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APPLICATON OF DESIGN RULES FOR THERMALLY INSENSITIVE MACHINES REGARDING A LATHE WITH ENCLOSURE

In a previous report, FEM (Finite Element Method) thermal simulation technology with 4 virtual models which are a virtual intake model, a virtual exhaust model, a virtual heat transfer model and a virtual convection model has been developed for analysis of the phenomenon of heat build-up in the enclosure. On the other hand, the heat from the internal heat source is transferred to the air in the enclosure and the warmed air causes thermal deformation of the machine structure, resulting in extremely complex thermal deformation. Therefore, in this research, thermally insensitive structure regarding a bench lathe with enclosure was considered by the previously proposed FEM thermal simulation. At first, an algorithm for the creation of thermally insensitive structure regarding the bench lathe with enclosure was considered. Then, the bench lathe with thermally insensitive structure was designed and evaluated using FEM thermal simulation. It is concluded from the result that (1) thermal deformation due to warmed air in the enclosure was identified, (2) the proposed structure can achieve a high degree of accuracy.

1. INTRODUCTION

High-precision industrial products are demanded, which in machine require high-precision machining of machine tools. Thermal countermeasures are essential for high-precision machining [1]. Thermal countermeasures are often used to reduce thermal deformation of machine tools [2–7], such as forced cooling [8, 9]. In these cases, FEM (Finite Element Method) thermal simulation is effectively used to qualitatively and quantitatively understand thermal problems of machine tools in advance during the design stage, and to study countermeasures against them. In recent years, machine tools must be interlocked for safety, and machine tools with enclosures and TVS (Thermal-Volumetric Space) are common (hereinafter referred to as machine tools with enclosure). However, the heat from the internal heat source is transferred to the air in the enclosure and the warmed air causes thermal

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deformation of the machine structure, resulting in extremely complex thermal deformation [10–13]. Nowadays, it has become common practice to cover the main body of most machine tools with enclosures, and the research on this is desired [5, 14, 15], however at present there are currently few research reports in the world, although it is urgent and essential.

In previous our research, the new FEM thermal simulation technology for the thermal behaviour in a machine tool with enclosures was developed [16]. The thermal behaviour in the CNC lathe with enclosure was experimented for evaluation the proposed FEM simulation technology in the reference. As the results, the proposed FEM thermal simulation technique was able to accurately calculate thermal deformation and processing accuracy with respect to the heat build-up phenomenon in the enclosure, and it has been shown that thermal deformation caused by the warmed air in the enclosure affects the machining accuracy of the of CNC lathe.

Therefore, in this research, thermally insensitive structuring regarding a bench lathe with enclosure was considered by the proposed FEM thermal simulation. At first, an algorithm for the creation of thermally insensitive structure regarding a bench lathe with enclosure was considered. The bench lathe with thermally insensitive structure is designed and evaluated using FEM thermal simulation.

2. ALGORITHM FOR THERMALLY INSENSITIVE STRUCTURE REGARDING A BENCH LATHE WITH ENCLOSURE

A thermally insensitive structure is one in which machining accuracy is not affected by thermal deformation of the machine tool. The use of thermally insensitive structure eliminates the need for forced cooling, refrigeration and its energy. In this research, the machine structure is designed so that the starting point of thermal deformation of the machine structure is near the machining point, so that machining accuracy is not affected by thermal deformation of the machine structure.

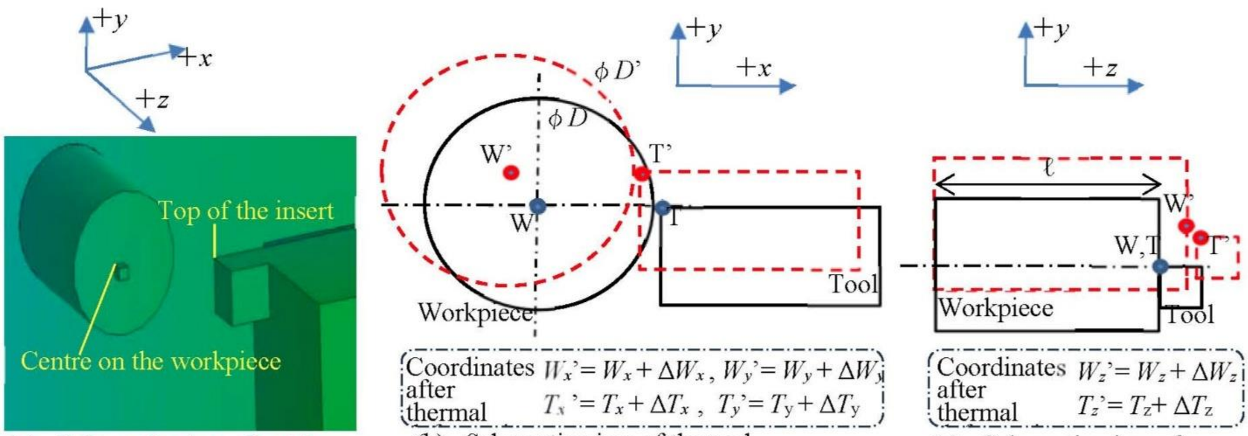
2. 1. FUNDAMENTAL POLICY FOR THERMALLY INSENSITIVE STRUCTURE

The relationship between thermal deformation of the lathe and the thermally insensitive structure was considered for high machining accuracy. Fig. 1 shows the changes in position and co-ordinates of the workpiece edge centre W and tool (insert) tip T before and after thermal deformation. The solid black lines before thermal deformation and the dotted red lines after thermal deformation are shown. The coordinates of the workpiece end face centre W before thermal deformation are (W_x, W_y, W_z) and those of the tool tip T are (T_x, T_y, T_z), while those of the workpiece end face centre W' after thermal deformation are ($W_x+\Delta W_x$, $W_y+\Delta W_y$, $W_z+\Delta W_z$) and those of the tool tip T' are ($T_x+\Delta T_x$, $T_y+\Delta T_y$, $T_z+\Delta T_z$). Where ΔW_x, ΔW_y, ΔW_z, ΔT_x, ΔT_y and ΔT_z are the thermal displacements in each axial direction of the centre W of the end face of the workpiece and the tool tip T. From Fig. 1(b), the diameter D' of the workpiece after thermal deformation is expressed by Equation (1).

$$D' = D + \Delta D = 2\times\sqrt{(D/2 - \Delta W_x + \Delta T_x)^2 + (\Delta W_y - \Delta T_y)^2} \quad (1)$$

Where ϕD is the diameter of the workpiece before heat deformation and ΔD is the machining error in diameter. Generally, the workpiece diameter is several millimeters to several tens of millimeters, and the thermal displacements ΔW_x, ΔW_y, ΔT_x and $\varDelta T_y$ in the x and y axes of the workpiece end face centre W and the tool tip T are several μm to several tens of μm. $(D/2\text{-}\Delta W_x+\Delta T_x)$ on the right-hand side of Equation (1) has a significant influence on the workpiece diameter after thermal deformation, while the influence of $(\Delta W_y-\Delta T_y)$ is very small. Therefore, a thermally insensitive structure of the workpiece and tool in the x-axis direction (smaller ΔW_x and ΔT_x) is effective to improve the machining accuracy of the workpiece diameter. The effect of a thermally insensitive structure in the y-axis direction (smaller ΔW_y and ΔT_y) is very small. From Fig. 1(c), the workpiece length l' after thermal deformation can be expressed by Equation (2).

$$l' = l + \Delta l = l - (\Delta W_z - \Delta T_z) \quad (2)$$



(a) Schematic view of cutting area (b) Schematic view of thermal deformation (c) Schematic view of thermal

Fig. 1. Calculation method for the machining accuracy using the analysis results of FEM static simulation

Where l is the length of the workpiece before heat deformation and Δl is the machining error in length. Thus, $(\Delta W_z-\Delta T_z)$ in the right-hand side of Equation (2) has a direct effect on the length of the works after thermal deformation. Therefore, a thermally insensitive structure of the workpiece and tool in the z-axis direction (smaller ΔW_z and ΔT_z) is effective for higher machining accuracy in the workpiece axial direction.

Based on the above considerations, a basic policy for the thermally insensitive structure was considered: I) First, a thermally insensitive structure is achieved by structural design alone, without forced cooling of the fuselage. This is also essential for energy saving, environmental protection and carbon neutrality. II) The design procedure was to first design a thermally insensitive structure against thermal deformation due to internal heat sources and then to adjust the thermally insensitive structuring against thermal deformation due to enclosure. III) For machining accuracy of the workpiece diameter, thermally insensitive structuring in the x-axis direction for the head stock and the tool post & the carriage respectively. IV) For machining accuracy of the workpiece length, thermally insensitive structuring in the z-axis direction at the location of the z-axis drive system. V) Mechanical elements with other internal heat sources are installed on the y-z plane at x=0, or made thermally symmetrical in the y-z plane at x=0. VI) If these are not possible, the mechanical elements with internal heat sources are installed outside the enclosure. VII) The enclosure should be thermally symmetrical in the y-z plane at x=0.

2.2. THERMALLY INSENSITIVE STRUCTURE FOR A HEAD STOCK (*X*-AXIS DIRECTION)

Since the workpiece is mounted on the head stock, its thermal deformation has a significant effect on machining accuracy. In this section, the machine structure is designed to tolerate large thermal deformation caused by the front and rear bearings, which are the internal heat sources in the head stock, and to maintain high machining accuracy.

A schematic diagram of the thermally insensitive structure for the head stock is shown in Fig. 2. As shown in the front view in Fig. 2(a), Wings A and A' installed on both sides of the head stock, which are supported by Legs B and B' respectively.

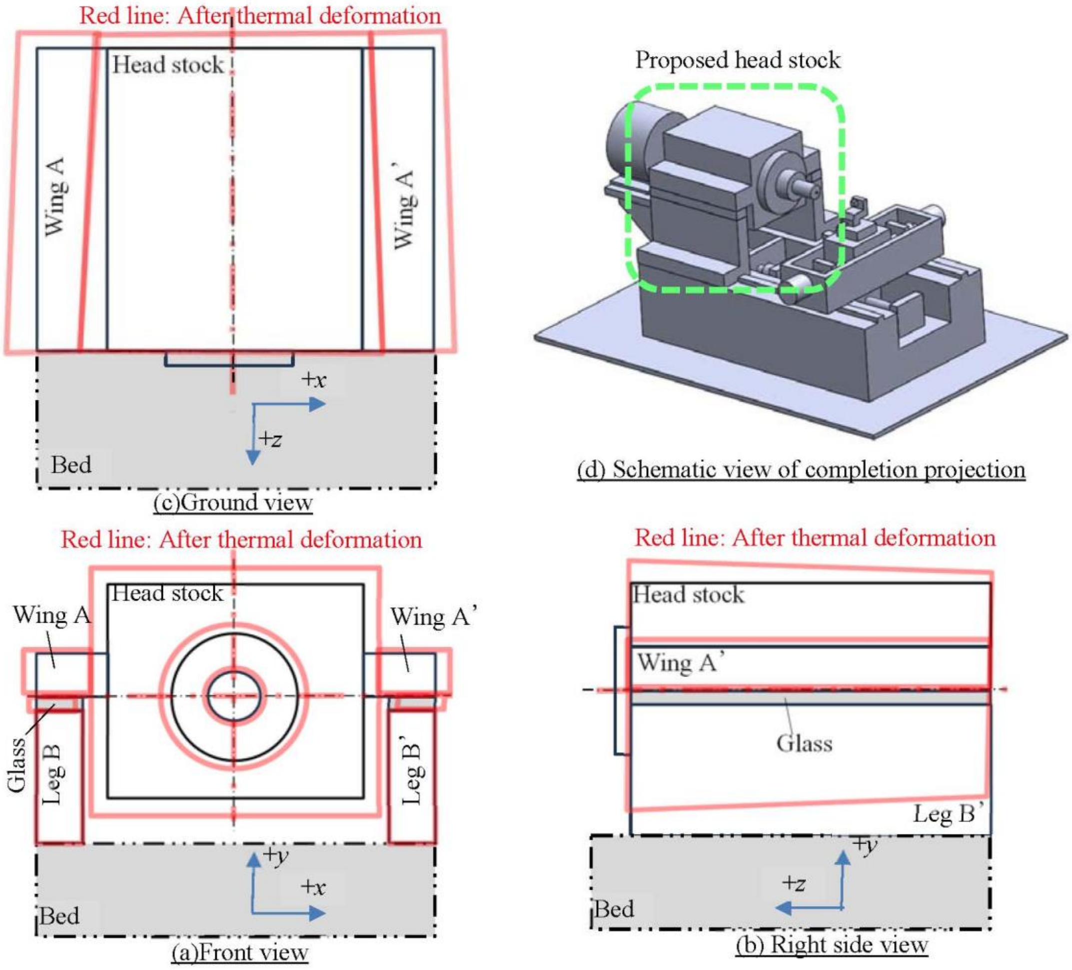


Fig. 2. Schematic view of the thermally insensitive structure for x-axis, y-axis, A-axis and B-axis directions on the head stock. Thermally insensitive structure of the two internal heat sources (front bearing and rear bearing) to thermal deformation

The top surfaces of the two glass plates are aligned with the centreline of the spindle. The two glass plates are thermal insulators, which reduce the conduction of heat from the spindle stand to the legs and the thermal deformation of the legs. The head stock is designed so that it is symmetrical with respect to the y-z plane at x=0. The black line is before thermal deformation and the red line is after thermal deformation. After thermal deformation, the head stock is larger due to thermal expansion. The heat generated by the front bearing is greater than that of the rear bearing because the rear bearing receives only radial loads while the front bearing receives thrust and radial loads, resulting in the head stock having a quadrangular pyramidal shape as shown in Fig. 2(b) and (c). If the head stock is mounted directly on the bed, as in a conventional lathe, these thermal deformations cause the spindle to rise in the +y direction and tilt in the -A-axis direction (rotation direction of x-axis), resulting in lower machining accuracy. In contrast, the proposed thermally insensitive structure has thermal displacements $\Delta x = 0$, $\Delta y = 0$, $\Delta A = 0$ and $\Delta B = 0$ in the x-axis, y-axis, A-axis and B-axis directions (in the direction of rotation of the y-axis) of the spindle centreline. This reason is because the proposed thermally insensitive structure of the head stock has the thermal deformation of the head stock, however the spindle centreline is the starting point of the thermal deformation, and as a result the spindle centreline is immobile before and after the thermal deformation.

Next, it is considered that the thermal deformation due to the enclosure affects the head stock, which is superimposed on the thermal deformation due to the internal heat source described earlier. At that time, the proposed thermally insensitive structure of the head stock in the x-axis direction (see Fig. 2) permits thermal deformation of the machine structure and the starting point of the thermal deformation is the spindle centreline, so that even if thermal deformation due to the enclosure is superimposed, it does not affect machining accuracy in the x-axis direction. However, Legs B and B' which support the head stock, are affected by the thermal deformation caused by the enclosure, so they are thermally deformed in the +y direction of the spindle centreline. This affects the thermally insensitive structuring in the y-axis direction. For this reason, it was decided to reduce the influence of thermal deformation in the y-axis direction on machining accuracy by cutting with the tool from the x-axis direction (See Section 2.1.). The tool post and the carriage also undergo similar thermal deformation in the +y direction due to the thermal deformation caused by the enclosure, so the thermal deformation (the +y direction) of the spindle rest is considered to be almost offset.

2. 3. THERMALLY INSENSITIVE STRUCTURE FOR A TOOL POST & A CARRIAGE (X-AXIS DIRECTIONS)

Since the tool is mounted on the tool post, thermal deformation of the tool post and the carriage has a significant effect on machining accuracy. In this section, thermal deformation caused by the motor for x-axis, the ball screw for x-axis, the motor for z-axis and the ball screw for z-axis as internal heat sources for the tool post and the carriage is tolerated to design a machine structure that enables highly accurate machining accuracy. When the internal heat source is a ball screw, the positioning error due to expansion and contraction of the ball screw has a significant effect on machining accuracy, in addition to the thermal deformation of the machine body structure. In this section, as an easy and inexpensive measure, the thermally insensitive structure in the *x*-axis direction, which has a significant influence on the machining accuracy of the workpiece diameter, is investigated.

As shown in Fig. 3, the tool post and the carriage are set up so that they are thermally symmetrical in the *y*-*z* plane at *x*=0. Therefore, the drive motors of *x*-axis are twin motors. The tool post and the carriage are always placed in the vicinity of the *x*=0, *y*-*z* plane (directly below the workpiece), and only a fine feed of the tool's depth of cut is performed. This makes the tool post and the carriage the starting point of deformation in the *x*-axis direction caused by the motor for *x*-axis, the ball screw for *x*-axis, the motor for *z*-axis and the ball screw for *z*-axis, and the tool post and the carriage are thermally insensitive to the *x*-axis direction. As shown in Fig. 4, a tool (insert) is mounted using an irregularly shaped tool holder to apply a cut from the *x*-axis direction. The tool holder is mounted at the centre of the carriage to ensure thermal displacement Δ*x*=0 of the tool tip. When the machining diameter of the workpiece changes significantly, the tool holder is replaced with a suitable one. The *x*-axis thermally insensitive structure of the head stock described in the previous section and the *x*-axis thermally insensitive structures of t the tool post and the carriage described in this section enable high machining accuracy of the workpiece diameter.

The effect of the thermal deformation due to the enclosure on the proposed thermally insensitive structure of the tool post and the carriage is then considered. Thermal deformation due to the enclosure also affects the tool post and the carriage, which is superimposed on the thermal deformation due to the internal heat source described earlier. At that time, the proposed thermally insensitive structure of the tool post and the carriage in the *x*-axis direction (see Fig. 3) permits thermal deformation of the machine body and the starting point of the thermal deformation is the carriage directly below the spindle centreline, so that even if thermal deformation due to the enclosure is superimposed, it does not affect machining accuracy in the x-axis direction.

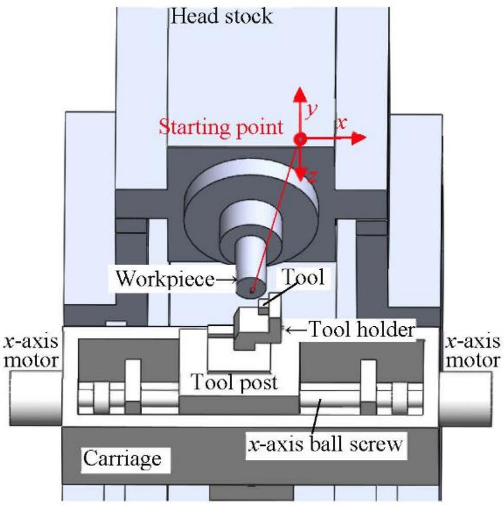


Fig. 3. Schematic view of the thermally insensitive structure for x-axis direction on the tool post and the carriage. The tool post and the carriage are symmetrically located in the *x*=0, *y*-*z* plane. Therefore, the x-axis driving system was used twin motors

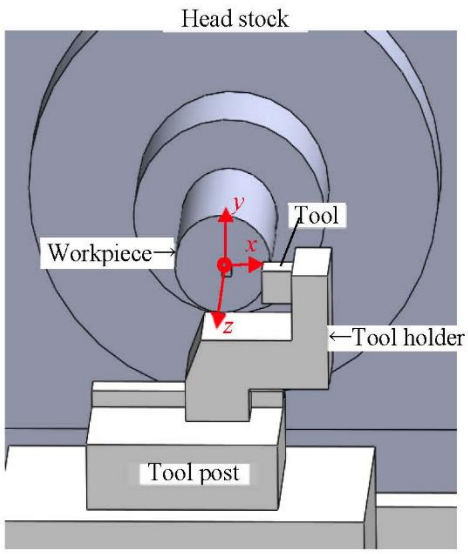


Fig. 4. The tool post is driven in the *x*=0, *y*-*z* plane (directly below the workpiece) for infeed movements. To make the cut from the *x*-axis direction, an odd-shaped toolholder is used

However, the tool post and the carriage structure are affected by the thermal deformation caused by the enclosure and the tool tip is thermally deformed in the +y direction. As in the previous section, this is not considered to affect the machining accuracy of the workpiece diameter.

2. 4. THERMALLY INSENSITIVE STRUCTURE FOR *Z*-AXIS DRIVING SYSTEM (*Z*-AXIS DIRECTION)

Thermal deformation in the *z*-axis direction of the head stock and the z-axis drive system has a significant influence on the machining accuracy of the workpiece length. For higher accuracy of the workpiece length (see Fig. 5, Equation (2)), it is effective to reduce the z-axis thermal displacements (ΔW_z and ΔT_z) of the workpiece and the tool. In this section, the thermally insensitive structure in the *z*-axis direction, which has a significant influence on the machining accuracy of the workpiece length, is investigated.

As shown in Fig. 5, the spindle is thermally deformed in the +z direction (ΔW_z) due to heat generated by the front and rear bearings. Therefore, as shown in Fig. 6, the starting point of the thermal deformation of the z-axis drive system is located directly under the workpiece in the machining area and synchronised with the thermal displacement ΔT_z of the tool in the +z direction. As the machining accuracy of the workpiece length is directly influenced by the z-axis thermal displacements ΔW_z and ΔT_z of the workpiece and tool, synchronising them enables a thermally insensitive structure in the *z*-axis direction. However, ΔW_z is affected by the amount of heat generated by the front and rear bearings, and ΔT_z is affected by the amount of by heat generated by the motor for *x*-axis, the ball screw for *x*-axis, the motor for *z*-axis and the ball screw for *z*-axis differs greatly depending on the machining conditions and workpiece material, making it difficult to achieve a completely thermally insensitive structure in the *z*-axis direction. Therefore, this countermeasure is designed to reduce the relative thermal displacement of the workpiece and tool in the z-axis direction. If the *z*-axis drive system is installed in the opposite direction, the thermal displacement -*z* in the *z*-axis direction will increase.

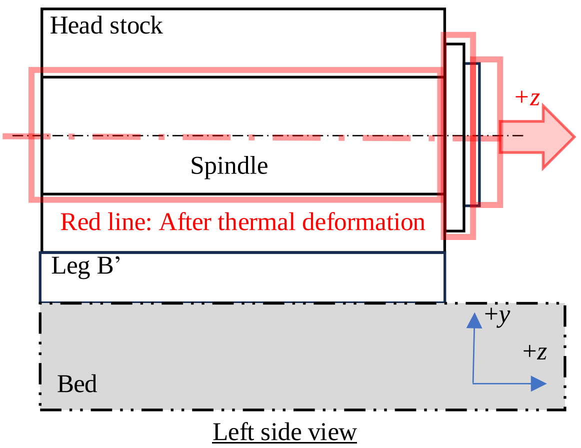


Fig. 5. The head stock is thermally deformed by the heat generated by the front and rear bearings, which thermally deforms the spindle in the +z direction

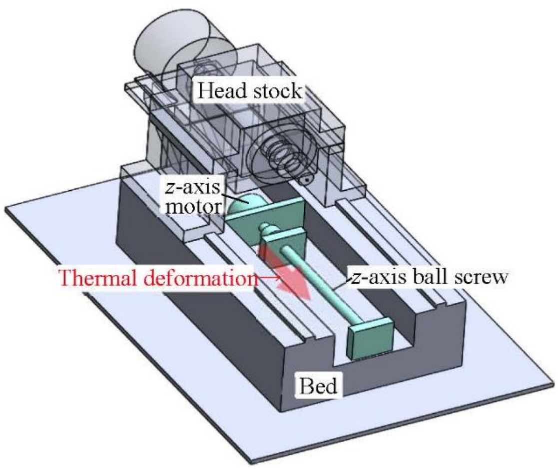


Fig. 6. The starting point for thermal deformation of the z-axis driving system is located directly below the workpiece in the cutting area

Then, the effect of the thermal deformation due to the enclosure on the proposed thermally insensitive structure of the z-axis drive system is considered. The z-axis drive system is affected by the thermal deformation due to the enclosure, which is superimposed on the thermal deformation due to the internal heat source mentioned earlier. In the thermally insensitive structure for z-axis (see Fig. 6), the thermal deformation due to the enclosure of the head stock, bed and z-axis drive system acts to cancel out. However, the heat capacity of each machine element is different, therefore it difficult to achieve a perfect z-axis thermally insensitive structure, even for thermal deformation due to enclosure. Thus, thermally insensitive structuring in the z-axis is difficult to achieve.

3. DESIGN AND EVALUATION OF THERMALLY INSENSITIVE STRUCTURE BENCH LATHE WITH ENCLOSURE

3. 1. DESIGN OF THERMALLY INSENSITIVE STRUCTURE BENCH LATHE WITH ENCLOSURE

A bench lathe with thermally insensitive structure and its enclosure are designed. Figure 7 shows the schematic view of the bench lathe, and Table 1 shows the specifications of the bench lathe. The bench lathe is designed with the same shape, referring to the basic policy described in the previous chapter.

Table 1 Specification of the bench lathe with thermally insensitive structure and the analysis condition

Specification of the bench lathe (See Fig.7)	
Head stock	Height of centre from bed: 175 mm
	Height of centre from floor: 335 mm
	Spindle speed: Max.3600 min^{-1}
	Front bearing: 50BNC10TYDBB
	Rear bearing: 45BN10TYDB
Bed	Size: 600×360×160 mm
Tool post	Stroke of x axis: 120 mm Stroke of z axis: 240 mm
Ball screw	x-axis: φ15 mm×210 mm, z-axis: φ20 mm×300 mm
Motor	Main: Power 0.75 kW, Inverter control x-axis: Twin motor, Power 30 W×2 z-axis: Power 50 W
Weight	200 kg

Analysis condition		
Heat insensitive structure bench lathe (See Fig. 7)		
With or without enclosure		With enclosure, Without enclosure
Internal heat sources using some rubber heater	Main motor	75 W
	Spindle front bearing	30 W
	Spindle rear bearing	15 W
	X-axis ball screw	2.2 W
	X-axis motor	15 W
	Z-axis ball screw	2.2 W
	Z-axis motor	30 W
Thermal boundary conditions		
Simulated thermal conductivity λ_H to simulate heat transfer coefficient in the enclosure: 0.135 W/mK ※Condition: Heat transfer coefficient 13.5 W/m^{2}K, Boundary layer thickness 0.01 m, Eq.→ [16]		
Simulated thermal conductivity λ_C to simulate convection in the enclosure: 714 W/mK ※ Condition: Representative length of convection layer 0.58 m, Wind velocity in enclosure 1m/s, Eq.→ [16]		
Heat transfer coefficient between the lathe and the outside air: 15.2 W/m^{2}K		

The machine structure is made of S45C and a 20 mm-thick quartz glass plate is inserted as a thermal insulator between the wings and the legs of the spindle head. The commercially available machine components are shown in Table 1. The head stock, bed and main motor are adapted from those used in a previous study [16]. The enclosure is simply made from a 1 mm-thick acrylic sheet.

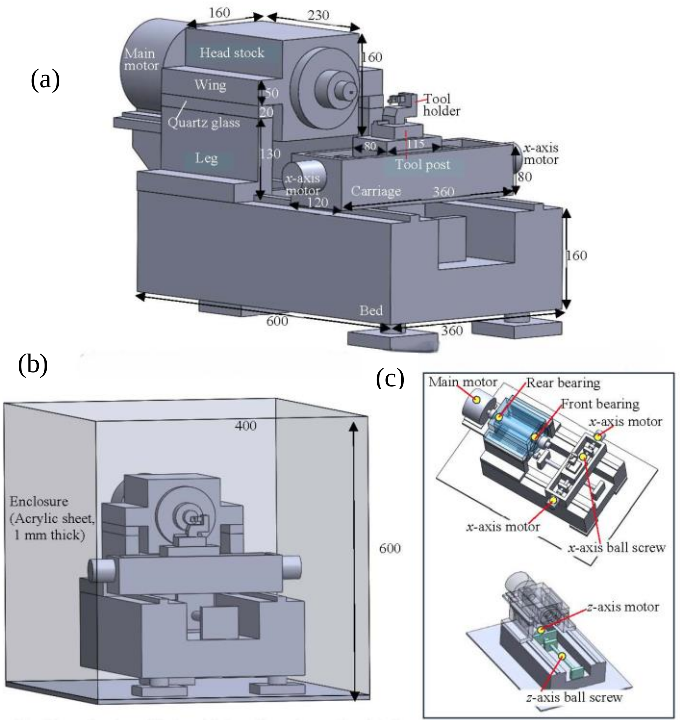


Fig. 7. Schematic view of the bench lathe with thermally insensitive structure (Enclosure hidden) – (a), Schematic view of the bench lathe with enclosure (Bench lathe hidden) – (b), Inner heat source positions – (c)

3. 2. ANALYSIS RESULTS OF THERMALLY INSENSITIVE STRUCTURE BENCH LATHE WITH ENCLOSURE

Figure 8 shows the FEM model of the bench lathe with thermally insensitive structure and the enclosure. When the number of nodes and elements was approximately doubled (number of nodes: 139325, number of elements: 74132), the machining error of the diameter (with enclosure) after 5 hours in Fig. 12(a) changed only about –0.58 μm from –0.59 μm.

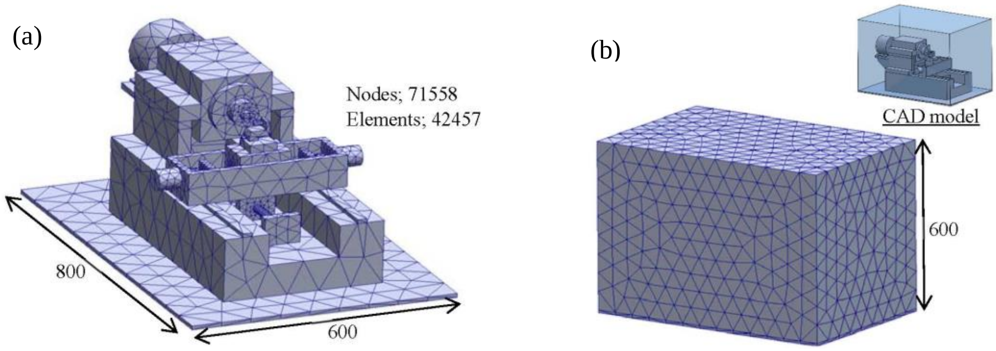


Fig. 8. FEM model with meshing for the heat insensitive structure bench lathe (Enclosure hidden) – (a), FEM model with meshing for the enclosure – (b)

It was therefore decided to use the FEM model of Fig. 8 from then on. In this chapter, this FEM model, analysis condition in Table 1 and the proposed FEM thermal simulation are used for analysis and evaluation. The inner wall of the enclosure of the bench lathe is covered by a heat transfer model (solid model with boundary layer thickness l_b) and furthermore, there is a convection model (solid model) inside it. The heat transfer and convection inside the enclosure can be simulated by inputting the simulated thermal conductivities shown in Table 1 as the thermal conductivities of those models [16].

Figure 9 shows the temperature distribution of the bench lathe over time. (a) is on the machine structure and (b) is on the atmosphere in the enclosure.

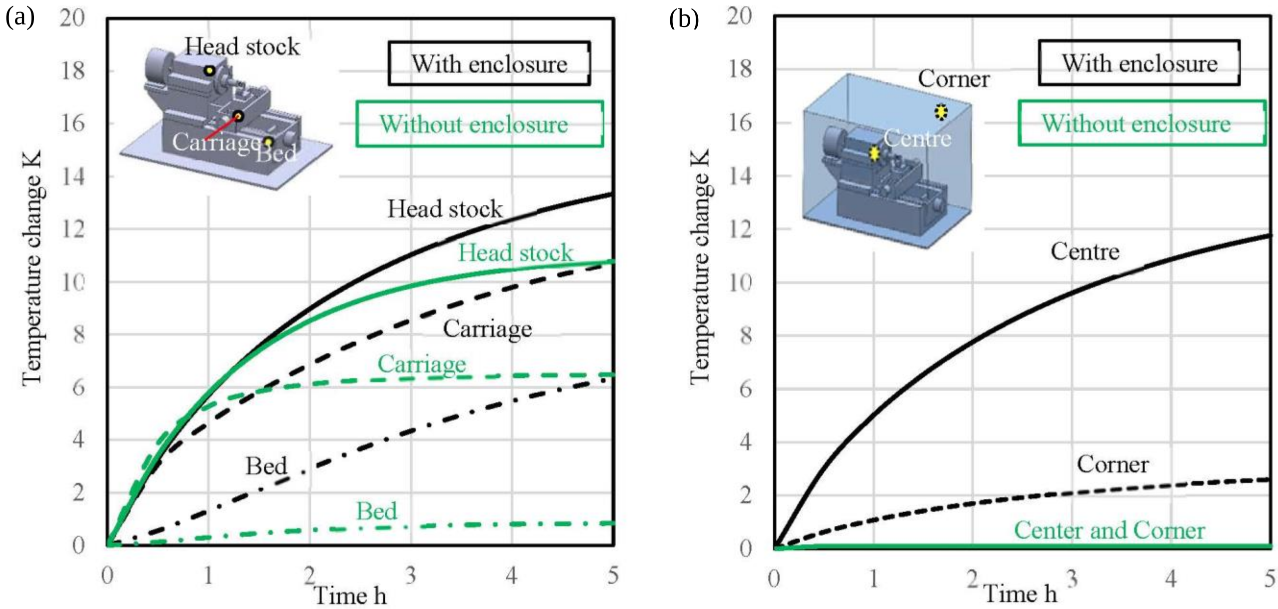


Fig. 9. Temperature distribution change on the machine structure – (a), Temperature distribution change on the atmosphere in the enclosure – (b)

Without enclosure, the temperature rise of the machine structure at a distance far from the internal heat source was low, but with enclosure, the machine body as a whole raised in temperature due to the effect of the warmed air in the enclosure. It can be assumed that the warmed air in the enclosure causes thermal deformation of the machine structure. And it contributes to heat accumulation due to the insulating effect of the warmed air and therefore also increased the internal structure temperature. Thus, the reheating due to the heat build-up in the enclosure has the effect of reducing the temperature gradient between the mechanical parts in the enclosure.

3.3. TOOL LIFE EVALUATION AND TOO LEDGE OBSERVATION

Figure 10 shows the thermal displacement of the bench lathe over time. (a) is with enclosure and (b) is without enclosure. Blue line is in the *x*-axis direction, black line is in the *y*-axis direction and red line is in the *z*-axis direction. The relative thermal displacement between tool and workpiece in the *x*-axis direction with and without enclosure remained at 0 µm in all cases. The relative thermal displacement of the tool and workpiece in the *y*-axis direction was larger with enclosure than without enclosure. This reason is because the amount of thermal deformation of the head stock and the tool post & the carriage due to the warmed air in the enclosure were not synchronised. However, this relative displacement of tool and workpiece in the *y*-axis is less likely to affect machining accuracy. The relative thermal displacement of tool and workpiece in the z-axis is smaller with enclosures than without enclosures. This relative thermal displacement in the *z*-axis directly affects the machining accuracy in the length direction of the workpiece, so the fact that it was reduced by less than half by the installation of the enclosure is commendable.

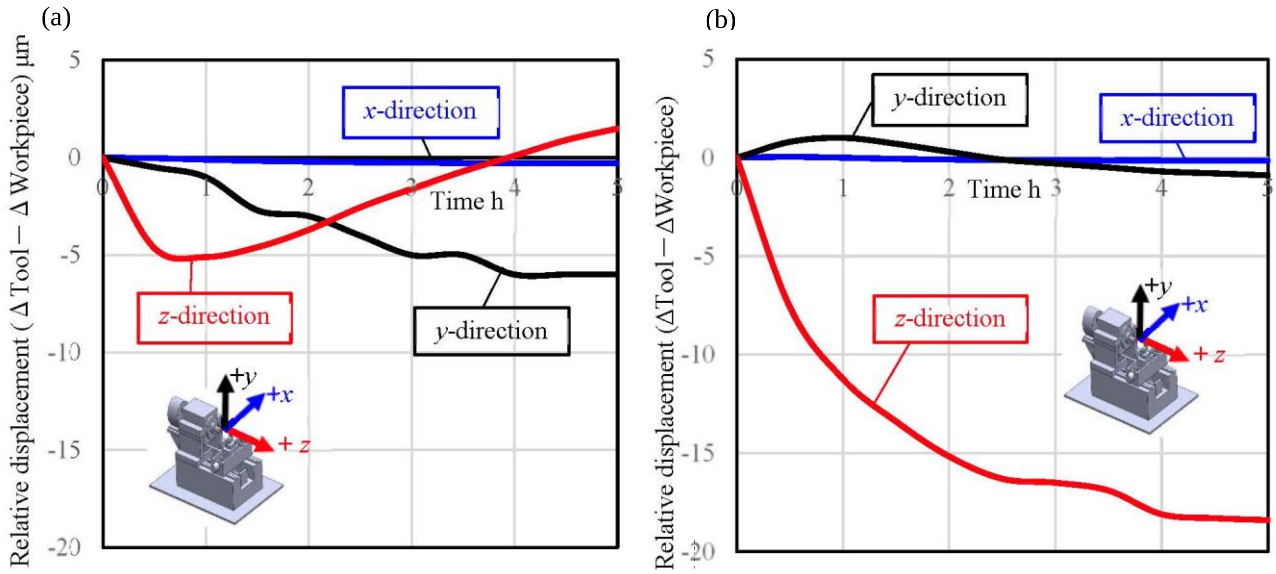


Fig. 10. Relative and thermal displacement changes for 5 hours on the bench lathe with thermally insensitive structure: (a) – With enclosure, (b) – Without enclosure

For reference, an example of an FEM simulation of the thermal deformation of the bench lathe with enclosure is shown in Fig. 11. The contour plots in Fig. 11 show the absolute values of thermal deformation, and both the workpiece and tool contours are light green, indicating that the relative displacements are small. The calculation method is as shown in Fig. 11(b), where the thermal displacements in each axis direction at the centre W of the end face of the workpiece and the tool tip T were searched in the software and these are substituted into Equations (1) and (2) to calculate the machining errors. The example in Fig. 11(b) corresponds to the diameter and length machining error (with enclosure) after 5 hours in Fig. 12(a), (b).

Figure 12 shows the change over time of the machining error of the bench lathe. (a) is the workpiece diameter error and (b) is the workpiece length error. Assuming that a workpiece with diameter φD = 50 mm and length l = 25 mm was machined, the diameter error ΔD and length error Δl were calculated by equations (1) and (2), using the FEM simulation results for the relative thermal displacements in Fig. 10. Black line is with enclosure, green line is without enclosure.

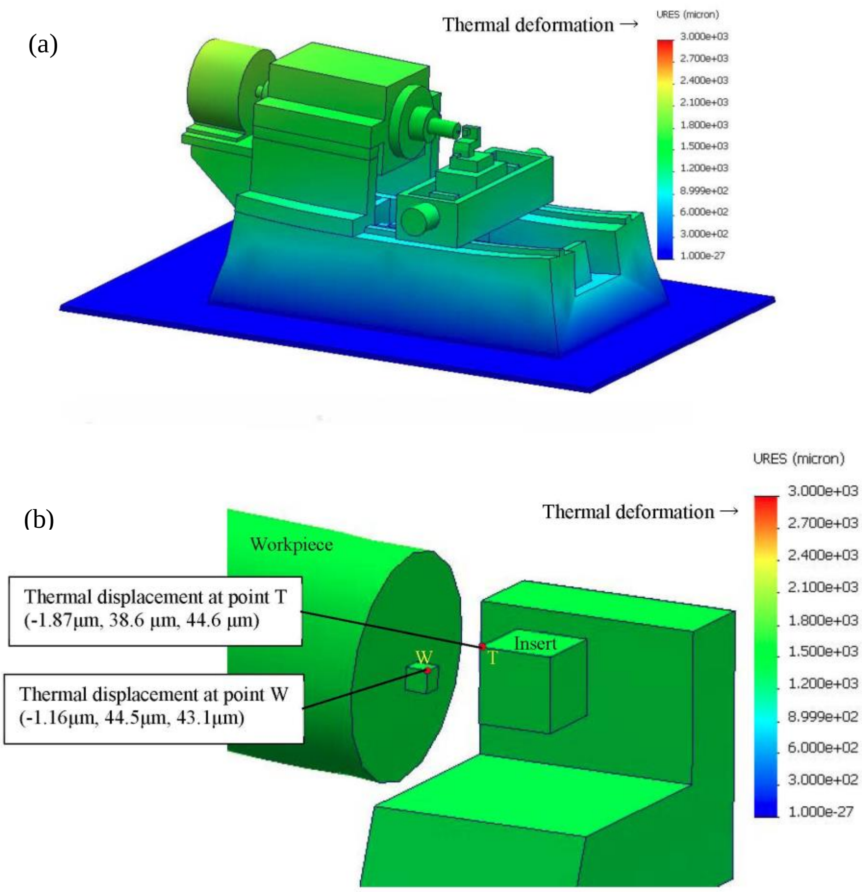


Fig. 11. An example of an FEM simulation regarding the thermal deformation on the bench lathe with thermally insensitive structure, (a) – Schematic view of thermal deformation on the bench lathe with enclosure, (b) – Around the cut tinging area, (Enclosure hidden, Condition: Fig. 10 (a), at 5 hours)

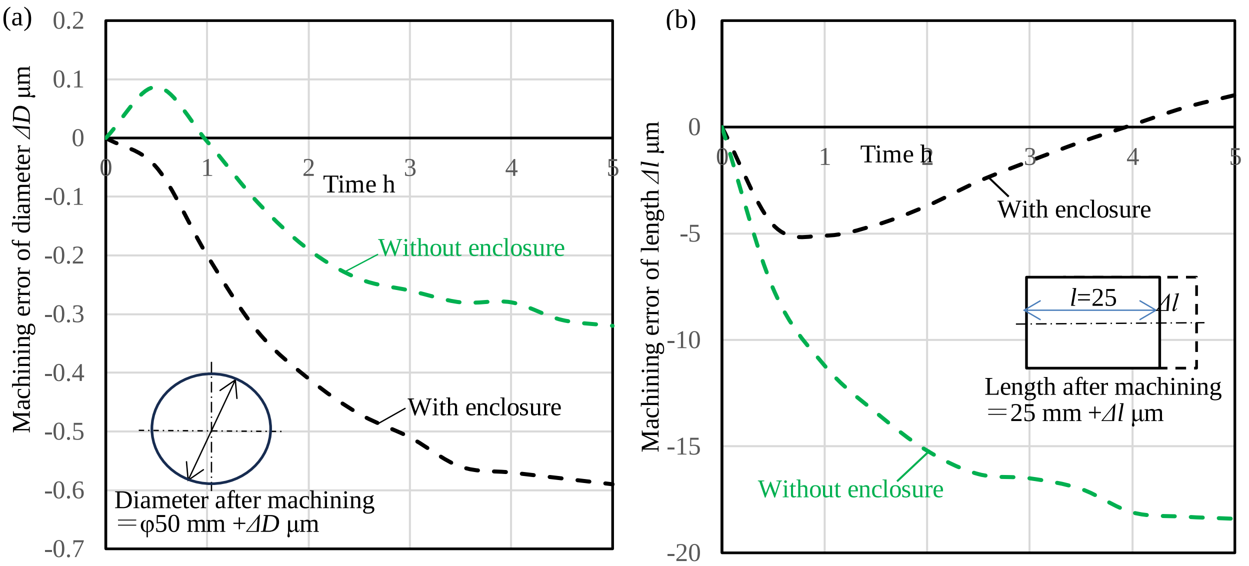


Fig. 12. Machining errors for 5 hours on the bench lathe with thermally insensitive structure, (a) – Machining error of diameter on the workpiece, (b) – Machining error of length on the workpiece

The diameter error ΔD in Fig. 12(a) is less than -0.6 μm, indicating that the proposed thermally insensitive structure, with or without enclosure, is capable of achieving high accuracy for the workpiece diameter error ΔD. This is the result of the effective influence of the thermally insensitive structure for the X-axis directions in the headstock and in the tool post & carriage. The length error Δl in Fig. 12(b) is improved by half by having an enclosure compared to the case without an enclosure.

5. CONCLUSION

A bench lathe with thermally insensitive structure was designed and evaluated using the application of design rules for thermally insensitive machines. The results are concluded as follows; (1) A thermally insensitive structured bench lathe with enclosure has been designed using the FEM thermal simulation. (2) The designed bench lathe was able to reduce the diameter error ΔD of the workpiece to –0.6 μm or less by thermally insensitive structure of the head stock in the *x*-axis direction and the tool post & the carriage in the x-axis direction. (3) The designed bench lathe was able to improve the workpiece length error Δl to half of that without enclosure by the thermally insensitive structuring of the z-axis drive system and the thermal deformation of the warmed air in enclosure. (4) Thermally insensitive structure was industrially effective for machine tools with enclosures.

Based on these evaluation results, a bench lathe is currently being developed. Experiments are being carried out on spindle drive, ball screw drive and actual cutting. These will be reported in the next report.

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