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Cooling Techniques for a Spindle of Machine Tool

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Abstract: ***Machine tools have imperative role in technology advances, escalating productivity and accuracy. However heat generated in machine tool results in thermal error that affects the machining precision and productivity. In machine tool the heat is generated due to internal and external heat sources. A spindle is the main internal source of heat generation. This heat can be dissipated by efficient cooling techniques. We have focused on forced cooling, conventional cooling and thermoelectric cooling techniques. This paper intended to provide investigational information about different cooling techniques for spindle of machine tool.***

Keywords: Spindle, Heat Pipe, Jacket Cooling, Chiller, Thermoelectric Cooler

1. Introduction

In Industries machine tools endowed with high precision machining capability and high productivity are essential. Meticulously, the spindle system is the most significant component in machine tool structures and its performance dominates machining accuracy and productivity. Heat generated in bearing clearance is proportional to square of rotational speed which results in thermal deformation of spindle [1]. The largest heat source in the machine tool is usually the main spindle [2].Cooling of spindle will provide superior accuracy, more steady power during the machining process [3]. Therefore cooling of the spindle is requisite to stabilize the temperature and to avoid side effects of excessive heat and the temperature changes during spindle operation [4].The proposed article investigates different cooling techniques for a spindle of machine tool.

2. Cooling Techniques

Broadly the cooling technique falls under one of following types.
1. Forced Cooling
2. Conventional Cooling
3. Thermoelectric Cooling

1. Forced cooling

Forced cooling technique makes use of Jackect and Heat Pipes for cooling [5].

1.1. Jacket Cooling

In this technique coolant fluid is forced to circulate through various parts of spindle to absorb heat generated. Coolant fluid is circulated through jacket. Coolant fluids are air, water or oil. In closed loop coolant system the coolant from spindle is fed to an external refrigeration unit and then pumped back into spindle. The refrigeration units have heat exchanger where the refrigerant circuit cools the coolant circuit [4].

Murthy Sathiya et al. [6] formulated the analysis of high speed motorized spindle with double helical water cooling channel. The heat generated by the motor is distributed on the inner wall of spindle housing. The heat is removed by the forced convection of cooling water and the natural convection of ambient air. Cooling water takes heat from heat source resulting in increasing temperature of cooling water. Increasing the velocity of water the cooling can be accelerated.

Ikuo Tanabe et al. [7] used dual cooling for the temperature control of spindle with bearing. The feed forward temperature control provides heat barter between spindle bearings and overcooled oil. At the suitable temperature oil is circulated through the inner jacket. In the meantime oil having temperature equal to machine body temperature is circulated through the outer wall to avoid the effect of super-cooled oil in the inner jacket. Temperature of bearing is maintained constant by oil along inner wall. They have controlled the temperature of oil along inner wall by using feed forward temperature control system. Figure 1shows heat flow diagram in headstock of spindle.

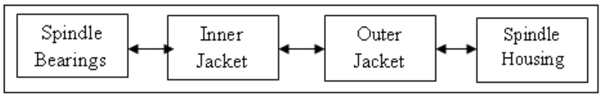

Figure 1: Heat flow in headstock of spindle

1.2. Heat Pipe Cooling

Heat pipes are used to transport the heat generated and it is removed with relieve. The heat pipe is passive heat transfer device with very high thermal conductance. The working of heat pipe involves the steps as shown in Figure 2. Heat pipe is installed in the centre of the spindle. The top end of the heat pipe housing is surrounded by air or ice or water mixture in beaker for cooling [8].

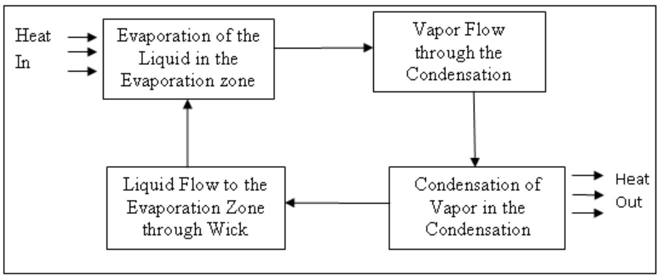

Figure 2: Heat Pipe working cycle

Gnanadurai et al. [9] investigated the effect of heat pipe in the cooling of the tool during hard turning with minimum cutting

fluid. Heat pipe is used to transport heat from one place to another by diffusion without the need of external power supply. Heat pipe housing consists of vacate container with sealing at two ends, a wick structure, and a small quantity of fluid. A heat pipe incorporated with evaporator section, adiabatic section, and condenser section. In the evaporator section working fluid gets vaporized. The subsequent vapor pressure impels the vapor through the adiabatic section to the condenser section. Heat is not absorbed or rejected in the adiabatic section. The vapor is condensed in the condensing section and the latent heat of vaporization of the fluid is rejected into the atmosphere. The capillary pressure generated in wick structure pump back, the condensed working fluid. Transport of heat can be protracted until there is sufficient heat input to the evaporator section so that sufficient capillary pressure is engendering to drive the condensed liquid back to the evaporator. Heat can be transported to great extent through a small cross-sectional area.
In case of heat pipe following limitations are observed in heat transfer.
i. If the capillary pressure is not enough to supply sufficient liquid flow from the condenser to the evaporator then dry out of the evaporator wick occurs that will limit heat transportation.
ii. When the evaporator heat flux causes nucleate boiling in wick structure. It creates a vapor bubble that blocks the liquid resulting dry out of the evaporator wick.
iii. If high shear force is developed when the vapor passes opposite direction over the liquid saturated wick here the liquid can be entrained by the vapor and returned to the condenser. That will cause inadequate liquid flow to the wick structure [10].

2. Conventional Cooling

Conventional cooling comprises of Air-to-water heat exchangers operated by removing the heat from inside an enclosure using cooled water that is supplied by a facility's chiller and channeled through an internal coil [11]. Chillers remove heat from a liquid by a vapor-compression or absorption refrigeration cycle. This liquid can be then circulated through a heat exchanger to equipment for cooling [12]. For spindle cooling air cooled chiller system or water cooled chiller system can be used [13].

2.1. Chiller System

1. Air Cooled Chiller system

Air cooled chiller system is admired in cooling process of manufacturing process. In air cooled chillers, condensers apply air as condensing medium and make use of fan to move air over the coil. The capacity of air cooled condenser varies with the temperature of refrigerant temperature.

2. Water cooled chiller system

Water cooled condenser employs water as condensing medium and use pump to circulate water through condensing medium and out to cooling tower that rejects the heat to the atmosphere. Water cooled chiller system requires water treatment plant to avoid contamination [14].
The basic refrigeration cycle in chiller is of following types.

- Vapor Compression Refrigeration Cycle.

In this refrigeration cycle liquid refrigerant used which absorbs or removes heat from area to be cooled and dispensed to a different place. Figure 3 shows vapor compression refrigeration cycles consist of evaporator, condenser, expansion valve and compressor. In the current refrigeration cycle, liquid refrigerant enters in the compressor, where it is compressed to higher pressure and temperature. It is transformed into superheated vapor. The superheated vapor condensed by either cooling water or cooling air depends on water or air cooled condenser is used. The condensed liquid refrigerant then passed through expansion valve, where its pressure gets lowered and some part of liquid refrigerant gets evaporated. Due to evaporation the temperature of liquid and vapor get lowered. The cold mixture then circulated through evaporator [15].

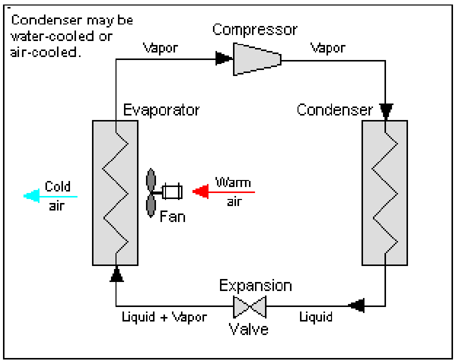

Figure 3: Vapor Compression Refrigeration Cycle [15].

A fan circulates warm air across the coil carrying liquid and vapor that evaporates the liquid part of the cold refrigerant mixture and at the same time circulating air is cooled down, and the temperature of space gets lowered to desire temperature. In the evaporator the circulating refrigerant absorbs or removes heat and condenser gives out heat in a different place by air or water used in it [14].

- Vapor Absorption Refrigeration Cycle

In vapor absorption refrigeration cycle heat source provide energy needed for cooling. The absorption cooling cycle shown in Figure 4 includes -
i. Evaporator: In evaporator a liquid refrigerant evaporates in a low pressure atmosphere and remove heat from its surroundings.
ii. Absorber: In absorber gaseous refrigerant is absorbed by

iii. Generator: The refrigerant liquid is heated that results in another liquid. It releases large amount of heat evaporation of liquid. This hot gaseous liquid circulated through condenser, transferring its heat.
iv. Condenser: In condenser heat is released and vapor is converted to high pressure liquid.
v. Expansion valve: It lowers the pressure on liquid in the evaporator where it evaporated by absorbing heat and provides cooling. The remaining liquid in the generator passes through valve where its pressure gets lowered when it recombines with low pressure vapor returned from evaporator. In this way the cycle is repeated [16].

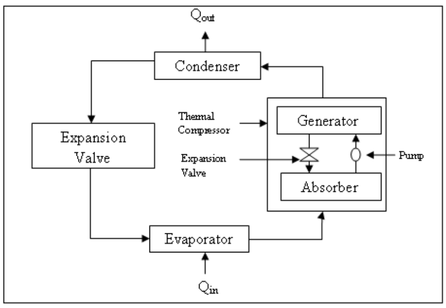

Figure 4: Vapor Absorption Refrigeration Cycle

3. Thermoelectric Cooling

Machine Tool cooling can be carried out by using cooling system including fan. The drive motor causes rotation of spindle. The fan may have temperature monitoring system outside the housing. Monitoring system will sense the temperature and operate the fan running speed on preselected temperature. Fan provides cool air to the housing and exhausts the heat generated in the housing [17].Thermoelectric cooler can therefore be used for cooling of spindle of machine tool.

- Thermoelectric Cooler

Thermoelectric cooling is plinth on peltier effect: when electric current is passed through dissimilar metals then change in temperature occurs at junction between metals. One junction point of the wire gets hot, while other junction gets cooled [11]. Thermoelectric cooler is a solid state heat pump and its working is based on peltier effect. In peltier effect electrical current is passed through junction of two dissimilar metals that result in cooling effect. If the direction of current is changed heating occurs.

Thermoelectric cooler includes-

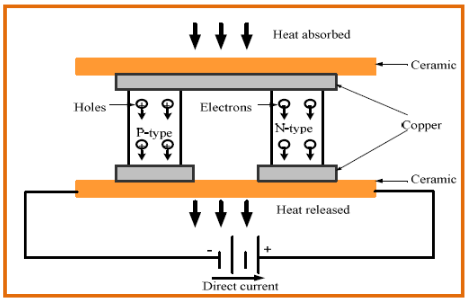

Figure 5: Schematic diagram of Thermoelectric Cooler [18]

- Thermoelectric Module

Figure 5 shows thermoelectric cooler consisting of P-type and N-type semiconductor. Mostly bismuth-telluride material is used. A pair of P-type and N-type semiconductor is called as a couple. Numbers of couples are used to obtain more cooling effect. The semiconductors are electrically connected in series and thermally in parallel. The P-type material has deficiency of electrons i.e. surplus of holes while N-type material has deficiency of holes and majority of electrons. When direct current is passed through semiconductor the electrons flow from lower energy level i.e. P-type material to the higher energy level i.e. N-type material thus absorbing the heat on cold side. When the higher energy electrons from N- type material jump to lower energy P-type material the heat is released on the hot side [18].

- Power supply

Thermoelectric module is a Direct Current (D.C) device. Performance of thermoelectric module is valid if a Direct Current (D.C) power supply is used.

- Heat sink

When the positive and negative terminals of thermoelectric module are connected to the respective positive and negative terminals of direct current power supply the heat will be rejected from the module's hot side, then the heat sink speeds up the removal of heat. Heat that flows through the heat sink is then transferred to an external medium.

- Cold side

When the power source is given to the thermoelectric module the heat will be absorbed by the cold side. In the TEC model the cold side of TEC is attached to the cooling load component and heat sink is attached on the hot side. The heat from the load is absorbed by cooling side and heat produced on the hot side is pumped away by using the heat sink [18]-[19].

Noriyuki Koreta et al. [20] have used thermoelectric cooling method for the cooling of a spindle for machine tool. The thermoelectric cooling method contributes to decrease the temperature at many different places of the spindle considerably more than that of the jacket.

Thermoelectric cooler has solid state design, rapid response time, precise temperature stability, no moving parts; no hazardous gases are used [21].

3. Conclusion

Thermal errors can be abridged by driving away the heat in the machine tool. The cooling system will increase the machining precision with heat confiscation. From this we can conclude that

- Forced cooling through Jacket absorbs heat by circulating coolant fluid through jacket however it involves complex and expensive equipment and encompasses heavy power loss. Forced cooling with heat pipe can transfer large amount of heat through a small cross sectional area over a substantial distance with no supplementary power in the system. However it has capillary limit, boiling limit and entrained limit in heat transfer.
- Conventional cooling provides cooling by vapor compression or by vapor absorption by using air or water condenser. However it requires maintaining cost, water treatment plant.
- Thermoelectric cooling has fewer moving parts, more flexibility and reliability and hence more suitable in high speed machine tool cooling.

4. Acknowledgment

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