm in idle mode), Feed speed: 280 mm/min, Cutting speed: 89 m/min. The grooving machining conditions were the following; Depth of cut: 40 μm, Length of cut: 40 mm, Width of cut: 6 mm. Subsequently, an analysis of the machining precision, the workpiece was left three days in a controlled temperature room after machining, was performed using a digital micrometer and measuring the difference between each machined groove depth when compared to the initial machined groove (target value = 40 μm). For each groove, the depth was measured in 5 points and the average was considered as the representative depth. This difference was then considered as the machining precision or "error of cut" during experimentation (e.g. 10 μm error cut would be a 50 μm depth value).

4.1. NC MILLING MACHINE SIMULATION AND ASSESSMENT

In Fig. 7, a compilation of NC milling machine maximum error of cut values in a yearlong period is shown. Here, it is possible to observe that both the FEM calculated values and the experimental values closely approximate. However, in order to observe the relationship between machining time and error of cut an example, shown in Fig. 6, was randomly selected and shows the NC milling machine temperature and error of cut values during a fine summer day cycle of 8 hours. In the same way, it is possible to observe that the FEM calculated values and the experimental values closely approximate when observed in terms of time during one cycle. As a results, it was assumed that the environmental thermal fluctuation data surveyed, temperature and heat transfer coefficient, did indeed have a significant influence over the machine tool thermal behavior and that the proposed simulation procedure was appropriate for the prediction of said behavior.

In Fig. 7, it is possible to observe that the error of cut during summer is particularly small, possibly due to the presence of large heat transfer coefficient values and a NC machine head stock effective cooling due to the convection regime of open windows and ventilating fans. However, the observed maximum error of cut during winter presented significantly large values due to their constrained regime of closed windows and heaters that affect convection. Thus, the observed maximum error of cut difference (15 µm), between summer and winter measurements, was arguably due to environmental thermal fluctuations at the machine shop. Here, seasonality and weather considerations regarding the management of the machine tool environment are important. Heat transfer coefficient and temperature data used on the FEM results from spring to autumn achieved a higher precision than those of winter. This, given that the winter data affected by convective interactions, such as a heater system and the closed windows regime, largely influenced FEM approximations. Consequently, it was thought that monitoring of environmental thermal fluctuations as well as iterative procedures to measure them are necessary to develop both improved machine tools and machine shops [12, 15].

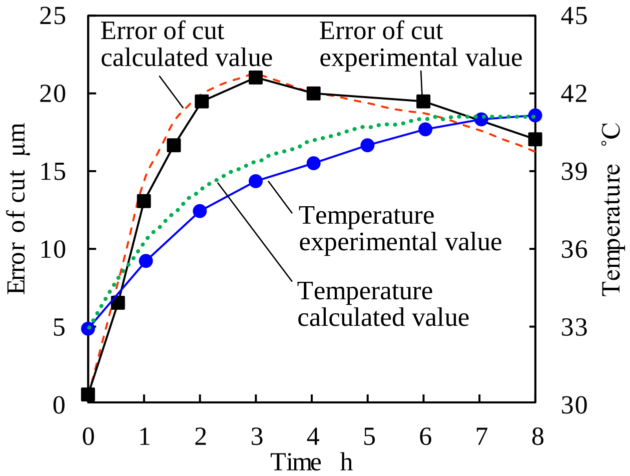

Fig. 6. NC milling machine temperature and error of cut values during a fine summer day cycle

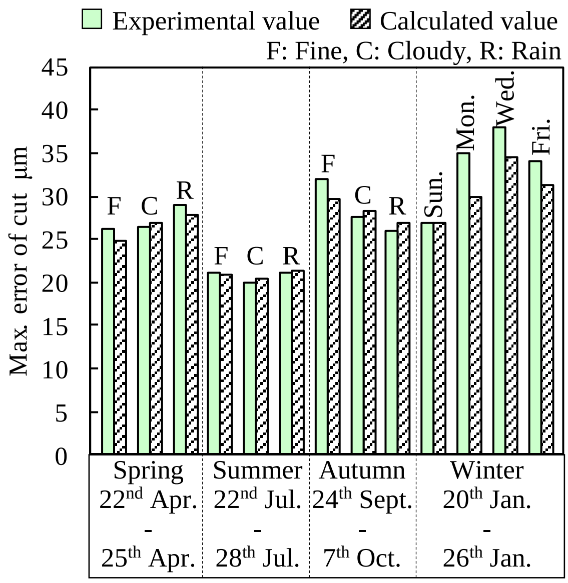

Fig. 7. NC milling machine maximum error of cut values in a yearlong period

4.2. CNC JIG BORER MACHINE SIMULATION AND ASSESSMENT

In Fig. 9, a compilation of CNC jig borer machine maximum error of cut values in a yearlong period is shown. Here, it is possible to observe that both the FEM calculated values and the experimental values closely converge. Nevertheless, in order to observe the relationship between machining time and error of cut an example, shown in Fig. 8, was randomly selected and shows the CNC jig borer machine temperature and error of cut values during a winter Friday cycle of 8 hours. In this regard, it is possible to observe that the FEM calculated values and the experimental values closely approximate when observed in terms of time during one cycle. Consequently, it was assumed that the environmental thermal fluctuation data surveyed, temperature and heat transfer coefficient, and coolant thermal properties did indeed have a significant influence over the machine tool thermal behavior and that the proposed simulation procedure was appropriate for the prediction of said behavior.

In Fig. 9, it can be observed that error of cut values are steady from spring to autumn but during winter said values become large. However, as the previous section already discussed the change of convection regimes throughout a year, this section pretends to stress the difference between the NC milling machine that does not use any kind of cooling and the CNC jig borer forced machining cooling. Here, the positioning accuracy for the CNC jig borer was 0.1μm (high precision machine). However, maximum errors of cut on the CNC jig borer at the machine shop during spring, summer and autumn ranged from 3.0 μm to 8.0 μm and in winter it was about 12μm. This was thought to be caused, particularly in the winter case, due to the temperature gradient generated from the use of forced cooling during machining (Coolant temperature: Room temperature –1°C) and the temperature of the ball screw (Temperature: Room temperature ±0°C). Nevertheless, here it was noted that the coolant could be set in thermal synchronicity with the machine tool temperature which in a FEM simulation would yield an error of cut that ranged from 2.0 μm to 3.0 μm.

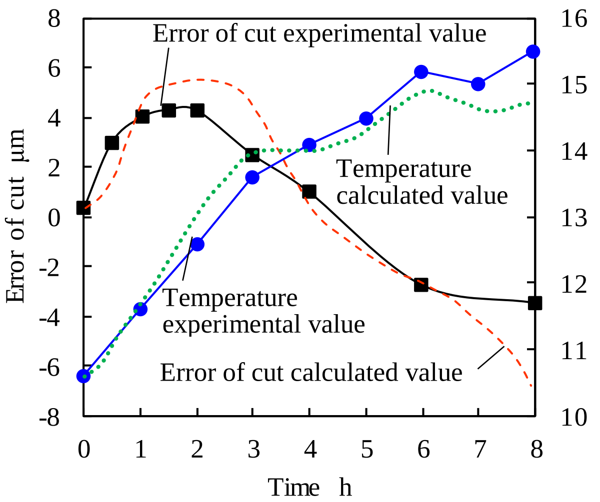

Fig. 8. CNC jig borer temperature and error of cut values during a winter Friday cycle

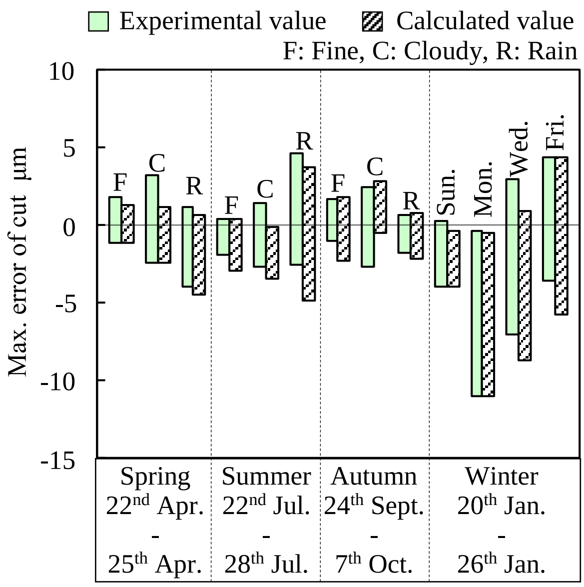

Fig. 9. CNC jig borer maximum error of cut values in a yearlong period

5. HEAT TRANSFER COEFFICIENT INFLUENCE

The modelling developed in previous sections was proved to accurately approximate the thermal behavior of the NC milling machine and the CNC milling machine due to environmental thermal fluctuations. Nevertheless, as the heat transfer coefficient in the machine shop was thought to play a major role in machine tool thermal behavior, this chapter applied previously registered maximum and minimum heat transfer coefficient values to additional NC machine and CNC jig borer simulations in order to calculate the difference that exists between the machining error under a minimum heat transfer coefficient constraint and a maximum heat transfer coefficient constraint. In this regard, Table 3 presents the maximum and minimum heat transfer coefficients found in literature and the ambient temperature gradient used in the FEM simulations used to determine the heat transfer coefficient influence.

Table 3. FEM boundary conditions used for the heat transfer influence analysis

Condition	Value
Maximum heat transfer coefficient (Forced convection)	48.8 W/m^2K (Wind velocity: 1.55 m/s) (References [18−22])
Minimum heat transfer coefficient (Natural convection)	7 W/m^2K (References [18−22])
Note: Ambient temperature used was based on the measurements that exhibited the greatest temperature change (January 23rd, 2015) on a single 9-hour shift day at the central machine shop of the Nagaoka University of Technology.	

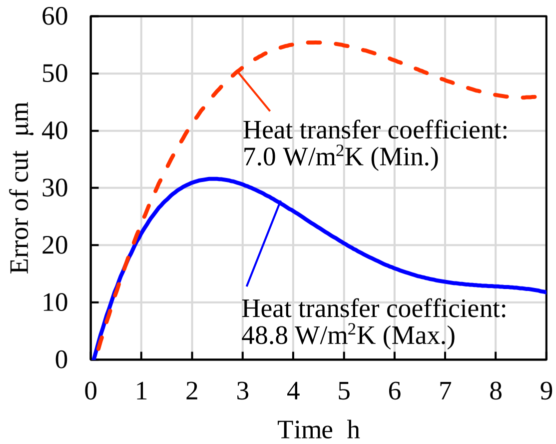

Fig. 10. NC milling machine error of cut simulated values under different heat transfer coefficients

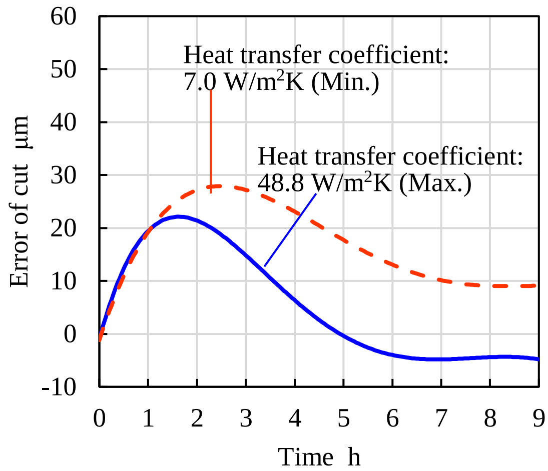

Fig. 11. CNC jig borer error of cut simulated values under different heat transfer coefficients

The results of the FEM simulations used to determine the heat transfer coefficient influence are shown in Fig. 10 and Fig. 11. It must be noted that the maximum heat transfer coefficient and the minimum heat transfer coefficient utilized for simulation and gathered from literature respond to two different convection regimes, a comparison to the changing convection regimes observed at the surveyed machine shop, that include a forced convection (heat transfer coefficient of 48.8 W/m^2K and a wind velocity of 1.55 m/s) and a natural convection regime (heat transfer coefficient of 7 W/m^2K). In Fig. 10, the results of the NC milling machine FEM simulations utilizing a maximum and minimum heat transfer coefficients are shown. Similarly, in Fig. 11, the results of the CNC jig borer FEM simulations utilizing a maximum and minimum heat transfer coefficients are shown.

In the case of the NC milling machine FEM simulations, while a mounting error of cut was expected, it was interesting to notice that, unlike the significant temperature increase shown in the time-dependent Fig. 6, the heat transfer coefficient related error of cut peaks early in the FEM simulation. Even more, when calculating the difference that exists between the machining error under a minimum heat transfer coefficient constraint and a maximum heat transfer coefficient constraint, the maximum difference was observed to occur not until after 6 hours with a 36.5 μm gap. On the other hand, in the case of the CNC jig borer FEM simulations, while a mounting error of cut was expected, it was interesting to notice that, unlike the significant temperature increase shown in the time-dependent Fig. 8, the heat transfer coefficient related error of cut peaks early in the FEM simulation. Moreover, when calculating the difference that exists between the machining error under a minimum heat transfer coefficient constraint and a maximum heat transfer coefficient constraint, the maximum difference was observed to occur not until after 5 hours with an 18.17 μm gap.

Here, it must be stressed that the aforementioned gaps represent a significant issue for precision machining operations. This issue, as part of the environmental thermal fluctuations, might have been overlooked but the validated FEM simulations shown above present a proof of principle regarding the influence of the heat transfer coefficient fluctuations. In the same way, to address this gap, given that the heat transfer coefficient is a variable that cannot be directly measured, technologies that constantly actualize heat transfer coefficient measurements in an iterative method to generate better FEM simulations could be utilized [11]; this considering that the heat transfer coefficient influencing factors are many (i.e. temperature distribution of the structure, surface orientation, ambient temperature and temperature-dependent material properties).

6. MACHINE TOOL SURFACE COLOR CONSIDERATIONS

In this last chapter, as the importance of the heat transfer coefficient was highlighted in chapter 5 through the definition of significant error of cut gaps and given that the heat transfer coefficient is influenced by temperature-dependent material properties [12], considerations regarding the machine tool surface color in terms of thermal radiation influence were deemed relevant. Specifically, data from machine tool builders gathered in a previously developed research that dealt with machine tool surface color was utilized [23]. Here, an experiment that measured the heat transfer coefficient of some machine tool surface color paints was explored.

The aforementioned experiment explored the relationship between thermal radiation, apparent heat transfer coefficient and surface color. Here, 8 samples of the developed device presented in chapter 2 were painted with paint used in commercially available machine tool surfaces, shown in Table 4, and put in a 1000 mm^3 container (at a room temperature of 20ºC ±1ºC; the geometric factor and absorption coefficient was set to 1.0 by covering the container walls with black oxide; air flux regulated with 10 mm ventilation openings). It was concluded from this experiment that the machine tool color surface influenced more the thermal behavior of the machine tool than the coloring of the machine shop walls [23]. The results to argue the aforementioned consideration are shown in terms of apparent heat transfer coefficient and heat flux in Fig. 12 and in terms of emissivity in Fig. 13. Specifically, while the emissivity for a black oxide covered device was 1 and 0.06 for aluminum, the maximum and minimum heat transfer coefficients measured were black oxide and aluminum paints, respectively.

Table 4. Machine tool surface color survey used for experimentation

Company (Color)	Munsell number	Paint material	Foundation
YA (Dark-gray)	7.5BG 4/1.5	Urea formaldehyde	Urea formaldehyde
Oe (Light-gray)	5Y 6/1	Epoxy	Primer
Ou (Light-gray)	5Y 6/1	Urea formaldehyde	Primer
YMb (Blue)	4PB 4/10	Epoxy	Primer
YMg (Green)	8.5GY 3.7/6.3	Epoxy	Primer
T (Orange)	1.5YR 6/12	Urea formaldehyde	Primer
U (Ivory)	10YR 8/3	Urea formaldehyde	Primer
K (Light-green)	2.8GY 6.5/2.8	Epoxy	Primer
(Metallic)	—	Aluminum	—
(Black)	—	Black oxide	—

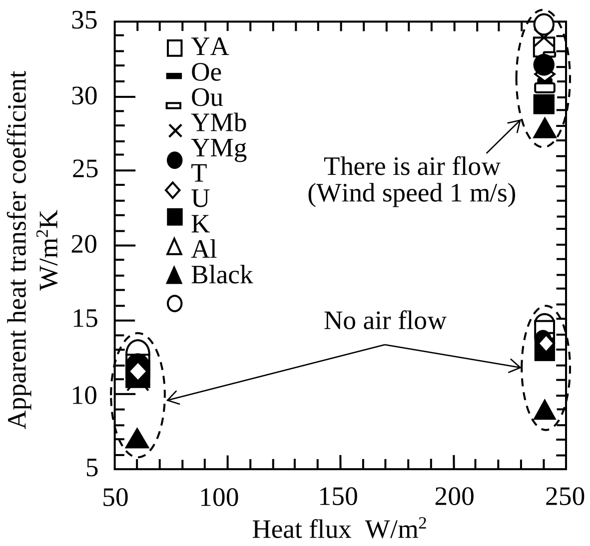

Fig. 12. Thermal radiation and heat transfer coefficient for multiple machine tool surface colors [23]

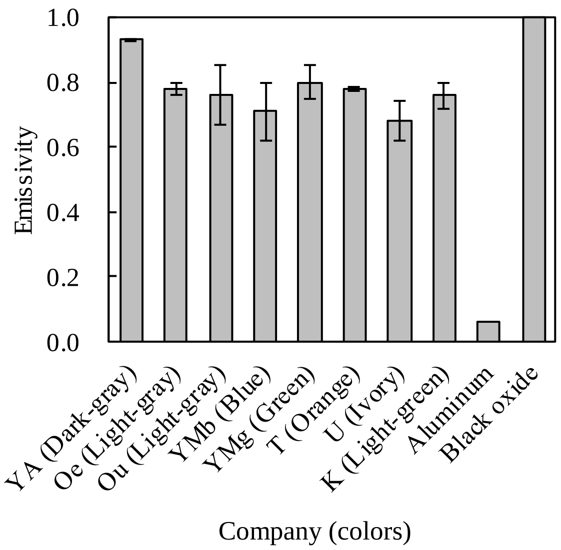

Fig. 13. Emissivities of the selected machine tool surface colors [23]

Even more, it was observed that machine color tool surface color largely influences the heat transfer coefficient when comparing paints in both convection regimes shown. Thus, it was thought that the current research would benefit from analyzing thermal radiation dependent material properties when considering overall machine shop environmental thermal factors.

7. CONCLUSIONS

1. It was possible to validate two different FEM models, a NC milling machine and CNC jig borer, through experimental data and available environmental thermal fluctuation data.
2. It was possible to determine the heat transfer coefficient influence over machining precision (error of cut) through FEM simulations utilizing the validated models and heat

transfer coefficient historical values. The NC machine and CNC jig borer simulations had an error of cut difference up to 36.5 µm and 18.17 µm, respectively.

3. As the importance of the heat transfer coefficient was highlighted, considerations regarding the machine tool surface color were also deemed relevant and explored.

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