AN EFFECTIVE GRINDING FLUID DELIVERY TECHNIQUE TO IMPROVE GRINDABILITY OF INCONEL-600

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Abstract

High heat generation is a common phenomenon of grinding and conventional fluid delivery system through nozzle is not so effective due to stiff air layer formed in the periphery of high-speed rotating grinding wheel. It obstructs grinding fluid to enter the grinding zone. Hence, surface burn of workpiece, high wheel wear, wheel loading, etc. are commonly found in grinding. These difficulties become acute when grinding a superalloy which exhibits high mechanical strength, creep resistance and good surface stability at elevated temperature. These difficult-to-machine alloys are extensively used in making turbine blade, heat exchanger parts, aerospace application, etc. In this present experimental investigation, a nickel based superalloy, Inconel 600, is ground by alumina wheel at different infeeds under dry, wet and wet with pneumatic barrier conditions. A pneumatic barrier is used to break stiff air layer formed around a grinding wheel periphery to allow grinding fluid reach deep inside the grinding zone. Effects of these environmental conditions have been studied in respect of grinding force, force ratio, chip formation, wheel condition, surface roughness and G-ratio. Results show grinding performance is better with the application of wet condition with a pneumatic barrier set-up as it facilitates coolant reach the grinding zone effectively.

Keywords: Surface Grinding, Flood Cooling, Pneumatic Barrier, Inconel-600

1 Introduction

Grinding is a well known finishing or semifinishing operation, and is widely used in industry. It requires high energy per unit volume of material removal. Most of this energy spent is converted to heat which is concentrated within the grinding zone causing high grinding temperature. This high temperature causes various types of thermal damages to the workpiece and wheel, such as surface burn, phase transformation, unfavourable tensile residual stress, open or sub surface crack, wheel loading, etc. (Malkin and Anderson, 1974; Malkin, 1990; Zhu et al., 1995; Baheti et al., 1998; Xu et al., 2002; Das, 2003).

To control temperature during grinding, generally large amount of cutting fluid is applied by a nozzle. Shibata et al. (1982), Das et al. (2000), Das (2003) and Mandal et al. (2010, 2011a) reported that due to formation of a thin and stiff air layer around a high speed rotating grinding wheel, cutting fluid applied by conventional nozzle can not penetrate properly. Therefore, most of the fluid by this conventional wet system using flood cooling is wasted.

Several research works were conducted to improve grinding fluid delivery into the grinding zone. Some important grinding fluid delivery techniques are

i) using scraper board technique Das et al. (2000) and Das (2003),

ii) applying fluid in form of high velocity jet (Baheti et al., 1998; Webster, 2007),

iii) rexine pasted wheel face (Das et al., 2000; Kundu et al., 2001),

iv) application of specially designed nozzle (Banerjee et al., 2008),

v) introduction of minimum quantity lubrication (MQL) technique (Tawakoli et al., 2009),

vi) using pneumatic barrier setup (Mandal et al., 2011b; 2012; 2013a; 2013b; 2014),
vii) mist cooling system (Das, 2003; Mahata et al., 2013),

viii) using cryogenic cooling to have improved grindability (Paul et al., 1993; Sokovic and Mijanovic, 2001), and

ix) applying super abrasive wheels (Das, 2003; Webster, 2007; Wenfeng et al., 2010).

In case of scraper board, a scraper board (hard or flexible) is physically placed in such a fashion that it rubs with the rotating grinding wheel and obstructs the stiff air layer surrounding it. When a fluid nozzle is placed just below the scraper, fluid gets attracted into the grinding zone due to development of slight vacuum (less than atmospheric pressure) there (Das et al., 2000; Das, 2003).

Application of grinding fluid in the form of high velocity jet is sometimes resorted to to penetrate the air layer facilitating supply of fluid in the grinding zone for controlling temperature through lubrication and cooling action (Baheti et al., 1998; Das, 2003; Webster, 2007).

A simple, cheap method employing rexine-pasted wheel face was tested by Das et al. (2000), Kundu et al. (2001) and Mandal et al. (2011a) to suppress formation of air-layer by restricting axial suction of air through porous grinding wheel. Although the effect of formation of laminar sub-layer under moving solid-fluid interaction remains, this technique showed some benefit in terms of reducing grinding temperature.

Some other group (Banerjee et al., 2008) introduced a specially designed nozzle to enable less wastage of grinding fluid. Introduction to minimum quantity lubrication (MQL) technique by Tawakoli et al. (2009) was also reported to be quite beneficial regarding temperature control as well as environment friendliness.

Use of pneumatic barrier setup, as introduced by the group lead by Das, gave remarkable reduction in grinding defects by reduction of grinding temperature. They used compressed gas to penetrate air layer around the grinding wheel, and supplied fluid nozzle to supply grinding fluid with less discharge. This improved effectiveness of applying grinding fluid and reduces the need of the amount of fluid requirement (Mandal et al., 2011b; 2012; 2013a; 2013b; 2014).

Table 1. Experimental Details

<table>
<thead>
<tr>
<th>Machine tool</th>
<th>Surface grinding machine, Make: Maneklal &amp; Sons, India, Main motor power: 1.5 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding wheel</td>
<td>Specification: AA 46/54 K 5 V8, Make: Carborandum Universal Limited, India Size: φ 200 mm OD x 13 mm thk x φ 31.75 mm bore</td>
</tr>
<tr>
<td>Dressing details</td>
<td>Dresser – Single point 0.5 carat diamond dresser, Dressing depth - 20 µm Dressing speed – 0.36 m/min</td>
</tr>
<tr>
<td>Grinding conditions</td>
<td>Up grinding, Grinding wheel velocity (Vc): 30 m/s, Table feed: 7 m/min Infeed: 10 µm</td>
</tr>
<tr>
<td>Environment</td>
<td>Dry Wet with water soluble oil (1:20) Conventional flood cooling with a flow rate of 1 lit/min Flood cooling using pneumatic barrier with a flow rate of 1 lit/min</td>
</tr>
<tr>
<td>Parameters of pneumatic barrier</td>
<td>Polar angle (θ): 45°, Swivel angle (α): 30°, Pneumatic barrier pressure: 400 mm of water column (3.90 kPa)</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>Inconel 600 (74.35% Ni, 15.83% Cr, 9.44% Fe, 0.38% Mn.)</td>
</tr>
<tr>
<td>Workpiece size</td>
<td>120 mm x 65 mm x 6 mm</td>
</tr>
</tbody>
</table>

Mist cooling system was also tested by a number of researchers (Das, 2003; Mahata et al., 2013), however, not much success was reported. On the other hand, this may cause health-related problems of the operator through inhalation of fluid mist (Das, 2003; Sokovik and Mijanovic, 2001).

Cryogenic cooling by supplying liquid nitrogen was reported (Paul et al., 1993; Sokovic and Mijanovic, 2001) to have improved grindability to a great extent. It reduces wheel wear and wheel material removal and gives defect-free ground surface by lowering grinding temperature quite effectively. However, the problem of choking the delivery nozzle through formation of ice from the atmospheric moisture still remains to restrict its wide applicability.

Applying super abrasive wheels made of cBN and PCD (Das, 2003; Webster, 2007; Wenfeng et al., 2010) can also provide quality ground surface without defect. This can be used when desired quality grinding machines are available.

Inconel, a nickel based superalloy, is widely used in the aerospace and nuclear industry owing to their high-temperature mechanical properties, and high resistance to oxidation and corrosion. Typical industrial applications include gas turbine components, space vehicles, rocket engines; submarines steam power plants, and petrochemical equipment. The combined effect of high shear strength, poor thermal properties (low thermal conductivity and thermal diffusivity), high temperature strength, tendency to severe work hardening, and high tool-workpiece affinity makes this class of material very difficult-to-machine. It...
always leads to high temperature at the grinding zone and possible thermal damage to the workpiece during grinding with abrasive wheels (Wenfeng et al., 2010; Mandal et al., 2013a).

In this present work, nickel based superalloy Inconel 600 is ground by alumina wheel under dry condition, conventional wet condition (flood cooling) and newly developed wet with pneumatic barrier system at 10 µm infeeds. Effects of different environment are investigated with respect to grinding force, force ratio, wheel condition, surface roughness and G-ratio.

2 Experimental Conditions

Experiments are done using a surface grinding machine as detailed in Table 1 for observing grindability of Inconel 600 workpiece under different environmental conditions using alumina wheel. A wheel velocity of 30 m/s, an infeed of 10µm and a table feed of 7 m/min are maintained throughout the experimental investigation. Three environmental conditions of dry, wet (conventional flood cooling) and wet with pneumatic barrier are used to observe its effects of inconel 600 workpiece. Up grinding mode is followed for all the experiments. Ten numbers of grinding passes are considered for each experiment. For flood cooling, grinding fluid is passed through a conventional nozzle having 6 mm outer diameter, and placed 10 mm above the work surface to discharge fluid at 1000 ml/min. For flood cooling with pneumatic barrier setup, along with the flood cooling nozzle, a pneumatic nozzle is positioned at a polar angle (θ) with respect to wheel contact surface, and 10 mm away from wheel periphery at a swivel angle (α) of 30°. Positions of the conventional fluid delivery nozzle and pneumatic barrier nozzle are shown in Fig. 1. Rate of fluid flow through the nozzle is same as flood cooling system. The pneumatic pressure of 400 mm of water column (3.90 kPa) is employed throughout these experiments considering substantial gain achieved at this moderate pressure that may be well suited practically.

A strain gauge type dynamometer (make: Sushma, India, model: SA116) is used for measuring grinding forces. During each pass, tangential (Ft) and normal (Fn) force components are measured. Surface roughness of work surface is also measured after ten passes of up grinding at various grinding conditions using a Taylor Hobson make talysurf (model: Surtronic 3+). Grinding wheel wear is measured using a dial indicator. Wheel loading is observed visually, and photographic image is captured by using a CCD camera.

3 Results and Discussion

Grinding is carried out on Inconel-600 workpiece using 10µm infeed under different environmental conditions. Figure 2 represents variation of tangential (Ft) and normal (Fn) grinding force components under different environmental conditions. It is observed that both tangential (Ft) and normal (Fn) grinding forces are higher in dry condition than that at the two wet grinding conditions. This is due to absence of lubrication in dry grinding. Normal force (Fn) in dry grinding is much higher, and is seen gradually increasing due to wheel loading and dulling of grit, as observed during experiments. This increases rubbing of wheel with the workpiece. In wet grinding, due to effect of coolant at wheel workpiece interface, grinding force is much less in comparison with dry grinding. At wet condition less wheelloading is observed that reduces grinding force also. Again, in case of wet grinding with pneumatic barrier, grinding forces (Ft and Fn) are reduced after 6th pass over conventional wet condition. Usually grinding process gets stabilized after four to five passes, and the same phenomenon is also noticed in this experiment as shown in Fig.2. From the 5th grinding pass, forces are becoming steady at the wet conditions. Uncontrolled grinding temperature causes steady increase in force at dry condition.

![Figure 1 Experimental setup indicating cooling arrangement with pneumatic barrier set up when barrier pressure is not provided](image)

![Figure 2 Variation of grinding forces with number of passes at infeed of 10 µm under different environment](image)
Generally with the increase in grinding passes, grinding temperature increases causing various thermal problems in grinding including hike in forces, wheel loading, grit wear, etc. With the application of the pneumatic barrier, grinding fluid reaches deep inside the grinding zone resulting in better temperature control. As a result, after 6th grinding pass, significant reduction in grinding forces are observed due to good temperature control, when otherwise, temperature is supposed to increase further.

It is observed from Figure 3 that in case of 10 µm infeed under dry condition, force ratio has an decreasing trend. It may be due to the fact that normal force (Fn) gradually increases with the increase in passes. The reason behind this may be decreasing sharpness of grits with the increase in grinding passes at dry condition when grinding temperature may have increased indicating decrease in grindability. However, at both the wet conditions, force ratio is much higher than that at dry condition. Beneficial effect of grinding fluid application may be the reason behind.

Depth of groove on grinding wheel made during grinding through removal of wheel materials, is observed after 10 grinding passes under different environment at 10µm infeed, and results are plotted in Figure 4. Wheel material removal through grit dislodgement is adequately more in dry grinding than other wet conditions. This is due to the fact that at higher grinding temperature, in case of dry grinding, grits become dull readily, and hence, grinding forces increase. The high grinding forces are responsible for grit pullout form bonding material of wheel. The phenomenon of grain pull out does not happen regularly. Intermittent grain pull out, as observed after a grinding pass, causes tendency of vibration in dry grinding. Also chips get loaded steadily even within the same grinding pass. In wet condition, removal of grits is much less compared to that at dry grinding due to the effect of cooling and lubrication in wheel workpiece interface. In wet with pneumatic barrier condition, wheel material dislodgement is comparatively less than that of other two conditions. This indicates that more quantity of fluid is penetrated into the grinding zone, and hence, better cooling and lubrication is achieved in comparison with conventional wet condition.
Figure 6 G-ratio after 10 grinding passes under different environment at 10 µm

Roughness of ground surface is measured by surface roughness tester (make: Taylor Hobson). Average surface roughness (Ra), ten point average (Rz) and maximum peak to minimum valley (Rmax) values are shown in Figure 5. It is clear from this figure that values of Ra, Rz, Rmax are much higher in case of dry grinding than wet and wet with pneumatic barrier grinding condition. It is likely to be due to lubricating action of coolant in wet and wet with pneumatic barrier condition. In case of wet grinding with pneumatic barrier, values of Ra, Rz and Rmax are reduced substantially than wet grinding. This indicates better ground surface can be achieved during wet grinding with pneumatic barrier than other two grinding conditions tested in this work.

G-ratio is the ratio of volume of work material removed to volume of wheel material removed. Computed G-ratios after 10 grinding passes at 10 µm infeed under different environment are shown in Figure 6. It is seen that a higher value of G-ratio is achieved under grinding with wet with pneumatic barrier. This indicates more material removal and/or lesser wheel material removal by wet with pneumatic barrier process in comparison with other two environment tested, and hence, the beneficial effect of using a pneumatic barrier.

4 Conclusions

On the basis of present experimental investigation on grinding of Inconel-600, following conclusions may be drawn:

- Both tangential force and normal force are found lower using wet condition with a pneumatic barrier than conventional wet (flood cooling) and dry grinding.
- Wheel wear is also observed to be much lower when applying the pneumatic barrier set up with wet system.
- It is observed that after using pneumatic barrier set up, good surface finish can be achieved.
- From the G-ratio point of view, using pneumatic barrier set up with flood cooling material removal is also high than flood cooling and dry grinding.
- Thus it is seen that using pneumatic barrier set up with flood cooling, grindability of Inconel 600 can be improved by using an alumina grinding wheel.
- Beneficial effects observed during wet grinding with a pneumatic barrier may be due to better control of grinding zone temperature by penetration of the grinding fluid through stiff air layer surrounding the grinding wheel. In this process, much grinding fluid reaches deep inside the grinding zone during grinding using flood cooling with the pneumatic barrier set up.

References

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