MACHINING CHARACTERISTICS OF INCONEL WITH CARBIDE TIPPED BANDSAW

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ABSTRACT

Bandsawing is generally preferred over other sawing techniques (e.g., circular sawing) owing to its lower kerf width, higher metal removal rate and competitive surface finish. Investigations on machining Inconel alloys are generally limited to turning or milling processes with very little or no attention paid on bandsawing Inconel. The paper presents an experimental investigation on machining Inconel 718 using carbide tipped bandsaw teeth. The machining tests were carried out using a modified machine tool with a single bandsaw tooth. Cutting forces were measured during the bandsawing operation and the wear modes and mechanisms in the bandsaw teeth were investigated in a Scanning Electron Microscope (SEM). Abrasive wear, adhesive wear and some degree of plastic deformation were identified as the main wear mechanisms on the flank face of the bandsaw teeth. The higher depths of cut applied during machining could cause chipping or premature failure of the carbide tip in bandsaw tooth.

Keywords: Bandsawing, Inconel 718, Wear mechanisms.

1 INTRODUCTION

Material engineers are continuously facing the challenges to develop high strength materials for demanding applications such as in aerospace industry. At the same time, the cutting tool industries are facing the challenges to machine the materials at an economic rate. One such material is Ni-based superalloy Inconel 718, which is commonly used in the aerospace industry. These alloys have been designed to retain their high strength at elevated temperatures and therefore, the forces involved in machining are considerably higher than that measured in the machining of conventional engineering materials such as steels. Inconel 718 is extremely difficult to machine due to many reasons (Ezugwu and Wang 1996; Rahman *et al.* 1997; Ezugwu *et al.* 1998; Arunachalam and Mannan 2000; Sharman *et al.* 2004) such as high shear strength, high work-hardening capacities, hard carbides in the microstructure leading to high abrasive wear in the cutting tool, low thermal conductivity and specific heat leading to high cutting temperature and strong tendency to weld with tool leading to built-up edge formation. Short tool life is one of the major concerns in machining Inconel 718. In order to achieve an economic tool life, it is absolutely vital to select right tool material, favourable tool geometry and optimum machining parameters (i.e., feed, speed and depth of cut). Cemented carbide cutting tools are most frequently used for machining nickel-based alloys. Flank wear, chipping or fracturing and notching at the tool edge are found to be the dominating failure modes when machining with the carbide tools due to a combination of high thermal and mechanical stresses. In addition, adhesion of workpiece material on the rake face is common while machining at low cutting speeds.

The characteristic feature of the material removal in bandsawing operation is a function of the cutting edge with limited sharpness (5 µm to 15 µm) and the layer of material being removed is also very small (5 µm to 50 µm). The understanding of bandsawing process has been improved significantly due to the scientific work carried out by several researchers (Ahmad *et al.* 1989; Owen 1997; Sarwar *et al.* 1991; Sarwar *et al.* 2005; Sarwar *et al.* 2007; Andersson *et al.* 2001), which was stimulated by demands for higher efficiency, better accuracy and improved surface quality. Most of these studies were focused on the bandsawing of steel workpieces with bimetal high-speed steel bandsaws. Although much attention has been paid on the secondary machining operations (e.g., turning, milling, drilling etc.) of Inconel 718, very little or no attention is paid on machining of the same by the primary machining processes such as bandsawing. The aim of the current investigation is to study the machining characteristics of Inconel 718 with carbide tipped bandsaw teeth.

2 EXPERIMENTAL PROCEDURE

Inconel 718 was selected as the workpiece material for this investigation. The chemical composition of the workpiece material measured by Energy Dispersive X-Ray Spectroscope (EDX) was as follows: Ni (50-55%), Mo (2.8-3.3), Ti (0.6-1.15), Cr (17-21), Co (1.1), Al (0.2-0.8), Mn (0.35) and Fe (bal.). Single bandsaw teeth made of tungsten carbide tips were used for the machining tests. All teeth were examined under an optical microscope and a Scanning Electron Microscope (SEM) for identifying any defects. The average geometrical features of the bandsaw teeth were characterised with tooth tip thickness of 1.6 mm, rake angle of 9.9°, primary clearance angle of 20.2° and cutting edge radius of 12.6 µm. Full product testing of bandsaw is expensive and time-consuming. In the current research work, the performance of carbide tipped bandsaw tooth while cutting Inconel 718 was evaluated using a “single tooth time compression technique” previously developed in Northumbria University, UK. Separate workpiece sections were attached in the chuck to simulate the interrupted cutting action in bandsawing. Three different feeds per tooth or depths of cut (10 µm, 20 µm and 30 µm) with a constant speed of 30 m/min were chosen for the cutting tests. The width of cut was approximately set to 1 mm. Cutting, thrust and side forces were measured during the bandsawing operation with a Kistler dynamometer and associated data acquisition equipment. Specific cutting energy was calculated from the force and material removal rate data (Sarwar *et al.* 2009). The wear modes and mechanisms in the bandsaw teeth were investigated in the SEM.

3 RESULTS AND DISCUSSIONS

3.1 Characteristics of New and Unused Bandsaw Tooth

Fig. 1(a) presents a typical SEM image of a bandsaw tooth, showing both the clearance and rake faces. The carbide tip can be clearly differentiated from the steel backing material. Fig. 1(b) shows a close view of the cutting edge, which appears to be free of any defects such as chipping. No sign of chipping was also observed in both rake and clearance faces.

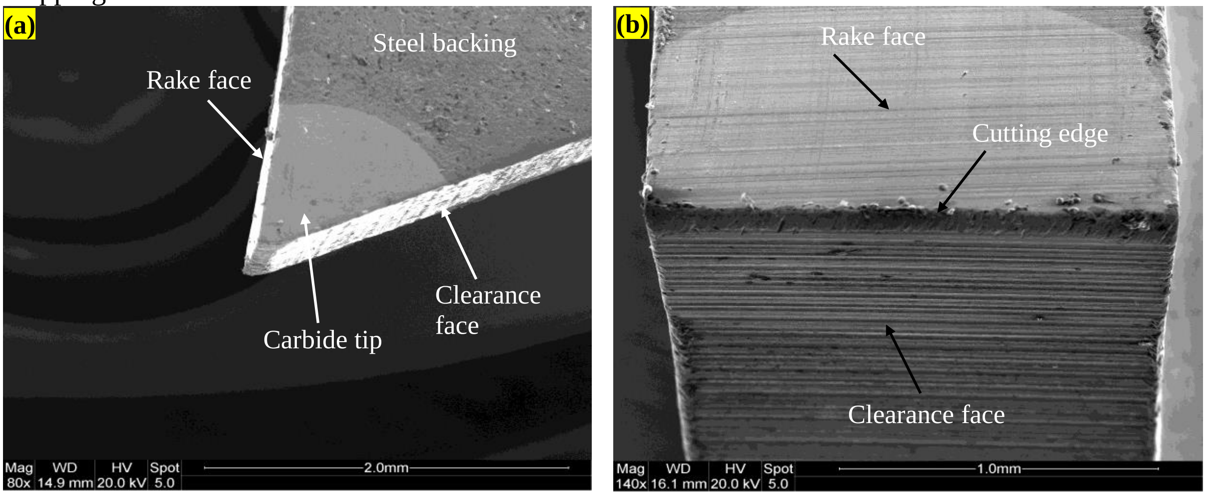

Figure 1: (a) Features of a carbide tipped bandsaw tooth and (b) Close view of the tooth cutting edge.

Horizontal grinding marks were clearly visible on the clearance face. However, no grinding marks were observed on the rake face due to an additional face polishing operation performed during the bandsaw manufacturing process. This helps easy chip flow over the smooth rake face.

3.2 Wear Modes and Mechanisms of Bandsaw Tooth

The bandsaw tooth was taken out after regular intervals and was observed under the SEM to identify the wear modes and mechanisms. SEM image of the worn bandsaw tooth after cutting 300 sections (45 m length of cut) clearly revealed that flank wear was the dominant mode (Fig. 2a). The image also showed that chipping occurred on the rake face due to the interrupted nature of the cutting process. Furthermore, the flank wear at the right hand corner of the tooth was more prominent than the rest of the cutting edge. This corner wear was caused due to the cutting action by the set tooth. Flank wear developed at the cutting edge due to the abrasive action between the flank face and machined workpiece (Fig. 2b). There was also a clear evidence of adhesion of workpiece material onto the worn flanks promoting the adhesive type wear. Evidence of plastic deformation at the corner of the tooth was also found possibly due to the high mechanical and thermal stresses generated at the cutting edge.

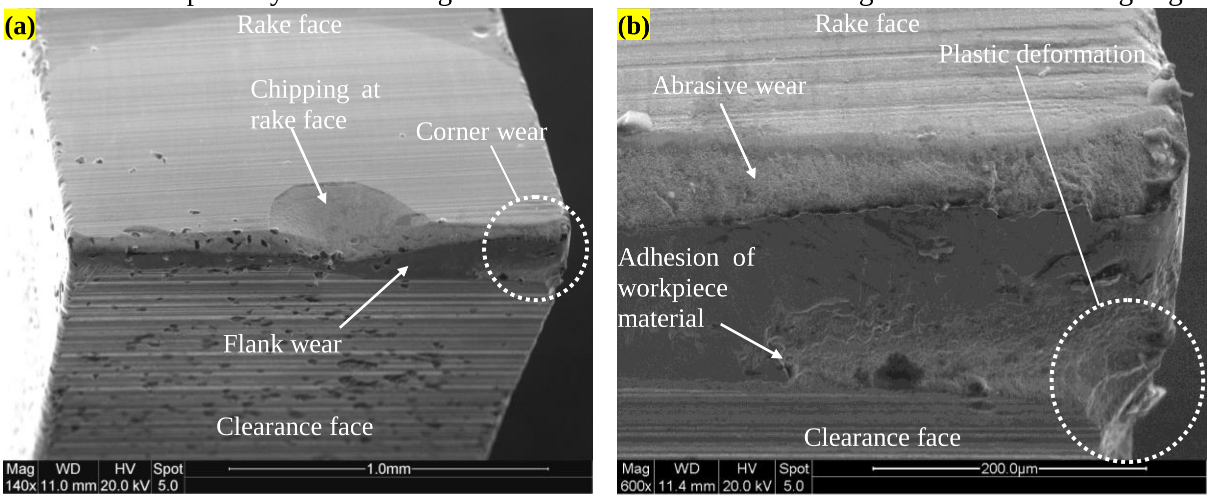

Figure 2: (a) Wear modes and (b) Wear mechanisms in carbide tipped bandsaw tooth.

3.3 Built-up Edge Formation and Chip Characteristics

After cutting 500 sections (~ 75 m length of cut), a metal cap or built-up edge (BUE) started to form on the rake face of the tooth due to the welding of workpiece material by the high stress and temperature generated at the cutting edge (Fig. 3).

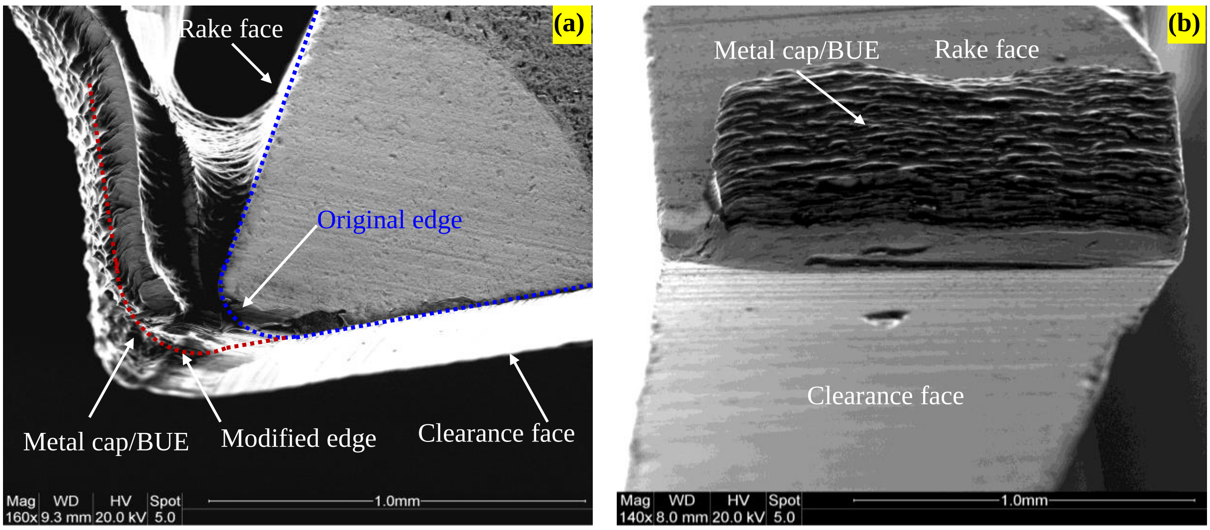

Figure 3: Metal cap or Built-up edge formation on bandsaw tooth (a) Side view and (b) Top view.

The formation of built-up edge modified the cutting edge geometry leading to an effective blunt cutting edge with higher edge radius, which reduced the efficiency of the cutting process. After continuing further cutting, it was observed that once the BUE reached a critical size, it got detached from the edge along with a fraction of tool material. This process further increases the wear at the cutting edge.

The condition of the bandsaw cutting edge affects the chip formation process. At the new condition of the tooth, sharp cutting edge leads to the formation of continuous chips indicating an efficient cutting process (Fig. 4a). On the other hand, short lumpy chips were formed when the cutting edge became blunt with a higher edge radius (Fig. 4b).

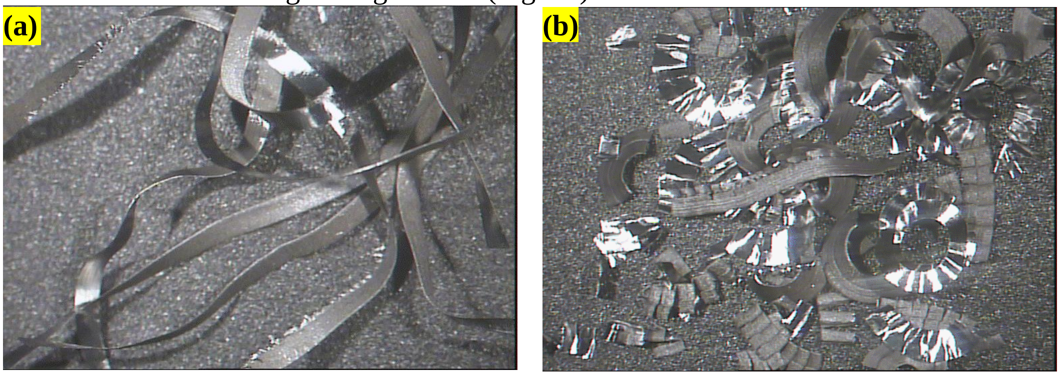

Figure 4: (a) Continuous chips (b) fragmented chips generated at the new and worn conditions of the tooth respectively (Magnification ×10).

3.4 Cutting Force Measurement

The development of cutting forces in the bandsaw teeth during the selected length of cut (150 m) at different feeds or depths of cut are plotted in Fig. 5. The force components increased steadily with the length of cut, which indicated the gradual degradation of the cutting edge. However, it was also noticed that at 10 µm depth of cut, the cutting forces reached the peak point after cutting 90 m and then gradually decreased to lower values. It was evident that after cutting approximately 75 m, the workpiece material started adhering to the rake face forming a metal cap or BUE (see Fig. 3).

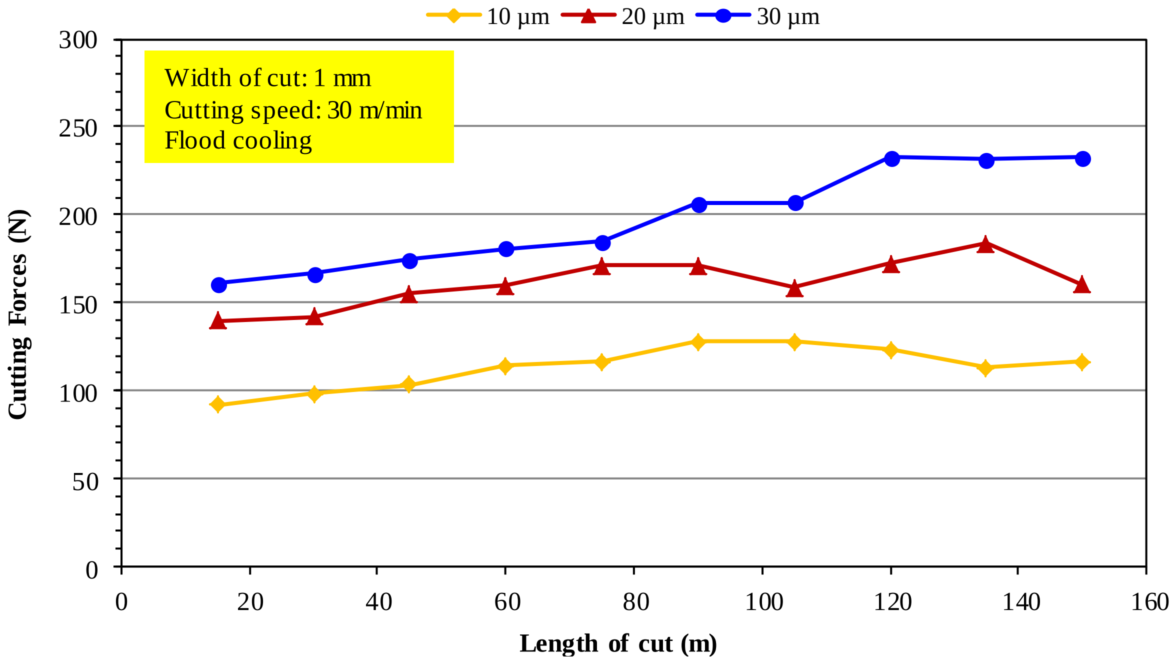

Figure 5: The variation in cutting forces with the length of cut at different feeds.

The BUE modified the geometry of the cutting edge (i.e., blunting and formation of higher edge radius) leading to higher forces in the tooth. Once the BUE was removed from the cutting edge, the forces started to decrease due to the improved condition of the cutting edge or a decrease in depth of cut (Zhang *et al.*2012). However, the forces at this point were still higher than the forces experienced by the carbide tooth at the initial stage of the cutting operation due to the wear took place at the cutting edge. Therefore, the forces served as a good indicator of the degradation of the cutting edge throughout its life. Similar fluctuations in the cutting forces were also noticed during cutting with the other depths of cut. In all cases, thrust forces were higher than the cutting forces (not shown in the graph). Two factors can be associated with this unusual phenomenon. First, a higher edge radius compared to the depth of cut, which is the general characteristics in bandsawing, can be attributed for this. Secondly, the unique material characteristics of Inconel 718 could also play a role in showing this characteristic (Fang and Wu 2009).

3.5 Specific Cutting Energy

Specific cutting energy (E_{sp}) is defined as the energy required to remove specific volume of workpiece material. E_{sp} is a quantitative way of measuring machining efficiency and can be used for assessing the condition of the cutting edge during cutting operation (Sarwar *et al.* 2009). E_{sp} parameter is particularly suitable for measuring bandsawing efficiency due to the low depth of cut compared to the bandsaw edge radius. Fig. 6 presents the variation in specific cutting energy with the depths of cut at different cutting lengths. It is very clear from the figure that higher depth of cut reduces the specific cutting energy or improves the bandsawing efficiency. On average, a 45% decrease in specific cutting energy was observed with the increase in depth of cut from 10 µm to 30 µm. However, it should be noted that higher depth can result in a premature failure of the bandsaw teeth. This condition is not desirable in practical bandsawing due to the fact that the failure of one tooth in a bandsaw loop can cause catastrophic failure of the entire bandsaw loop. Therefore, based on the E_{sp} results from the range of parameters investigated, it can be concluded that 20 µm depth of cut in combination with the other fixed cutting parameters will give the optimum machining efficiency. It was observed that E_{sp} at a particular depth of cut increases with the length of cut due to the wear and degradation of the cutting edge. E_{sp} is also more sensitive at lower depth of cut as evidenced with a greater change in the E_{sp} values at 10 µm depth of cut compared to that at 30 µm.

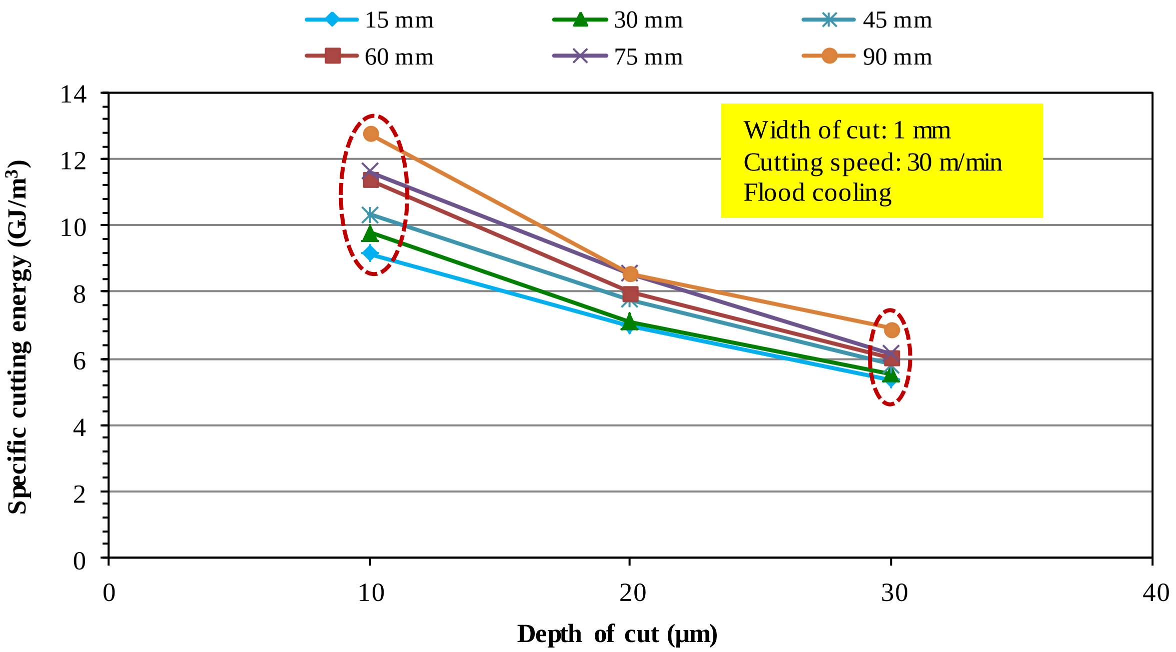

Figure 6: Variation of specific cutting energy with the depths of cut at different lengths of cut.

4 CONCLUSIONS

The following conclusions can be drawn based on the machining tests carried out on Inconel 718 using the carbide tipped bandsaw teeth:

(1) Flank wear was identified as the dominant mode and evidences of chipping on the rake face and corner wear were also found.
(2) The mechanisms of flank wear involved a combination of abrasive wear, adhesive wear and plastic deformation to some extent.
(3) The formation of built-up edge or metal cap modified the geometry of the cutting edge leading to an increase in the force components and a reduction in the machining efficiency.
(4) It was evident that selection of higher feed could improve the machining efficiency due to the reduction in specific cutting energy; however, this could cause premature failure of the carbide tip in the bandsaw tooth.
(5) The wear and degradation of the cutting edge was indicated by the general trend of continuous increase in the cutting forces and specific cutting energies with the length of cut.
(6)The effect of the wear in the cutting edges was also observed through the generation of continuous chips at the new condition of the cutting edge to short lumpy chips at the end of the cutting test.

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