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The Effects of Heat Generation on Cutting Tool and Machined Workpiece

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Abstract-

Metal cutting processes usually cause heat generation at the cutting zone (around the workpiece-tool intersection). The heat generated during these processes may cause different effects on both the workpiece and tool, this in turn may affect the finished product and the general performance of the machined piece. In this study, a review was done on various types of machining conditions available, effects of heat generated on the workpiece and tool, and the approaches adopted to reduce this heat at cutting zones. This study also focuses on the simulation of percentage ratio of heat removal. To handle the simulation, various approaches of heat removal methods were used to get the percentage ratio using the ansys version 19.1 software. It was discovered that heat generation causes two major types of wear on the tool, crater and flank wear, resulting in the reduction of cutting tool life as well as dimensional inaccuracy, surface damage and severe corrosion cases on the workpiece. Various heat reduction methods and coolant application types were as well studied and their merits and demerits were discussed.

Key words: Machining, Heat generation, Coolant, Wear, Simulation

1. Introduction

Machining is a very important part of Manufacturing. It involves cutting of metals to obtain a desired geometry with accurate dimensional tolerances and proper surface finish.

In every machine operation, heat is mostly concentrated on the cutting zone [2]. At this zone, it was reported that the chip-tool, workpiece-tool and the Shear-Plane interfaces evolved [1], and this is as shown in Figure 1. These formations are detrimental to the tool, workpiece and the machines. [3] expatiated why the cutting temperature plays a pivotal role in workpiece surface finish and the precision of the machine tools. [4] opined that work surface integrity is directly affected by cutting temperature. The surface finish is however essential since it helps in ascertaining the rate at which materials fail extensively. The generation of heat during machining may result in the degradation of the quality of the machined workpiece surface together with the machined part [2] and such may cost manufacturing industries a fortune. The distributions of temperature during machining rely on the specific heat capacities and thermal conductivities of the workpiece and the tool with the highest temperature occurs at interface between the chip and the tool. In the primary deformation zone, a larger shear angle leads to smaller heat generation and vice versa. The total heat generated at the tool-workpiece interface is distributed as follows; 80% goes to the chip, 10% to the tool, and the rest to the workpiece [5]. Many researchers have studied heat generation during machining with the aim of developing means of reducing the



adverse effect on workpiece and cutting tool. Various approaches ranging from types of cutting fluids, cutting fluid application techniques and studies involving machining parameters have been. This work is therefore a review of some of these previous research works into the effect of heat generation during machining on workpiece and cutting tool.

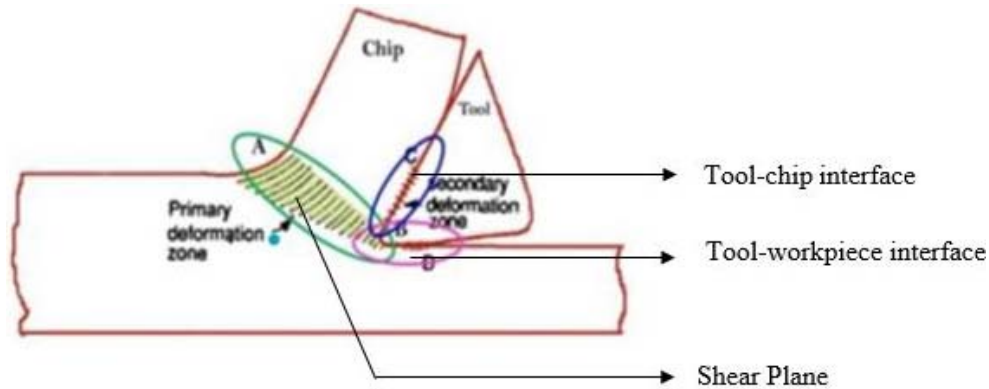


Figure 1: Sources of heat generation in metal cutting [1].

2. Review of Existing Literatures

[4] reviewed the cutting temperature measurement while machining and this covered the calorific; tool-work, embedded and single wire thermocouples; fibre bragg gratings, PVD film; infrared thermometers; infrared cameras; remote measuring, and thermographic thermometry methods. The paper explained in details various temperature measurement methods as well as their limitations.

[6] reviewed the implication heat generation and prediction in metal cutting under high speed machining. The work was a comparative analysis of heat generation on machining processes from previous research works. Emphasis was laid on temperature in metal cutting, temperature measurement in high speed machining and model types (analytical and numerical). Accuracy and reliability of HSM machining simulation models as reported is crucially limited.

[7] investigated the effects of cryogenic cooling on electrode wear and surface roughness of Ti-6Al-4V. The paper considered machining parameters like current intensity (I), pulse on-time (ton), pulse off-time (toff), and gap voltage (v), respectively, while electrode wear and surface roughness were considered to be the responses of investigation. It was reported that reduction in electrode wear ratio is possible up to 27% by electrode cooling. The paper also reported a reduction in surface roughness while machining with electrode cooling. It was concluded that irrespective of machining parameters used, heat reduction during machining results in lower surface roughness and smoother machining.

[8] worked on tool temperature during machining of particle boards and solid wood. The authors utilized high speed steel with cemented tungsten carbide tool and cutting temperature was measure using a thermocouple wire. The paper reported that cutting tool temperature is always lower than temperature at cutting zone.

[1] reviewed the heat generation in metal cutting focusing various factors that influences temperature generation. The paper reviewed and investigated the heat generation points and distribution in metal cutting operations. Results from the study showed that heat distributed to the chip, workpiece and tool are in the ratio 80:10:10. It was concluded that the highest heat generated occurred at tool-chip interface.

[2] studied the effect of coolant temperatures on machining characteristics of high carbon steel. High carbon steel was machined dry, wet and cooled at low temperature of 7.9°C using cutting speed, feed rate and depth of cut as machining parameters. The cutting temperatures while monitoring material surface roughness and removal rate were taken with a thermocouple wire (k-type) while. A total of 54 experimental runs were carried out and results show that surface finish improved by 65% with the use of the developed cooling system. It was concluded that the reduction in temperature of coolant resulted in an improvement in surface finish.

[9] studied the effects of lubrication and machining conditions on tool wear and tool life during the machining of tool steels. Dry and wet milling process was used to investigate machinability of tool steels. Tool steels with different composition and hardness (100 – 341 HB) was machined with carbide inserts to study the tool wear and tool life. Lubrication played a vital role in tool life preservation as wet machined tool steels produced longer tool life compared with dry machined tool steels.

[10] studied the effect of the machining parameters on the temperature changes in milling S45C carbon steels. The parameters utilized in the work include; speed of the spindle (1700 – 2700rev/min), rate of feed (105 – 165 mm/min) and Depth of cut (0.4 – 0.8mm). A total of 16 runs were taken in the experiment and the obtained results showed that depth of cut was the most significant factor that contributes to the generation of heat compared to spindle speed and feed rate.

[11] carried out comparative analysis on machined stainless steel with soluble and vegetable oils as cutting fluids. Machining parameters used for the experiment where spindle speed (75 - 135m/min), feed rate (0.01 - 0.05mm/rev) and depth of cut (0.01 - 0.08 mm), respectively. The surface roughness and cutting temperatures were measured with a profilometer and a thermocouple wire (k-type) attached to a digital meter. A total of 18 runs was carried out, 9 runs each for the two cutting fluid types. Findings show that during the machining of stainless steels, vegetable oil was a better lubricant compared to soluble oil with an improvement of about 60% on surface finish.

[12] investigated the influence of machining parameters on heat generation in milling aluminium alloy. The machining parameters used were spindle speed (1000 - 10,000 min⁻¹), feed per tooth (0.08 – 0.3mm), axial depth of cut (25mm), radial depth of cut (1mm), milling direction (down milling), respectively. It was reported that chamfered cutting edges have a much higher heat generation in the workpiece compared to sharp cutting edges.

2.1 Machining Conditions

The condition of operation is very necessary as some of these operations expose the tools to heat

for long period. For example, in drilling operation, cutting tool is exposed to the material for prolong period which could have chip formation in the space preventing the process from going smoothly. Therefore, liquid coolant is necessary to remove the chips. Apart from dry machining, other types of machining conditions available include wet, minimum quantity of lubricant (MQL), flooded and cryogenic cooling [13].

2.1.1 Dry Machining Condition

This is a machining condition where no lubricant or metal cutting fluid is used instead of the usual traditional coolant and oil for cooling. It is mainly used for milling operation and not advisable for drilling operation as already stated earlier [14]. It could be used in turning operation if hard cutting technology is present at the industry. Hard cutting is the use of hard cutting tools like diamond and Cubic Boron Nitride. These are expensive tools, but the technology produces some great advantage/benefits [15]. Dry machining, requires no coolants hence the working environment is cleaner and more comfortable eliminating the possibility of slippage during machining [16]. It is cheaper as there is no consumption of water and oil for cooling nor cost incurred for used coolant disposal. However, during dry machining, cutting tool life is short; this result from high temperature generated due to absence of coolant. The absence of coolant to lubricate during cutting results in high energy consumption.

2.1.2 Wet Machining Condition

Here, both the tool and the workpiece require the right quantity of coolant. Under wet machining, the heat generated and chip removal rates occur at the same time [17]. Tools utilized here are either externally or internally cooled, depending on the machining process and the workpiece material. Cooling fluid fed by the pump also carries away chips produced during the cutting process [18]. The application of coolant during machining reduces friction between the two surfaces thereby improving machinability, preserving tool life and improving surface finish. However, operator exposure to coolant during wet machining may result in skin/health problems [19] [11].

2.1.3 Flooded Machining Condition

Flooded machining is direct application of coolants in a flood to the tool/workpiece interface. It was considered to be more effective to simply splash fluid around the work area [20]. Flooded cooling could however be carried out at room temperature or under refrigeration.

a. Room Temperature

Most machining on conventional lathes are done at room temperature. In this form of coolant application, the coolant is applied at room temperature (25- 27°C), hence coolant temperature in this case may not be a control factor [2].

b. Cold Temperature (Refrigerated cooling)

The effect of reduced temperature of coolant may be of interest to researchers, hence coolant temperature becomes a control factor and the influence of cold temperature on wet machining is

different from that of room temperature. [2] machined steel using coolant at 7.9°C and reported that reduced temperature improved the surface roughness compared with dry machining or wet machining at room temperature.

2.1.4 Minimum Quantity Lubrication (MQL)

This is also called near- dry machining condition; it is an alternative to conventional fluids like water and oil [21]. It implies the use of a minimal amount of quality lubricant directly on the surface of the cutting tool. It is almost like the opposite of the use of conventional coolants. For drilling operation, when using the fluid as coolant the application is done externally to cool the tool surface but for MQL, lubricant is applied on the surface of the cutting tool which means that cooling is done internally [22]. Major advantages of MQL include reduction in health risk and energy consumption. It is cheaper because of limited use of coolant. However, MQL technology is much more technical and could pose challenges for machinist and chip evacuation in MQL is poorer compared to those of wet machining.

2.1.5 Cryogenic Machining

Cryogenic cooling is a cooling type that delivers liquid nitrogen of low temperature (up to -195°C) directly to the cutting edge to facilitate faster processing speeds and improve tool life compared to conventional cooling methods [7].

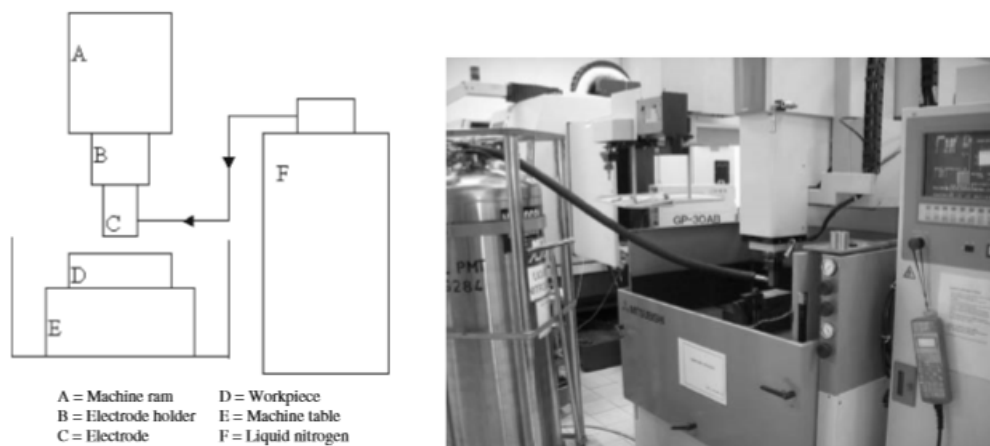


Figure 2: Experimental Set-up showing the application of Cryogenic Cooling in Machining [7].

It is an alternative to conventional machining processes. In the past, this technology was difficult and costly since it was focused on spraying the liquid nitrogen all over the tool rather than on the selected cutting edge. The implication was, the coolant will almost evaporate completely before it gets to the cutting surface, this reduces the ability of cutting and cooling too. Today, the technology enables the nitrogen to be delivered on the cutting surface which means the evaporation takes place close to the cutting edge, cooling it beyond its conventional cutting limits and at the same time increasing the wear resistance which implies longer life span of the tool [23]. Although, reduced wear on the cutting edge, increased cutting tool lifespan and increased processing speed are major advantages of cryogenic cooling, the gases may explode hence handling and storage of cryogenic gases can be dangerous.

3. Effect of Heat Generated on Cutting Tool and Workpiece

The effect of heat generated on cutting tool and workpiece is presented here:

3.1 Effect of heat generated on cutting tool

High hardness and heat resistance are major considerations for the choice of cutting tool depending on the type of materials under consideration. However, heat generated during machining results in tool wear eventually leading to high surface roughness of workpiece [24]. [2][9] reported that the use of cutting fluid during machining greatly increased tool life compared to tool life obtained when cutting fluid was not applied under same machining parameters. This was so because hardness value was preserved over a longer period of time during wet machining hence temperature reduction at cutting zone resulted in a preservation of tool and elongation of tool life.

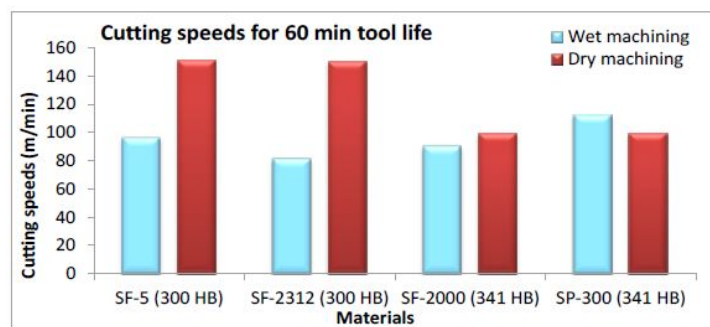


Figure3: Tool life comparison for steel in wet and dry conditions [9]

Thermal cracking which is due to the expansion and cracking caused by thermal stresses is another way the cutting tool can fail [5]. After some time, the cutting tool experiences a reduction in weight due to the wear (flank and crater) at the face.

3.2 Effect of heat generated on the workpiece

Heat generated during machining could have both positive and adverse effects on the workpiece material. Heat generated during machining could result in the reduction of strength/hardness of the workpiece material, thereby lowered cutting forces. The reduction of cutting forces more often results a reduction of power consumption and an improvement in machinability of the workpiece material [14]. However, higher temperature at the cutting zone due to chemical reactivity of workpiece and cutting tool at high temperature, results in adhesion and diffusion wear [14]. Higher rate of heat is generated at the cutting zone during machining of metals and alloys with low thermal conductivity, this heat cannot be rapidly dispersed into the rapidly-moving chip. Higher temperature generation also affects the micro-structural constituents of the alloys, which may pose danger since the alloy is used for sensitive purposes [25][26]. One major effect of heat on workpiece is its influence on surface roughness during metal cutting processes. In the design of machined parts, surface roughness is highly essential and is known to have considerable influence on properties like wear resistance and fatigue strength. During machining, it can be influenced by a number of factors like cutting parameters, cutting fluid, and workpiece hardness [24]. Depth of cut, feed rate and cutting speed also have greater influence on the workpiece surface temperature and an increase in workpiece temperature could result in higher surface roughness [24]. Some other problems heat generation could have on workpiece include; dimensional inaccuracy in the products as a result of thermal distortion

together with expansion-contraction in the process and after machining, surface damage due to oxidation, burning and rapid corrosion [27]. Summarily, when the heat generated affects and causes deterioration of cutting tool, there is a resultant effect on the workpiece as surface integrity becomes compromised and this has contributed to failure of most fabricated parts.

4. Modelling of heat distribution on cutting tool

The cutting tool geometry created with CREO Parametric design software was modelled and later livelinked to ANSYS, the model was subjected to mesh and the physics considered was the Steady-State-Thermal analysis to obtain the temperature distributions across the surface of the model. Two different cutting tools made from Tungsten-Carbide and High Carbon Steel were examined to consider the effect of heat removal under dry, wet and cooled machining conditions. The data from [2] and [11] were used for the modelling as shown in Table 1.

Table 1: Cutting Temperature during machining in various conditions [2] [11]

Run	Cutting Temperature (°C)					
	Tungsten Carbide (T.C)			High Carbon Steel (HCS)		
	Dry	Wet	Cooled	Dry	Wet	Cooled
1	909	301	62	547	233	72
2	863	277	55	456	188	70
3	780	270	44	401	166	65
4	652	264	32	373	144	58
5	620	234	24	350	125	55

As shown in Figure 4a, a maximum temperature of 909°C was recorded close to the edge of the cutting tool. However, machining with high speed steel, the tool temperature reduced to a maximum of 233°C and 72°C during wet and refrigerated (cooled), respectively. Heat dispersal is therefore quicker in wet and cooled machining. Hence coolant, especially when refrigerated before application, could reduce heat generation hence preserve tool life. The same trend was noticed when machining using tungsten carbide as cutting tool presented in Figure 4 (d)-(f). Generally, heat generated during machining has results in and reduction of tool life.

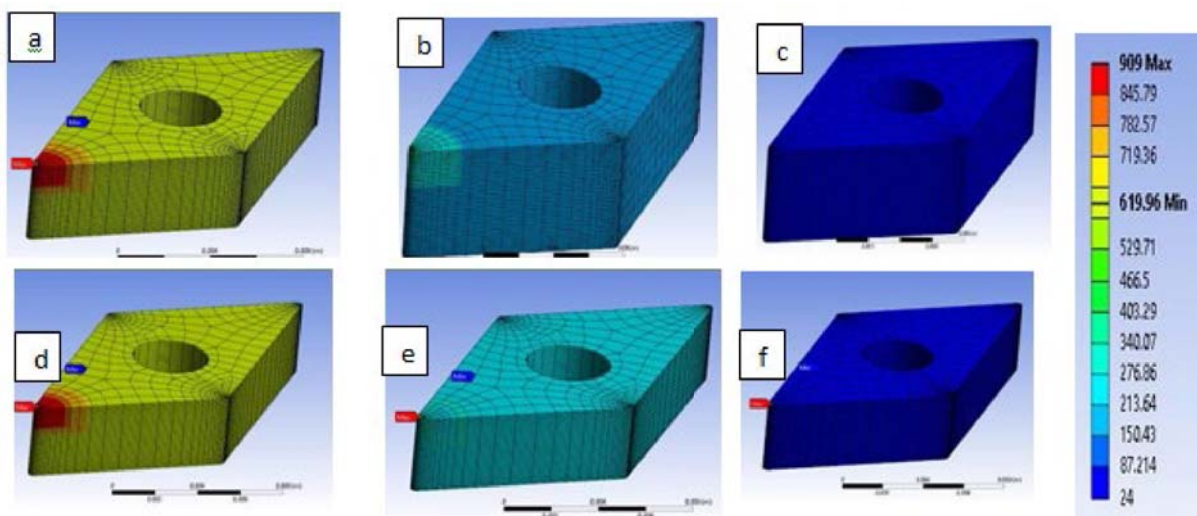


Figure 4: Cutting temperature distribution (a) Dry_{HCS} (b) Wet_{HCS} (c) Cooled_{HCS} (d) Dry_{T.C.} (e) Wet_{T.C.} (f) Cooled_{T.C.}

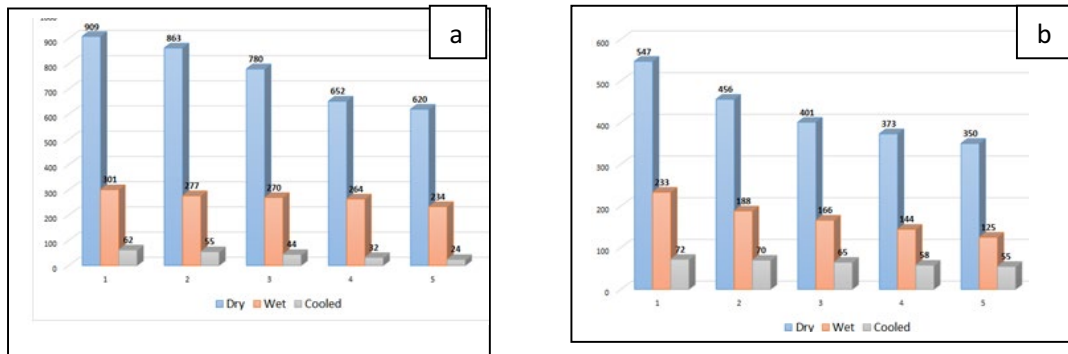


Figure 5: Experimental Temperature Graph Data (a) Tungsten-Carbide (b) High Carbon Steel.

5. Conclusion

In this research work, the effects of heat generation on cutting tool and machined workpiece during machining has been reviewed. The various heat reduction methods were also reviewed. The following conclusions have been made based on the review done

1. The heat generated could reduce the magnitude of the cutting forces leading to reduction in power consumption and then improve the machinability of workpiece.
2. The heat generated during machine operations also affect the material surface roughness significantly as there is a direct relationship between the two. High values of surface roughness could result in an eventual failure of parts fabricated
3. Tool life reduces with an increase in heat generation during machine operations. Coolants play a pivotal role in reducing the rate of heat generation in machining. However, it might still pose a challenge if not well applied.

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