896 *KSME International Journal, Vol. 17 No. 6, pp. 896~905, 2003*

Effects of Insulation Layer upon the Thermal Behavior of Linear Motors

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A linear motor has many advantages next to conventional feed mechanisms: high transitional speed and acceleration, high control performance, and good positioning accuracy at high speed. Through the omission of a power transfer element, the linear motor shows no wear and no backlash, has a long lifetime, and is easy to assemble. A disadvantage of the linear motor is low efficiency and resultant high-temperature rise in itself and neighboring structures during operation. This paper presents the thermal behavior of the linear motor as a feed mechanism in machine tools. To improve the thermal behavior, an insulation layer is used. By placing the insulation layer between the primary part and the machine table, both the temperature difference and the temperature fluctuation in the machine table due to a varying motor load are reduced.

Key Words : Machine Tools, Linear Motor, Feed Mechanism, Thermal Behavior, Optimization, Insulation Layer, Water Cooling

1. Introduction

Electrical linear motors can drive a linear motion without intermediate gears, screws or crank shafts. Because the linear motor moves directly through the induction force, it has a high linear velocity, acceleration, and good positioning accuracy. Therefore, the linear motor can successfully replace ball screw system in machine tools (Gieras and Piech, 2000 ; Weck, 2001).

On the other hand, the linear motor has a low efficiency and emits large amount of heat during operation. This causes a thermal deformation of machine structures and decreases the positioning accuracy of driving axes. Therefore, water-cooling is necessary for the application of linear motors to machine tools in order to transport the heat generated in the motor to outside and to maintain the machine structure without overheating. Water-cooling is also necessary to reach high continuous force of linear motors (Sogabe, 1994). Because linear motors are located in the middle of machine tools, it is necessary to reduce the heat flow from the heat source to the machine structure through the changing of cooling method, motor structure, or insulation. Control technology for water inlet temperature, flow rate and direction also can be applied to improve the thermal behavior of linear motors (Eun, 1999).

The thermal behavior of precision machine tools affects greatly the machining accuracy and the thermal errors in machine tools are caused by unbalanced temperature distribution and assembly of many components of different thermal expansion coefficient and specific heat. For improvement of the thermal behavior of machine tools, many mechanisms are derived, such as reduction of thermal load, change of machine structures, use of new materials and thermal compensation. Especially, the thermal behavior of the feed mechanism determines the positioning and machining accuracy of machine tools. Therefore it is necessary to reduce the thermal load, to

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equalize temperature distribution and to minimize the temperature fluctuation in a machine table by varying load (Weck, 2001 ; Eun, 1999).

This work presents the thermal behavior of a linear motor with high force and speed for machine tools. For the thermal analysis, heat sources of the linear motor are located. To improve the thermal behavior of a machine table, an insulation layer between the linear motor and the machine table is utilized, and its effects are presented.

2. Technical Data of the Linear Motor and Experimental Set-Up

For this research a synchronous linear motor with high speed and force is used. A synchronous linear motor is a linear motor in which the mechanical motion is in synchronism with the magnetic field (Gieras and Piech, 2000). Synchronous linear motors have higher force density and lower power loss than asynchronous linear motors. Therefore, synchronous linear motors are often used in high-speed precision machine tools (Eun, 2001).

Table 1 shows some important technical data of the linear motor used. With water-cooling, the continuous force of the linear motor reaches to 3200 N with the continuous velocity of 90 m/min. Such a linear motor is suitable for high speed and heavy cutting machine tools. The power loss, which influences the thermal behavior, is measured to 2600 W in the primary part and 20 W in the secondary part. Therefore, the main heat source of the linear motor is the primary part and the power loss in the secondary part is negligible (Eun, 2002). The magnetic attraction between the primary part and the secondary part reaches 14600 N and it directly affects the frictional heat on the linear guidance. The length of the primary part is the same as that of the machine table and is 650 mm.

Table 1 Technical values of the investigated synchronous linear motor *with water cooling

	Value
Continuous force [N]*	3200
Maximum force [N]	7000
Magnetic attraction [N]	14600
Continuous velocity [m min^{-1}]	90
Maximum velocity [m min^{-1}]	170
Nominal current [A]	22.6
Maximum current [A]	57
Force constant [N A^{-1}]	141
Mass of primary part [kg]	30
Mass of secondary part [kg m^{-1}]	33
Length of primary part [mm]	650
Maximum power loss in primary part [W]	2600
Maximum power loss in secondary part [W]	20
Air gap [mm]	1.5

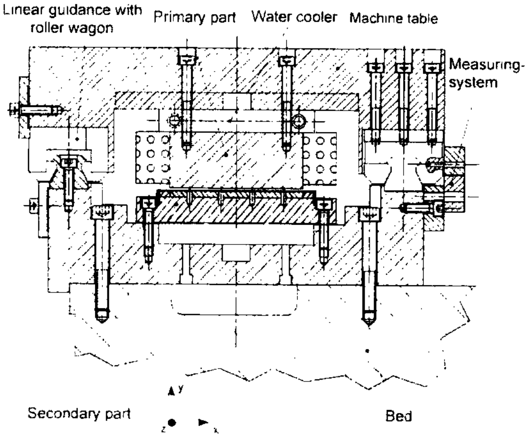


Fig. 1 Experimental set-up with the synchronous linear motor

Figure 1 shows the experimental set-up equipped with the linear motor in Table 1. The machine table is connected to the primary part through bolt joints and moves in the z-direction due to the induction force in working. The secondary part is fixed on the machine bed. For the cooling of the primary part and the machine table, a water cooler is installed between the primary part and the machine table. The cooler is connected to the cooling unit, and the inlet temperature and the flow rate of cooling water can be controlled. To take the great magnetic attraction and to enable the high feed rate, a rolling linear guidance is used. To measure the position, an optical measuring system-LC181 manufactured by Heidenhein, and to control the linear motor, a digital numerical control system-DDS2.1 SERCOS interface manufactured by Indramat is respectively used.

3. Heat Sources

When the linear motor is applied to machine tools, there are two heat sources : electrical power loss in the motor and mechanical frictional loss on the linear guidance. These losses cause temperature rise in the linear motor and thermal deformation of machine structure. In this section, power loss in the linear motor and frictional loss on the linear guidance are measured and compared.

3.1 Power loss in the linear motor

As with other electrical machines, electrical power loss occurs in linear motors during operation. The electrical power loss is divided into Ohmic resistance loss in the windings and iron loss in the sheet metal. The iron loss is the sum of hysteresis loss and eddy current loss (Henneberger, 1997). In this research, the electrical power loss is measured depending on the force. The counter force is applied up to the limit of the continuous force of the linear motor under the position-controlled condition, and the power loss is measured directly by a digital power meter (Fig. 2). Because the linear motor does not move by position-control, the supplied power is consumed entirely into heat. As Fig. 2 shows, the power loss of the linear motors is proportional to the square of the force. The power loss is directly dependent on the current, and the induction force of the linear motor is proportional to the current as follows :

$$F = k_K \cdot I \tag{1}$$

$$P_{Ohm} = I^2 \cdot R \tag{2}$$

where F is induction force, k_K force constant, I current and R electrical resistance.

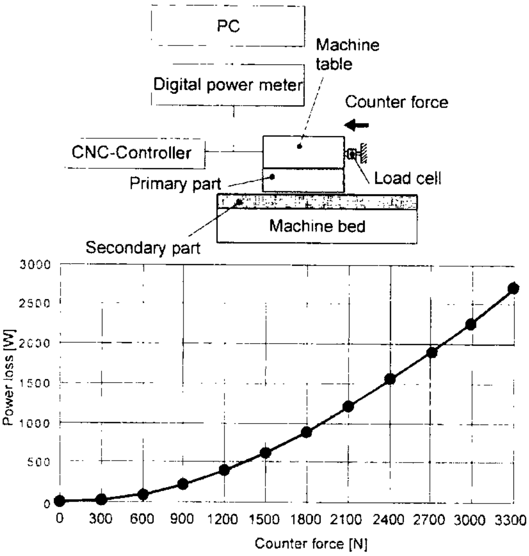


Fig. 2 Electrical power loss of linear motor in dependence on the force

3.2 Power loss on the linear guidance

The mechanical heat source is the frictional loss on the linear guidance during linear motion. The total friction on the linear guidance results from rolling and sliding friction in ball contact, friction in the turning zone, and friction through smearing substance and through sealing (Ispaylar, 1996). The frictional force is dependent on normal load, preload, linear velocity, smearing substance, temperature, assembling precision, and the sealing. With a linear motor, the normal force is a sum of the magnetic attraction between the primary and secondary part and the weight of the moving machine components. The frictional coefficient depending on the normal force is given by the manufacturer. Figure 3 presents the frictional force and heat of four linear wagons having a scraper and lubricated with grease with respect to the feed rate. When the linear motor moves from the stoppage, the frictional force leaps to 112 N. With the increase of the speed, the frictional force increases. The frictional heat is linearly proportional to the speed and reaches 124 W at 60 m/min and 248 W at 120 m/min.

These frictional losses appear only when the linear motor moves. With the stoppage of the linear motor or in the case of the load by a

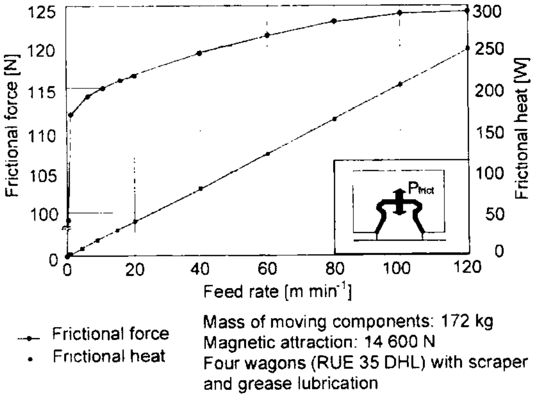


Fig. 3 Frictional heat on the linear guidance depending on the velocity of the linear motor

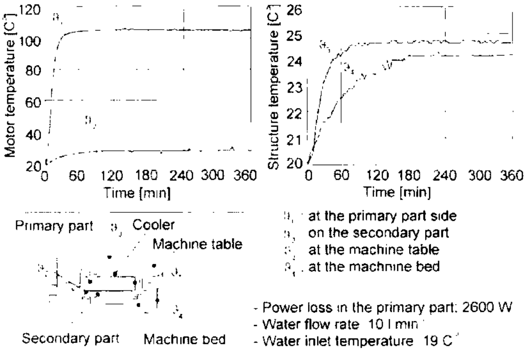


Fig. 4 Temperature measured with the linear motor

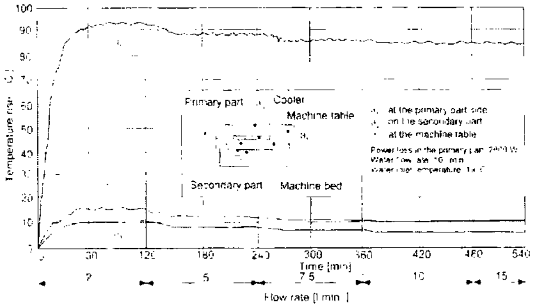


Fig. 5 Temperature rise related to water flow rate

counter force at a low linear speed, the frictional losses can be neglected. As Fig. 3 shows, the linear profile rolling system does not show any considerable frictional loss in comparison with the electrical power loss. The main heat source, when a linear motor is applied to machine tools, is the electrical power loss in the motor.

4. Temperature Measurement

The temperatures of the machine structure, the environment, and the cooling water were measured by thermo-resistant sensors, which have a good linearity between their electric resistance and temperature. These elements are platinum sensors with 0℃ resistance of 100 Ohm (PT100-elements) (Weck, 2001). For better heat transfer between the thermal sensors and the machine structure, conducting paste is used. The temperature sensors are connected to a multi-channel measuring device THERM 5000. The THERM-5000 measuring device sends the temperature values via RS232 interface to a computer.

Figure 4 shows the temperature measured on the experimental set-up with the linear motor loaded by a nominal continuous force of 3200 N. The corresponding power loss in the primary part is 2600 W, and the power loss in the secondary is 20 W. The primary part is cooled with a water cooler, which has a flow rate of 10 l/min and a water inlet temperature of 19℃. The surrounding temperature is 20℃. The temperature at the primary part side (ϑ_1) reaches 105℃. The secondary part (ϑ_2) is also warmed by the heat transferred from the primary part and the temperature is 26.7℃. The temperature at the machine table (ϑ_3) is 24.7℃ and at the machine bed (ϑ_4) is 24.3℃. As shown in Fig. 4, there is a great temperature difference between the primary part and the machine structure, and the linear motor itself is not sufficiently cooled even with a water-cooling.

Figure 5 shows the temperature rise of the linear motor and the machine table depending on the water flow rate. A counter force of 3200 N loads the linear motor, and the power loss generated is 2600 W in the primary part and 20 W in the secondary part. The cooling water inlet temperature is 19℃ and the water flow rate varies from 2 l/min to 15 l/min. Temperature rise on the primary part side (ϑ_1) is 93℃ at a water flow rate of 2 l/min and 85℃ at 10 l/min. Temperature rise on the secondary part (ϑ_2) varies between 15℃ and 10.5℃ with the given water flow rate.

Temperature rise on the machine table reaches 10℃ at a flow rate of 2 l/min, 7℃ at 5 l/min, and 5.3℃ at 10 l/min, respectively. All measured temperature rises decrease with the increase of water flow rate. Decrease of the temperature rise is notable especially when flow rate increases from 2 l/min to 5 l/min. With the increase of the flow rate beyond 7 l/min, temperature rise does not decrease significantly, and water flow rates more than 10 l/min have no effect on the decrease of temperature rise. We can here induce the following : If the power loss of a linear motor is measured, minimum and maximum flow rates can be decided. For the linear motor in this research, a minimum flow rate should be more than 2 l/min and maximum value is about 10 l/min. Although flow rate exceeds a critical value, the temperature on the linear motor and the machine table cannot be further reduced. Therefore, we must devise another mechanism to reduce the temperature in the linear motor and machine table through the structure optimization or insulation.

In Fig. 6 the heat transfer mechanism of the linear motor is presented. The primary part is the main heat source, from which heat is transferred to the machine table and bed. The heat generated in the secondary part and on the linear guidance is small in comparison with that in the primary part. Most of the heat generated in the primary part is transported out of the system through the water cooler and the rest of the heat is transferred to the machine table by conduction. The heat is also transferred from the side of the primary part to the table inside by convection and radiation. The frictional heat on the linear guidance is conducted to the table and bed during linear motion. The heat from the primary part through the air gap warms the secondary part and flows to the bed. On the surface of the machine structure the heat is transferred to the surroundings by convection and radiation.

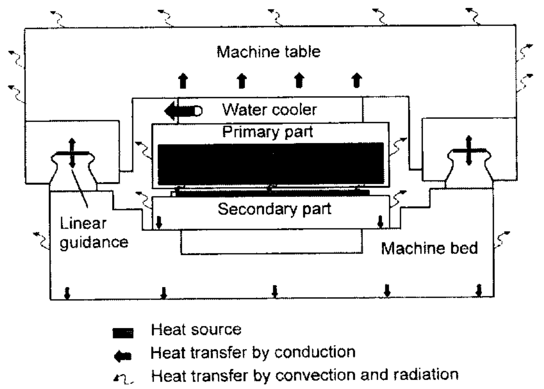


Fig. 6 Heat transfer mechanism in machine structure with linear motor

5. Improvement of the Thermal Behavior through the Insulation

Linear motors are located in the middle of machine tools and the heat transferred from them warms the machine structures, which causes the thermal deformation of the table and positioning errors. Therefore, insulation is a simple and effective mechanism to reduce the heat flow from the linear motor to the machine structure.

5.1 Physical properties and arrangement of insulation layer

As a method to reduce the heat flow from the linear motor to the machine table, an insulation layer is used. An insulation layer, which has low thermal conductivity, is arranged between the linear motor and the machine structure. In Table 2 the physical properties of the insulation layer used and steel are compared. The thermal conductivity of the insulation layer is 225 times lower than that of steel, while the specific heat of the insulation layer is only three times greater than that of steel. Such an insulation layer having very low thermal conductivity is suitable for reducing the heat flow from linear motors.

The insulation layer can be arranged in various ways. Figure 7 presents two arrangements of the insulation layer. Case 1 is an arrangement of the insulation layer between the primary part and the machine table to reduce the heat flow by conduction. Insulation for the secondary part is not necessary because its power loss is very small. For use of the insulation layer two points must be carefully considered. First, the insulation layer may cause a temperature rise in the linear motor

Table 2 Physical properties of the insulation layer and steel

Properties	Insulation layer	Steel	Insulation layer : Steel
E module E [N mm^{-2}]	7000	210 000	1 : 30
Density ρ [kg m^{-3}]	1300	7800	1 : 6
Stiffness range σ [N mm^{-2}]	18-170	400-1300	1 : 2.3-16.3
Specific heat c_p [J(kg K)$^{-1}$]	1420	460	1 : 0.3
Thermal conductivity λ [W(m K)$^{-1}$]	0.2	45	1 : 225
Thermal expansion coefficient ε [10^{-6} K^{-1}]	20-40	11.1	1 : 0.3-0.6
Maximum temperature [℃]	110	–	–
Heat class	E	–	–

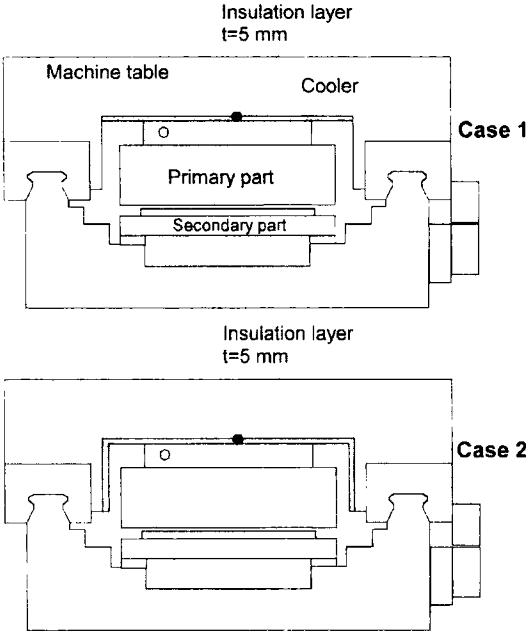
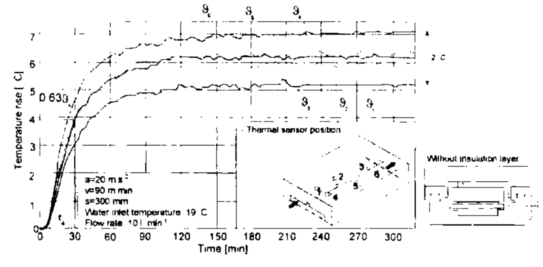
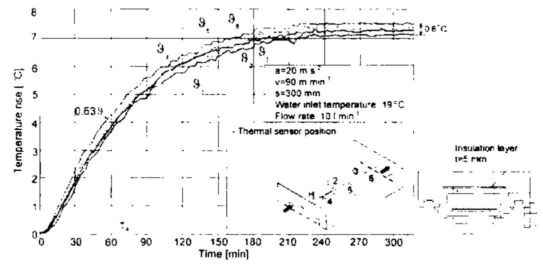


Fig. 7 Arrangements of the insulation layer



(a) Temperature rise in the machine table without insulation layer



(b) Temperature rise in the machine table with insulation layer

Fig. 8 Temperature rise in the machine table without and with insulation layer

when it is located directly above the linear motor. Thus, the insulation layer must be inserted between the cooler and the machine table as shown in Fig. 7. Second, the insulation layer should have a sufficient stiffness because it lies in the force flow of the machine structure. Otherwise, the static and dynamic behavior of the linear motors can be deteriorated. The thickness of the insulation layer used for this research is 5 mm. Case 2 is an arrangement of the insulation layer around the primary part to reduce the heat transfer from the primary part to the machine table by conduction, convection and radiation.

5.2 Effects of the insulation layer

5.2.1 Insulation layer between the primary part and the machine table (Case 1)

Figure 8 shows the temperature rise in the machine table with and without the insulation layer arranged according to Case 1. To investigate the effects of the insulation layer, the linear motor is driven under the same operating and cooling conditions and the temperature rise is measured as shown in Fig. 8. The linear motor is driven with a velocity of 90 m/min, an acceleration of 20 m/s^2 and a travel length of 300 mm. The linear motor system is cooled with a water inlet temperature of 19℃ and a flow rate of 10 l/min. Thermal sensors are installed in six sensor holes grooved between the cooler and the table. The position of the sensor 1 is near to the water inlet and that of the sensor 6 to the water outlet.

Comparing the two results, effects of the insulation layer of case 1 are analyzed from three respects : temperature difference, steady-state temperature (end temperature) and thermal time constant in the machine table.

Temperature difference in the table : Even though there is a cooling water flow in the cooler, the temperature of the cooling water rises, which causes a temperature difference in the machine table. Therefore, the temperature rise of each thermal sensor is different ; for example, the temperature rise of the sensor 1 is 5.2℃ and that of the sensor 6 is 7.2℃ without the insulation layer as shown in Fig. 8(a). This temperature difference is reduced to 0.6℃ with the insulation layer as presented in Fig. 8(b). This effect for reducing temperature difference in the machine table through the insulation layer is very useful because the temperature difference results in an undesirable thermal deformation of the machine table.

Steady-state temperature : Comparing the two results, the temperature rise in the table in the steady state is not reduced through the insulation layer, contrary to expectation. The temperature rise of the six positions measured lies in the range of 5.2-7.2℃ without the insulation layer, while it is in 7.1-7.2℃ with the insulation layer. With the insulation layer the temperature in the machine table is increased slightly. The reason for this phenomenon can be explained by the heat generated on the linear guidance during linear movement, which cannot be transported to the cooler due to the insulation layer and causes the temperature rise in the machine table with time.

Thermal time constant (τ_t): The thermal time constant is defined by the time at which a thermal system reaches 63.2% of its end temperature (steady-state temperature). The thermal time constant is an important factor for the evaluation of thermal stability of a machine tool system. If the thermal time constant is longer, a system is more thermally stable. In Fig. 8 the thermal time constant of the sensor position 4 is 25 minutes without the insulation and 75 minutes with the insulation layer. The insulation layer affects the thermal time constant significantly, and the time constant of the machine table is increased due to the insulation layer. Increasing the thermal time constant through the insulation layer can be understood by the analogous behavior between the thermal and electrical system. A thermal system is analogous to an electrical system and the thermal time constant can be defined as

$$\tau_t = R_t \cdot C_t \tag{3}$$

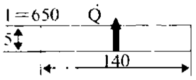
R_t is the thermal resistance to conduction heat transfer and Ct is the lumped thermal capacitance and defined as follows :

$$C_t = \rho \cdot V \cdot c_p \tag{4}$$

where ρ is density, V volume and c_p specific heat. Any increase in R_t or C_t will cause the thermal system to respond more slowly to change in its thermal environment and will increase the time required to reach thermal equilibrium (Incropera and DeWitt, 1996). For the insulation layer used in the experimental set-up, the thermal resistance, the thermal capacitance, and the thermal time constant are calculated and compared with steel in Table 3.

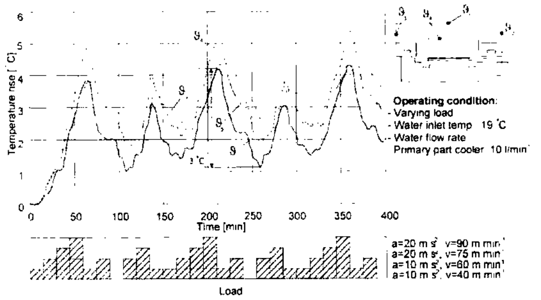
The thermal time constant of the insulation

Table 3 Thermal resistance, capacitance and time constant of the insulation layer and steel

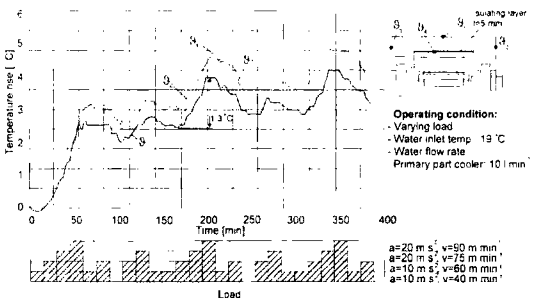
	Steel	Insulation layer	Steel : Insulation layer
Thermal resistance [$l/A\lambda$]	0.001	0.27	1 : 270
Thermal capacitance [$\rho V c_p$]	1633	840	1 : 0.5
Thermal time constant [$(l/A\lambda)\cdot(\rho V c_p)$]	1.63	227	1 : 139

layer is 139 times higher than that of steel as illustrated in Table 3. The reason for a greater thermal time constant of the insulation layer lies in its 270 times higher thermal resistance. The thermal capacitance of the insulation layer is half of that of steel and does not play an important role for the thermal time constant. Therefore, by the application of an insulation layer the thermal time constant is more influenced through the thermal resistance than the thermal capacitance.

The insulation layer with a longer thermal time constant can be used effectively, especially for a varying load of the linear motor. By the application of linear motors to machine tools, the power supply is always changeable through cutting force or acceleration or deceleration. By varying the load of the linear motor the temperature in the machine table responds directly. Varying the load of the linear motor causes the temperature fluctuation in the machine table. In Fig. 9 temperature fluctuation in the machine table by varying of the load is presented. Operation conditions are varied by the strength of velocity and acceleration in 4 steps: 1 st step—v=40 m/min, a=10 m/s^2, 2nd step—v=60 m/min, a=10 m/s^2, 3rd step—v=75 m/min, a=20 m/s^2 and 4th step—v=90 m/min, a=20 m/s^2. The cooling condition is same as in Fig. 8. Different bar height under the horizontal axis is correspondent with operation condition. Operation conditions are changed arbitrarily so that temperature fluctuations in the machine table can be caused.



(a) Temperature fluctuation in the machine table without insulation layer



(b) Temperature fluctuation in the machine table with insulation layer

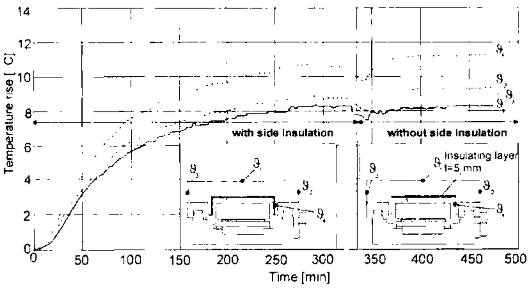
Fig. 9 Temperature fluctuation by varying of load with and without the insulation layer

As Fig. 9 shows, the temperature fluctuation in the machine table is dependent directly on variation of the load. Comparing the two results, the temperature fluctuation on all measuring points with the insulation layer is reduced under the same operation condition. For example, the temperature fluctuation at the middle point 1 (θ_1) reaches 3℃ without the insulation layer, but is reduced to 1.3℃ with the insulation layer. Through the insulation layer the machine table is thermally stabilized with a varying load.

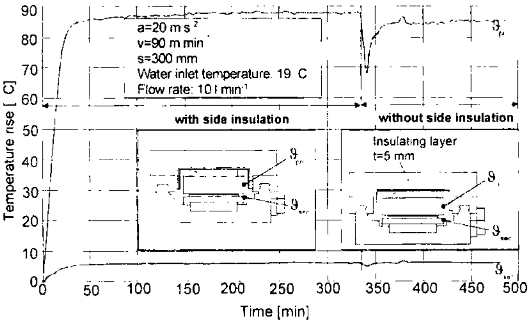
A linear motor is usually located in the middle of machining space and the power supply of the linear motor changes incessantly, which causes temperature fluctuation in the machine table through face contacts between linear motor and the machine table. Therefore, reducing temperature fluctuation on the machine table by varying load of the linear motor through an insulation layer is an important and effective measure for the thermal optimization.

5.2.2 Insulation layer around the primary part (Case 2)

The temperature measured in case 2 is presented in Fig. 10. The temperature rise in the table (a) and on the linear motor (b) is shown with and without the side insulation. The linear motor is operated in the first 330 minutes with the side insulation and then the side insulation layer is removed. The operating and cooling conditions are identical with those of case 1. As Fig. 10(a) shows, the temperature rise on the machine table is reduced slightly through the side insulation. The reason for this is that the side insulation layer reduces the heat transferred from the primary part to the table inside. On the other hand, the side insulation layer increases the temperature on the primary part (Fig. 10(b)) because the air temperature in the intermediate space between the primary part and the table inside is increased through the side insulation. The temperature on the secondary part is not affected by the side insulation. Temperature increase of the primary part through the side insulation is a negative effect and this arrangement is not recommended.



(a) Temperature rise in the machine table with and without side insulation



(b) Temperature rise on the primary part side with and without side insulation

Fig. 10 Temperature rise on the table and linear motor through side insulation

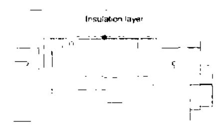
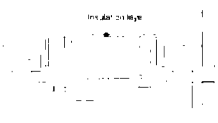
Cases	Effects
Case1 	↓ Reduction of the temperature difference in the table ↓ Reduction of the temperature fluctuation in the table by varying load
Case2 	↓ Reduction of the heat flow to the table inside or the temperature in the table ↓ Reduction of the temperature difference in the table ↓ Reduction of the temperature fluctuation in the table by varying load ↑ Temperature rise in the intermediate space and on the primary part

Fig. 11 Thermal effects of the insulation layer for case 1 and 2

In Fig. 11 the thermal effects of the insulation layer for case 1 and 2 are summarized.

6. Conclusion

In this paper, the thermal behavior of a synchronous linear motor with high force and speed is presented. High power loss and temperature rise during operation is an important disadvantage of the linear motor. The main heat source is the electrical power loss in the primary part and the frictional heat on the linear guidance is very small compared to the electrical power loss. To improve the thermal behavior, the insulation layer is inserted between the cooler and the machine table and also arranged inside the machine table. Through the temperate measurement, some important thermal effects of the insulation layer are found :

(1) Through the use of the insulation layer arranged between the cooler and the machine table the temperature difference inside the machine table is reduced.

(2) The insulation layer between the cooler and the machine table does not always reduce the temperature rise in the machine table, and the steady-state temperature of the machine table is dependent on the operating and cooling conditions of the system.

(3) Through the use of the insulation layer the thermal time constant increases, and when the motor load varies, the temperature fluctuation in the machine table is reduced.

(4) Side insulation causes a temperature decrease in the machine table, but it also causes an increase of temperature on the primary part.

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