Ultrafast Cooling: A Methodology to Achieve Energy Efficient and Environmentally Benign Manufacturing

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Abstract: Both the physical dimensions and metallurgical and mechanical properties are important for quality products. For the precise controlling of the desired properties; the rate of cooling of the product plays a vital role. In the manufacturing world, quenching is widely used in different processes such as cutting, extrusion, casting, forging, annealing and so on. This paper presents the experimental results on energy efficiency and environmentally benign manufacturing ability of ultrafast cooling during machining of a steel bar. Temperatures at different locations of cutting zone were measured by the help of a FLUKE IR camera. Machining surface quality was measured by the help of a Taylor's surface tester. The ultrafast cooling was achieved by the help of a controlled spray impingement cooling system. Temperatures were high when cutting dry, followed by cutting with an oil lubricant, and finally with water as the cutting fluid. Since water is the best conductor of heat among the three choices, it gave the lowest temperature, reinforcing water's ability as a good coolant. Ultrafast cooling in manufacturing addressed a number of manufacturing matters, including conservation, waste management, water supply, environmental protection, regulatory compliance, pollution control, and a variety of related issues. Due to high heat transfer capability, the method also found to be very suitable for energy saving and environmentally convenient.

1. INTRODUCTION

Cutting fluids have seen extensive use and have commonly been viewed as a required addition to high productivity and high quality machining operations. Cutting fluid related costs and health concerns associated with exposure to cutting fluid mist and a growing desire to achieve environmental sustainability in manufacturing have caused industry and academia to re-examine the role of these fluids and quantify their benefits. Two relatively recent strategies focused on reducing fluid use are Minimum Quantity Lubrication (MQL) and dry machining. There are four primary categories of cutting fluids that differ in terms of their thermo-physical properties, common process applications, and method of treatment. Straight oils are made up entirely of mineral or vegetable oils, and are used primarily for operations where lubrication is required [1]. Despite being excellent lubricants, they exhibit very poor heat transfer capabilities. Soluble oils are mixtures of oil and water and have increased cooling capabilities over straight oils and offer some rust protection. Concerns with using soluble oils center upon maintenance issues like evaporative losses and bacterial growth. Semi-synthetics are similar to soluble oils in performance characteristics, but differ in composition because 30% or less of the total volume of the concentrate contains inorganic or other compounds that dissolve in water. Semi-synthetics have better maintenance characteristics than soluble oils, but do contaminate easily when exposed to other machine fluids and may pose a dermatitis risk to workers. Synthetics are chemical fluids that contain inorganic or other chemicals dissolved in large amounts of water and offer superior cooling performance. Maintenance is also not a major issue with synthetics, however, cases of dermatitis are more prevalent in workers and the lubrication functionality is weaker than with semi-synthetics.

As is evident, the application of the fluid produces airborne particles of varying sizes. Cutting fluid mist (especially the small particulate that can be inhaled and is too small to be seen in the figure) produced during machining operations may pose a significant threat to worker health/safety. Safety/health regulations focus on the time weighted average of the mass concentration of fluid mist to which a worker may be exposed for a given work period. Common strategies to control the amount of mist exposure include the use of enclosures, air filters, and mist collectors. However, these approaches prove to be costly both in time, as access to machine tools may be restricted by enclosures thus increasing part loading/unloading time, and money, including the slowing of production and reduction in process efficiency [2]. To prevent or counteract the problems associated with the cutting fluid mist produced in machining operations, there first must be an understanding of the mist formation process. As illustrated in Figure1, two different mechanisms have been proposed as sources for cutting fluid mist: atomization and vaporization/condensation. "Ultrafast cooling", one of the mechanisms by which cutting fluid mist is produced, is the process by which a liquid jet or sheet disintegrates by the kinetic energy of the liquid itself, by exposure to high-velocity air, or as a result of mechanical energy applied externally through a rotating or vibrating device.

This paper addresses the effect of cutting temperature on surface finish of the workpiece generated by SNMG cutting inserts during controlled spray assisted machining of steel bar. Air-water spray at different pressure combinations was employed for achieving the ultrafast cooling.

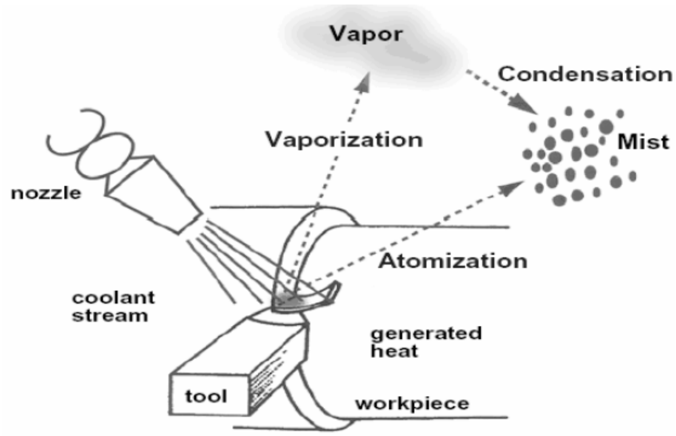

Fig. 1. Cutting fluid mist generation

2. REVIEW OF PREVIOUS WORKS

Traditionally, cutting fluids have been widely used in machining operations in efforts to increase cooling and lubricity, and as a result enhance tool life, reduce process variability, etc. However, over the last decade, it has become apparent that fluid-related decisions have all too frequently been based upon industrial folklore rather than knowledge-based quantitative evidence.

According to Mackerer [3] and Thorne et al [4], the application of cutting fluids within a machining operation often produces an airborne mist, and medical evidence has linked worker exposure to cutting fluid mist with respiratory ailments and several types of cancer. This makes the use of cutting fluids a health issue with the potential of both long and short-term consequences.

Novel approaches have been identified that can be utilized to eliminate or greatly reduce the amount of fluid that is needed for a machining operation. Novel approaches have also been proposed to eliminate or control cutting fluid mist for those situations in which, for the short term, a cutting fluid is deemed to be a necessary process requirement.

3. CASE STUDY

The purpose of the experiment was to collect temperature data of an orthogonal cutting process using a FLUKE Ti32 Thermal Imager. Turning tests were performed to determine the temperature during the machining of SAE 1015 steel alloy. The experiment was set up to try for machine turning of SAE 1015 steel with controlled air-water spray impingement external cooling. Infrared imaging was performed to measure the temperatures at the workpiece surface, tool rake surface and tool-chip interface.

Orthogonal turning operations lead to generation of high temperature between workpiece-tool interfaces leading to problems like heat affected zone on the workpiece, high tool wear, and change in surface hardness and microstructure of the workpiece, micro-cracks and other effects. Application of coolant jet in conventional methods reduces these problems to a certain extent by lubricating and cooling of the cutting zone, but the rate of cooling using just a coolant jet is low. At high speed machining, much higher rate of cooling is desired thus making it necessary to rely on an alternative. Spray impingement cooling is one of the alternatives to the conventional flood cooling which minimizes the use of cutting fluids and due to its evaporative nature, achieves a better surface finish and minimizes the chance of tool failure. The purpose of choosing air-water combination as the coolant was basically to avoid multifold problems in machining such as: health and environment safety, better surface quality, cost effectiveness, atomized cooling and improved material processing.

In this research all the experiments concerning spray impingement cooling during turning were done on a cylindrical steel bar of dimensions Φ 50 mm and 150 mm length. The laboratory test facility developed at School of Mechanical Engineering, KIIT University, Bhubaneswar, Odisha, consisted of three major sub setups: (i) Machining setup (ii) Spray setup (iii) Temperature measurement setup and (iv) Surface measurement setup.

4. EXPERIMENTAL PROCEDURE

The experiment began once the set up was complete. The tool was placed into the tool holder and the initial settings for the input parameters such as speed of cut, depth of cut, feed and air-water pressure combination were performed as per a full factorial orthogonal array of the design of experiments (DOE). The DOE for each level was carried out by the help of MINITAB software. As per the DOE, a total 81 number of experiments were designed to perform under air-water spray impingement cooling. The spray nozzle was positioned vertically downward in a self-fabricated holder. The perpendicularity of spray was checked before experimentation with number of trial runs. The distance between nozzle exits to the workpiece surface was set at 130 mm, so as to achieve an optimal cooling.

The camera was operated manually and an infrared snapshot was taken of the experimental set up prior to cutting. The filming was initiated once the camera was positioned correctly and calibrated properly. After each experiment was over, the workpiece was made ready to test the surface finish. The workpiece was kept on a flat plate with flexible holder after each iteration. The surface finish was measured by the help of a surface roughness tester. The diameter of the workpiece was measured after each experiment with the help of a digital caliper as shown in Figure 2. The camera snapshot, chips, and the temperature data were stored in a computer providing numbers separately for each experiment. The water temperature before the start of experimentation was measured by the help of a thermometer.

Fig. 2. The digital caliper used in the Work

The above procedure was executed for 81 experiments and required data were stored as separate files. The camera snapshots were then processed by the help of application software i.e, SMARTVIEW to extract the temperature results in each experiment and the experimental (input and output) data were processed in the MINITAB software. Finally, different plots were generated to study input-output relations. Correlations were found from the plots and the data were optimized.

4.1 Infrared Imaging

The temperature was measured using a FLUKE (Ti32) Thermal Imager. The camera was operated manually, so enough care was taken to maintain the field of view for the camera had to be consistent during each of the experiment. The camera lens was pointed towards the cutting tool, and operated for some trials in order to keep a constant field of view. The snapshots were stored in a 4 GB memory chip mounted within the camera. After a set of experiments completed, the stored data was transferred to the computer which was loaded with SMARTVIEW application software. Figure 3 shows an example of the cutting process as it is viewed in SMARTVIEW.

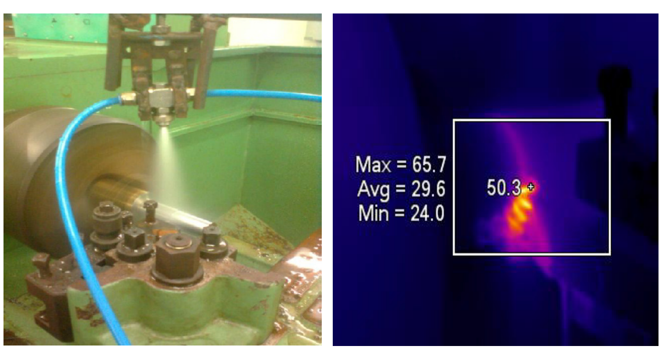

Fig. 3. Cutting process under spray impingement cooling and thermal image in SMARTVIEW software

5. EXPERIMENTAL RESULTS AND DISCUSSION

Orthogonal cutting of SAE 1015 steel cylindrical bar was carried out under spray impingement cooling applied to the surface of the cutting tools. Each condition underwent 3 trials giving 81 different sets of data total. The results were obtained by monitoring the temperature profiles for each trial performed.

5.1 The Design of Experiments (DOE)

The experiments were conducted using one work piece material namely SAE 1015 steel with SNMG 120408 - THM tool. The different alloying elements present in a work piece are shown in the Table 1. The Cutting insert used was manufactured by Kennametals and named as SNMG. The tests were carried for a length of 150 mm. This machine was having variable revolution per minute and variable feed. The cutting parameters are shown in the Table 2. Three levels of cutting speed, feed, depth of cut and air-water pressure combination were used. All the parameters have been selected as per tool manufacturer's recommendation as well as industrial practices for machining steel with carbide insert.

Table 1 Composition of SAE 1015 alloy steel

Material (% per weight)	C	Si	Mn	P	S	Cr	Ni	Cu	Mo
SAE 1015	0.14	0.29	0.40	0.021	0.035	0.30	0.28	0.30	0.06

Table 2 Experimental conditions

Machine Tool	: HMT Lathe, NH-22
Work Specimen	:
Material	: SAE 1015 Steel
Hardness	: 101 BHN (Hot Rolled)
Size	: 50.72 ϕ and 150 mm length
Cutting Insert	: SNMG 120408-THM carbide insert, Kennametal
Tool Holder	:PSBNR 2525 M12
Tool Geometry	: -6^0, -6^0, 6^0, 15^0, 75^0, 0.8 mm
Process Parameters	:
Cutting Speed	: 325, 550 and 930 rpm
Depth of Cut	: 0.4, 0.8 and 1.0 mm
Feed Rate	: 0.04, 0.08 and 0.12 mm/rev
Spray Impingement	:
Water pressure	: 1.0 bar (fixed)
Air Pressure	: 1.0, 1.5 and 2.0 bar
Environments	:External cooling (Wet machining)

High energy spray impinging beneath the flowing chip acts as a wedge that lifts up the chip facilitating chip breakage by reducing curl radius as well as plastic contact and coolant reach to the interface. Coolant having high cooling capacity cools the interface expectedly, effectively and lubricate between the chip-tool and work-tool contact thus reduce frictional heat generation. However, the high-pressure coolant spray could have reduced the cutting temperature quite significantly though in different degrees for different cutting speed, feed and air-water pressure combinations for the SNMG insert as shown in Figure 4. Traditionally cutting temperature increases with the increase of cutting speed and feed. It is clear from Figure 4 that cutting temperature increases with the increase of cutting velocity and feed for both the under both the environments but temperature under high-pressure coolant condition is lower than that of under dry environment. It is an indication of effective cooling and lubrication of high-pressure coolant jet. The difference in the effectiveness of spray impingement cooling observed under different cutting speed and feed rate can be reasonably attributed to variation in the nature and extent of chip-tool contact.

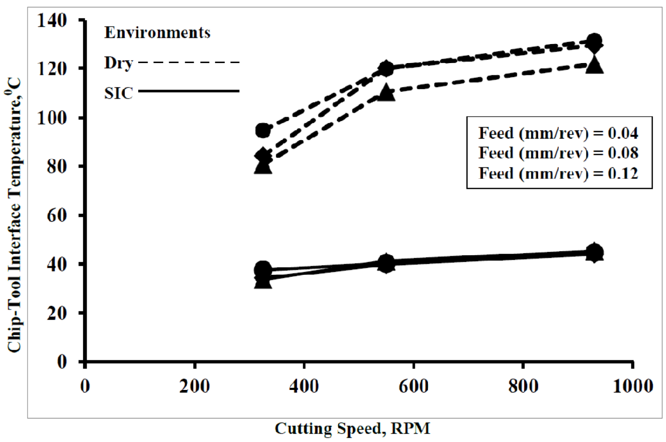

Fig. 4 Chip tool interface temperature during dry and spray machining

5.2 Surface Roughness (Ra)

Figure 5.3 shows comparison of surface finish in SIC with dry turning of alloy steel SAE 1015 by SNMG insert. It is observed that, the surface finish in SIC is much better than that of in dry turning. The Ra value for dry turning is 3.2 µm and whereas in SIC turning it is 1.4 µm. The reduction in cutting force results in reduction in friction. Thus, reduction in friction i.e. cutting force results in better surface finish. The major advantage of using cutting fluids in machining operations is reduced of tool wear at high speed. The other advantage is the lowering of cutting forces.

Besides, during minimal application, the cutting fluid is applied at the tool–work interface and there is a possibility of some tiny fluid particles penetrating the work surface near the cutting edge that forms the top of the chip in the next revolution. These particles, owing to their high velocity and smaller physical size can penetrate and firmly adhere to the work surface resulting in the promotion of plastic flow on the backside of the chip due to rebinder effect. This relieves a part of the compressive stress and promotes chip curl that reduces tool-chip contact length. This phenomenon, in turns, helps in reducing the chip–tool interface temperature further. Nevertheless, still Spray Impingement Cooling (SIC) was found to be more effective as compared to dry and flood cooling conditions.

6. CONCLUSION

Air-Water Spray Impingement Cooling (SIC) enabled substantial reduction in cutting zone temperature and favourable chip-tool interaction under all the investigated speed-feed combinations. Under lower speed and feed condition temperature reduction is more than under high speed-feed condition because of easy entrance of high velocity jet overcoming the bulk contact.

Ultrafast cooling with the present spray impingement technique has significantly reduced flank wears and hence is expected to provide improved tool life. Air-water spray as coolant helps to retain the sharp edge of the cutting tool for a long time by effectively reducing the cutting temperature and ensure efficient cooling.

Surface finish significantly improved under Spray Impingement Cooling condition in turning SAE 1015 steel. It provided more efficient chip removal and heat reduction. Consequently, the work piece surface is less blemished by chips or distorted by excess heat.

The Spray Impingement Cooling was found to be an effective method to reduce the heat transfer during machining steel and to improve the tool and surface properties.

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