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Optimising the AWJ Cutting Process of Ductile Materials Using Nozzle Oscillation Technique

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Abstract
Striations and roughness on workpiece surfaces produced by abrasive waterjet (AWJ) have been the most persistent problems that stand in the way of wider applications of the technology in industry. This paper presents the an experimental investigation on the impact of using nozzle oscillation cutting technique in minimising or reducing these AWJ cut surface irregularities. The technique was used for cutting ductile materials, i.e. mild steel and aluminium, at various traverse speeds, oscillation angles and frequencies of oscillation. The results show that by oscillating the nozzle during cutting, the improvement in surface finish as measured by center-line average R_a can be obtained by as much as 30%.

Keywords: AWJ cutting; Materials processing; Nozzle oscillation; Surface roughness; Surface striation.

1 Introduction

Surface irregularities in the form of striations and roughnesses have been ongoing problems associated with abrasive waterjet (AWJ) cutting of engineering materials. The causes of these surface defects that put multifaceted limitations on the wider use of the AWJ technology in industry have been the subject of a large number of investigations. A number of mechanisms that are thought to cause these observed striations and roughness on the cut wall surfaces have been proposed by various authors who conducted studies in this area [1,2]. Although most of these proposed mechanisms have been generally accepted by the wider community of researchers in AWJ cutting, there still remain some important disagreements regarding the exact nature of these proposed mechanisms and their relative contributions to the observed material surface defects [3]. The characteristic feature of the cut-wall surface topography of relatively thick materials constitutes a distinctly smooth upper zone and a striated or wavy lower zone [4,5] as shown in Fig. 1(a). In addition to these waviness or striations in the lower zone, the material surfaces also exhibit roughness of a random nature superimposed on these wavy patterns as shown in Fig. 1(b). However, the division between the smooth zone and the rough zone has been rejected by some of the researchers [6].

Chao and Geskin [6] suggest that the striations begin at the top of the cut and progressively worsen as the depth of the cut increases due to vibration and the decrease in the energy of the abrasive jet. The explanation given for the conflicting view in the surface texture is also reflected in the explanation given for the physics of the cutting process.

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The sources for the formation of striations and roughness highlighted by the research work reported so far include mechanisms that are internal and external to the AWJ cutting process [3,7]. Although two types of surface defects, striations and roughness, have been observed, in most of the published work on AWJ cutting, no distinction was made between these two types [5]. The striations or waviness generally follow a characteristic pattern; however, the roughness, which is superimposed on these striations or waviness patterns, is often of discontinuous and random nature [6].

The large amount of research work reported in the literature does only provide a qualitative explanation for the various mechanisms. In addition, until recently, there was very little that has done to develop cutting techniques that could be implemented to assist in reducing these defects from the cut wall surfaces of AWJ machined products. The cutting head or nozzle technique, which was introduced by Veltrup [8] and successfully used in AWJ cutting by Siores et al. [7] and Chen et al. [9], has been found to be an effective way in increasing the performance of AWJ cutting. In this technique, the cutting head is moved in an angular direction parallel to the cutting direction (in the cutting plane) at a given angle and frequency of oscillation. This paper presents an experimental investigation on using this nozzle oscillation technique in the AWJ cutting of ductile materials and a quantitative evaluation of the improvement in the depth of the smooth cutting zone and the reduction of the striations from the rest of the machined surfaces as a result of the oscillation.

2 Literature Review

The widely accepted explanation for the physics of the material removal process and the striation formation mechanisms is that of Hashish [5,10] who conducted an investigation of the AWJ cutting process using a high-speed camera to record the material removal process in a plexiglass sample. He found that the material removal process is a cyclic penetration process that consists of two cutting regimes which he termed “cutting wear zone” and “deformation wear zone” following Bittar’s erosive theory [11,12]. The two zones of cutting and the abrasive particle trajectory path in these zones are shown in Fig. 2.

Hashish also proposed that the cutting process consists of three stages, which are the entry stage, the cyclic cutting stage and the exit stage as shown in Fig. 3. In the cutting wear zone, material removal is by abrasive particles striking the workpiece at shallow angles of attack while material removal in the deformation wear zone is by the abrasive particles impinging at large angles of attack.

The general erosion process proceeds in a cyclic manner with steady material removal up to a critical depth h_c followed by the formation and removal of steps as the cutting depth increases. Below this critical depth h_c, the material removal process is unsteady, resulting in the formation of striations or waviness on the wall of the cut surface [3]. Thus the change of material removal process from one mode to another is suggested to be the cause of striation or waviness [5].

The two-stage cyclic material removal process and the associated striation formation mechanisms are generally accepted by a large number of researchers in this area [6,13]. Niu et al. [2] who also conducted a similar experiment confirms the cyclic nature of the cutting process that was observed by Hashish [10]. However, in contrast to Hashish who made a clear distinction between the two stage cutting processes that result in two types of surface profiles, their finding show that the step formation begins close to the top of the surface thus suggesting a singular mode of material removal process [2]. Accordingly, they conclude that striations begin at the section of the workpiece material surface that to the contrary has been considered to be a smooth zone by Hashish [10].

Other mechanisms such as abrasive particle kinetic energy and machine vibrations have also been sighted as contributory or main causes of striations [4]. However, in some cases these proposed models for striation formation mechanisms are of a complimentary nature while in others they are fundamentally different.

Raju and Ramulu [14] proposed a model for striation formation in which the waviness appears symmetrically around the axis of the kerf as shown in Fig. 4 (a). In this model striations occur during the jet travel from one channel to the next. However, experimental investigations by Gosper et al. [16] and Wang [17] showed that striations at both kerf sides are anti-symmetrical. The reason given by these researchers for this is the oscillation of the jet path as shown in Fig. 4 (b). The amplitude of oscillation of the abrasive jet was found to increase as its energy decreases. This also decreases the jet ability to penetrate deeper into the material. The non-uniform abrasive loading of the jet or the deflections of the particle trajectory caused by secondary impacts is given as the possible reason for these observed oscillations [16].

In contrast, Arola and Ramulu [4] proposed a material removal and striation formation model based on the existence of a critical kinetic energy of the high speed slurry flow that has to undercut to produce the striations on the cut surface. Their model exploits the fact that energy is continuously dissipated by the abrasive particles as cutting progresses along the depth of workpiece material. This is because of some of the energy contained in the high velocity abrasive particles being used in eroding materials close to the surface of the workpiece and particle fragmentation due to primary or earlier impacts. Therefore, the jet with this lower energy is deflected in angular direction resulting in striations on the cut surface [4]. They also suggested that the material removal process, although it can be different for different materials, is independent of depth of cut for a given material. Zeng and Munoz [13] also suggested that striation formation mechanisms are closely related to the jet characteristics and support the same view.

Siores et al. [18], who used a non-invasive LDA technique to investigate abrasive particle distribution in the incoming jet stream, proposed a mechanism of striation formation that is due to internal and external factors. The factors associated with abrasive particle kinetic energy distribution were considered as internal while the vibrations of the nozzle and control system were considered external factors. The internal factors that were suggested by these authors are similar to that of others such as Arola and Ramulu [4] and Zeng and Munoz [13] mentioned earlier. Chao and Geskin [6] have also proposed the external factors such as machine and nozzle vibrations to be the causes of the observed striations.

By experimentally studying the cutting head control and robot dynamics under various operational conditions, Chao and Geskin [6] have found that the machine vibration is the main cause of striation formation in AWJ cutting process. A second-degree polynomial function of the penetration depth was found to fit the increase in amplitude of striations from the smooth upper zone to the striated lower zone. The reason given in their study for the difference in the amplitude of these striations was the small amount of vibrations at the top surface that progressively increased and the abrasive waterjet with the reduced energy flowing back along the already cut channel. With these vibrations, a side way velocity is added to the forward motion, which cuts to the sidewall surface, thus forming the striated channel with relatively large amplitude of oscillation.

As has been seen on the review of the pertinent literature above, a number of researchers have investigated the striation formation mechanisms and some have proposed various models of differing accuracy to describe this phenomenon associated with the abrasive waterjet cutting processes. Among the various techniques developed to increase the performance of AWJ cutting, such as multipass cutting [19], angling the jet forward in the cutting plane [7,17] and cutting head oscillation [9,17], the cutting head oscillation technique has been found to be the most effective way that can result in a reduction in striations and improve the quality of surface finish of products without significantly compromising its competitive advantages. The work in this paper is to study qualitatively the effect of cutting head oscillation on the performance of AWJ cutting on ductile materials.

3 Experimental Setup and Procedure

The experimental set up used for the experiments consisted of a high pressure intensifier pump and a 6-degrees of freedom robot fitted with the high pressure waterjet accessories, a receiver and an abrasive feeding and mass flow monitoring system. The intensifier was capable of suppling water up to a maximum pressure of 55,000 psi (380 Mpa), while the robot was to position and move the nozzle to carry out the cutting.

A number of experiments were conducted in which the oscillation angle, frequency of oscillation and the nozzle traverse speed were varied within practical ranges. In these experiments, the oscillation angle was varied from two degrees to seven degrees while the oscillation frequency was varied from 60 to 360 cycles per minute or one to six cycles per second. The traverse speeds used for processing the materials were in the range from 150 to 300 mm per minute.

The robot was programmed to simultaneously execute the linear motion (the traverse speed) and the oscillation motion of the cutting head in a given sequence. The oscillation movement consisted of a forward angular movement at a given angle and angular speed and a backward or return movement to the original position of the arm with the same speed. The original position of the nozzle is perpendicular to the workpiece surface.

The other parameters used were:

- Nozzle diameter: 1.33 mm
- Abrasive mass flow rate: 0.32 kg/min
- Water-jet pressure: 50,000 psi (or 345 Mpa)
- Stand off distance: 2 mm

The R_a values for each of the surfaces were measured using stylus type equipment at three points from the top edge of the cut-wall. The sampling length used for measuring the R_a values at these preselected points was 16 mm with a cut-off of 2.54 mm.

In addition to the experiments conducted using mild steel and aluminium specimens, visualisation experiments that could help in illuminating further the significant mechanisms involved in each of the two cutting processes, traditional AWJ cutting and AWJ cutting with head oscillation, were also carried out. A high-speed video camera was used to record and view the cutting process while cutting plexiglass samples. The recorded images were also later analysed using image analyses software.

5 Results and Discussion

The experimental results for the mild steel processed at traverse speeds of 150 and 180 mm/min. are shown in Fig. 5 for normal (with no oscillation) and oscillation cutting. The frequencies of oscillation used with these traverse speeds were 4 and 6 cycles per second. The results show that the surface qualities for materials processed using the head oscillation technique were significantly better than that of surfaces produced by the traditional or normally AWJ cutting technique. At the lower traverse speed of 150 mm/min., the average value of R_a for the samples cut with head oscillation was about 30 percent lower than that using the normal AWJ technology, while this improvement shows increase when the R_a was measured further down along the cut wall.

Figures 5(a) and (b) also show that in addition to the traverse speed, the difference in surface quality was also influenced by the angle of oscillation used for cutting the samples. The improvements in surface quality were directly proportional to the oscillation angles used for processing the samples; i.e. better improvements in quality for higher angles of oscillations and less improvement for lower angles of oscillations. The angles of oscillations used in these experiments also influenced the trends exhibited by the R_a values measured along the cut-wall surface. The change in R_a values with an increase in distance from the top surface of the sample was almost linear for materials processed at high angles of oscillations for both traverse speeds. However, materials processed at lower angles of oscillation showed a non-consistent variation with depth of cut. This was at first decreasing in the measured R_a values starting from a high value close to the top edge, followed by an increase as the distance from the edge was increased.

Additional sets of experiments were conducted at other frequencies of oscillations to determine their effect on surface quality. The results found for mild steel at an oscillation frequency of 4 cycles per second (or Hz) and a traverse speed of 150 mm per minute were plotted as shown in Fig. 5(c). These results show that a slight improvement in surface quality over those processed at the higher oscillation frequency of 6 Hz. However, the improvement in surface quality was much more consistent across the cut-wall thickness for all angles of oscillations.

Other sets of experiments were also conducted using Aluminium samples. The results of these experiments are shown in Figures 6. Figures 6(a) and (b) show that unlike the significant improvements obtained with mild steel samples at the same traverse speeds (150 and 180 mm/min), the results for aluminium samples showed only slight overall improvements when processed using the cutting head oscillation technique as compared with samples processed with traditional AWJ cutting technique. However, the improvements were significant up to a distance half the sample cut-wall thickness, that is about 7 mm from the top surface. This indicates that superimposing cutting head oscillation for cutting thinner materials results in better surface quality than the use of the traditional AWJ cutting technique alone.

The results found at the lower oscillation frequency of 4 Hz with the same traverse speeds were similar to those found at the higher frequency of oscillation for a distance to about half the thickness of the material measured from the top surface as shown in Fig. 6(c). However, the measured values of the roughness at higher depth were significantly larger than those found for 6 Hz oscillation frequency at the same traverse speed. This was also different from that found for mild steel samples that show improvement in surface quality with a decrease in frequency of oscillation from 6 Hz to 4 Hz at the same traverse speed.

A more significant improvement in surface quality for aluminium samples was obtained by increasing the traverse speed used in the experiments. Results of the experiments conducted at the higher traverse speed of 240 mm/min. for aluminium samples plotted in Fig. 6(d) show that oscillation cutting results in better surface quality than traditional AWJ cutting at all angles of oscillations. In some of these samples the measured values of R_a were at first decreasing, starting from some high value close to the surface of the sample, until to about half the depth of the material, followed by an increase or a decrease in the measured R_a values as the depth of cut increased. This was also the case with some of the earlier mild steel investigations. These results, however, were not consistent with most of the other published research [3,4]. However, these other studies were conducted using traditional AWJ cutting.

Increasing the traverse speed further to 300 mm/min. resulted in a dramatic improvement in the surface quality of aluminium samples processed with the head oscillation technique as compared to those processed with traditional AWJ cutting as shown Fig. 6(e). In addition to the high overall improvement in the surface quality at this traverse speed, the measured R_a values were also changed slightly or remained constant with the change of distance from the top surface of the samples. These results were similar to those found in mild steel samples at traverse speeds of 150 to 180 mm/minute.

The 300mm/min. traverse speed used to process the aluminium samples was the maximum traverse speed at which cutting can be effectively conducted in traditional cutting, that is without superimposing cutting head oscillations, and with the maximum pump pressure used in these experiments. The limiting speeds for cutting mild steel were around 150 to 180 mm/min. at the same maximum pump pressure. These results indicated that maximum improvements in surface quality can be achieved by superimposing cutting head oscillation at the higher traverse speeds.

A regression analysis was applied on the experimental data obtained for both aluminium and mild steel to gauge the effects of the operating parameters used in oscillation cutting. The results of these analyses that in addition to the operating parameters, oscillation frequency, angle of oscillation and the traverse speeds, which also included the change of Ra values with the distance from the top edge of the cut-wall surface, were of the following form:

$$R_a = 3.01 - 0.15d - 0.25\,S + 0.39\xi - 0.26\alpha$$

for mild steel samples and

$$R_a = 4.82 - 0.28d - 0.20S + 0.43\xi - 0.50\alpha$$

for aluminium samples. R-squared values were 76 and 68.3 percent for mild steel and aluminium samples respectively with a confidence interval of 95 percent.

Where d is the distance from the top edge of the cut-wall surface in mm, S the traverse speed in mm/min., ξ and α are the oscillation frequency in Hz and the angle of oscillations in degrees respectively.

In addition, a polynomial regression analysis on the results for both mild steel and aluminium samples was applied using the R_a data averaged to a distance from the top edge that is equal to half the thickness of the samples. This was done because the improvements found at these regions were consistent throughout the traverse speeds and frequencies used to process these materials. The particular motivation for this analysis was to identify the qualitative effects of the use of different combinations of angles of oscillations and oscillation frequencies on the subsequent surface finish. Figs. 7(a) and (b) show the results of these regression analyses for mild steel and aluminium samples respectively.

The graphs show a decrease in the measured R_a values with an increase in the angles of oscillations. However, the variation in the measured R_a values with change in the oscillation angle was somewhat different for the two materials. In particular, mild steel samples show a monotonic increase starting at a smaller value at the lower end of the oscillation frequency continuum while aluminium shows minima at both the high and the lower end of this continuum. In addition, the effect of angle of oscillation was much more pronounced in the case of aluminium samples than mild steel samples. The absolute values of R_a were also much larger in the case of aluminium samples. This, however, was in line with the results of other reported works in the literature including that of Raju et al. [15]. However, the other reported investigations were conducted using the traditional AWJ cutting method.

The visualisation experiments showed some of the possible reasons behind the observed differences between the two cutting techniques, while the difference between the two materials might be related to the different physical properties and microstructures of these materials. Unfortunately, the visualisation study was unable to be performed on the two non-transparent materials. Figure 8 shows the traces of solid/jet interface of the plexiglass samples used in the visualisation experiments for traditional AWJ cutting and AWJ cutting with head oscillation, respectively. For materials processed with the head oscillation, the cut-wall surface of the material was repeatedly scanned by fresh abrasive water-jets that improved the cut-wall surface quality. This is unlike the traditional AWJ cutting technique in which the cut-wall surface is only momentarily exposed to a stationary jet the residence of which depends on the traverse speed used. With lower traverse speeds, the residence of the jet at a particular spot is longer and results in a better surface finish. However, at higher traverse speeds the residence time of the jet is lower, thus resulting in a rough and striated cut-wall surface. As the results show, superimposing head oscillation at these higher speeds produces a better cut-wall surface quality by increasing waterjet residence time at a particular spot without decreasing the linear traverse speed.

In addition, the slopes of the successive traces of the solid/jet interfaces for the head oscillation cutting technique are much more steeper than that of traditional AWJ cutting as shown in the figures. This indicates that a higher depth of cut can be achieved for a given set of parameters using the head oscillation cutting technique as the penetration rates were higher. However, this was not clearly established by this current work as the plexiglass samples were cut through in the visualisation experiments conducted. Therefore, further research work is needed to establish the total depth that can be achieved by each of these cutting techniques under given sets of operating parameters.

6 Conclusion

The results obtained indicate that improvements in surface quality as measured by R_a values can be achieved by using oscillation cutting. The results also indicate that:

- For relatively thin materials a consistently improved surface quality can be achieved using head oscillation technique.
- For relatively thick materials better consistency across the cut-wall thickness and overall improvements in surface qualities can be achieved when head oscillation is superimposed at higher traverse speed.
- The angle of oscillation used should be high and frequency low for processing mild steel
- For cutting aluminium samples, higher oscillation angles still need to be used to achieve a better surface quality.

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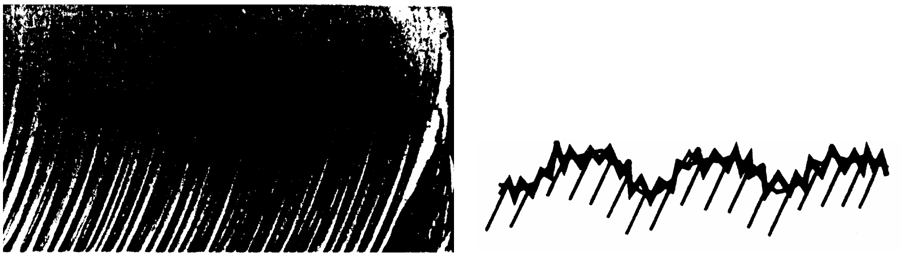


(a) (b)

Fig. 1. Typical appearances of the smooth upper zone and the striated and rough zone [5].

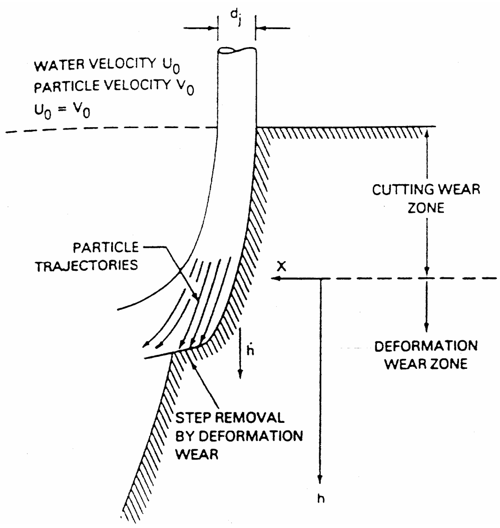


Fig. 2. The wear cutting and deformation cutting mode parameters proposed by Hashish [10].

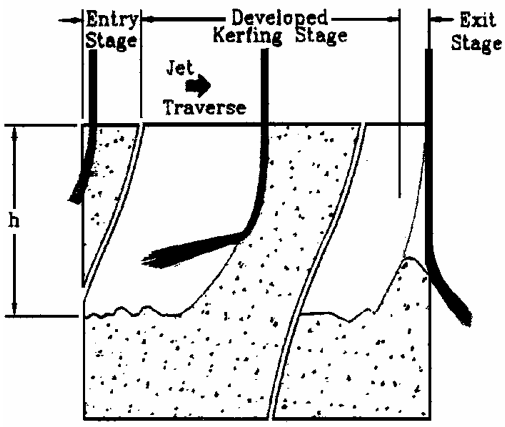
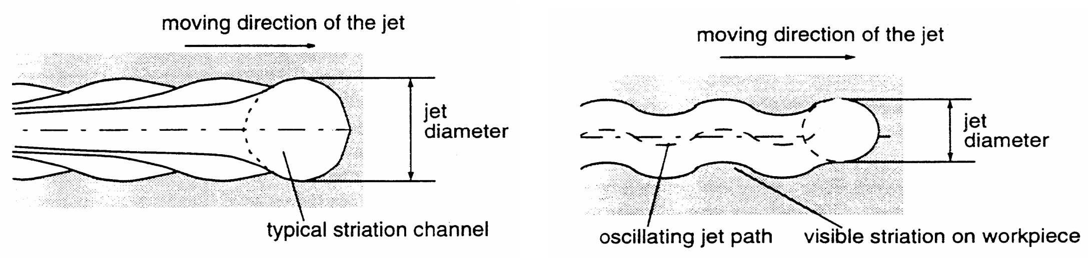
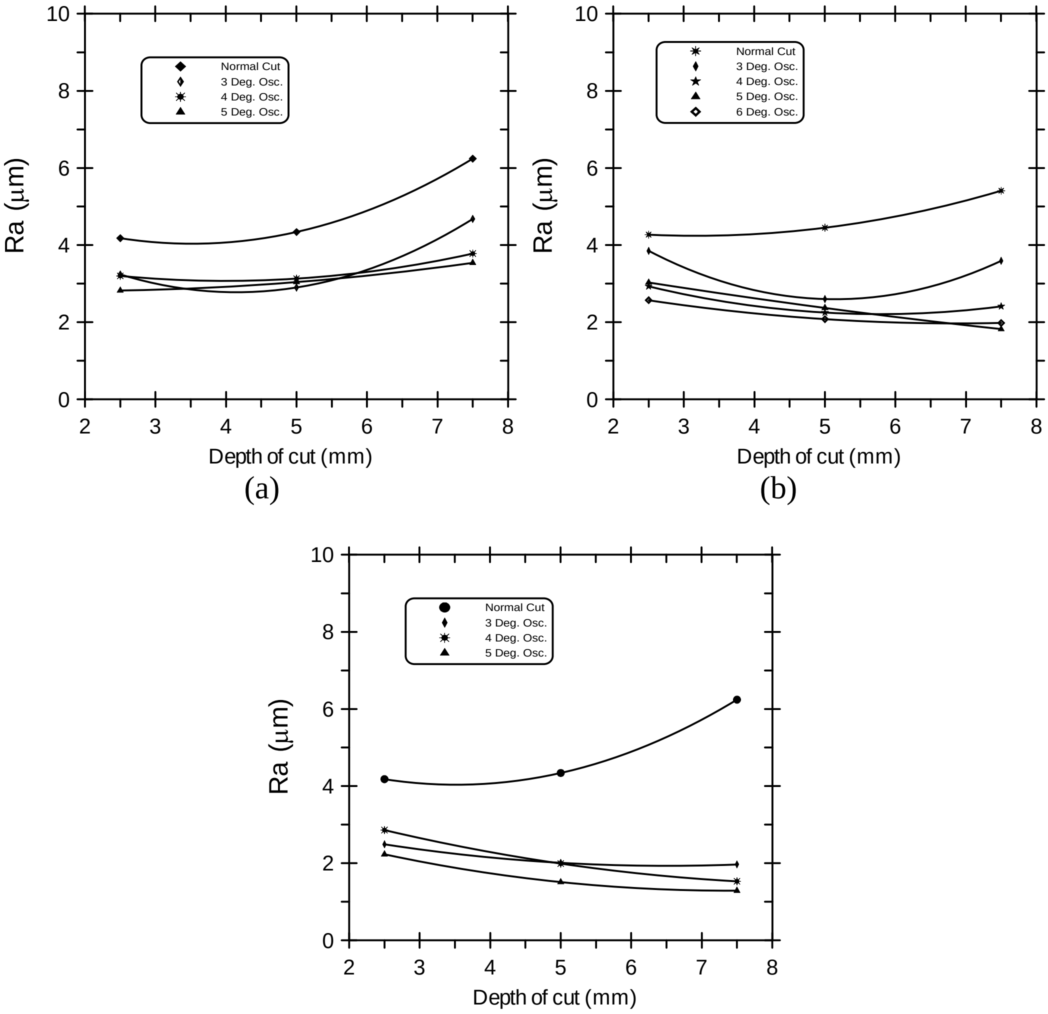


Fig. 3. The three stages in the cutting process, the entry stage, the cyclic cutting or developed kerfing stage and the exit stage[10].



(a) (b)

Fig. 4. Mechanism of striations proposed by Raju and Ramulu (a) and observed striation formation mechanisms (b) [14,15].



(a) (b)

(c)

Fig. 5. Oscillation cutting results for mild steel: (a) traverse speed = 150 mm/min. and oscillation frequency = 6 Hz; (b) traverse speed = 180 mm/min. and oscillation frequency = 6 Hz; (C) traverse speed = 150 mm/min. and oscillation frequency = 4 Hz.

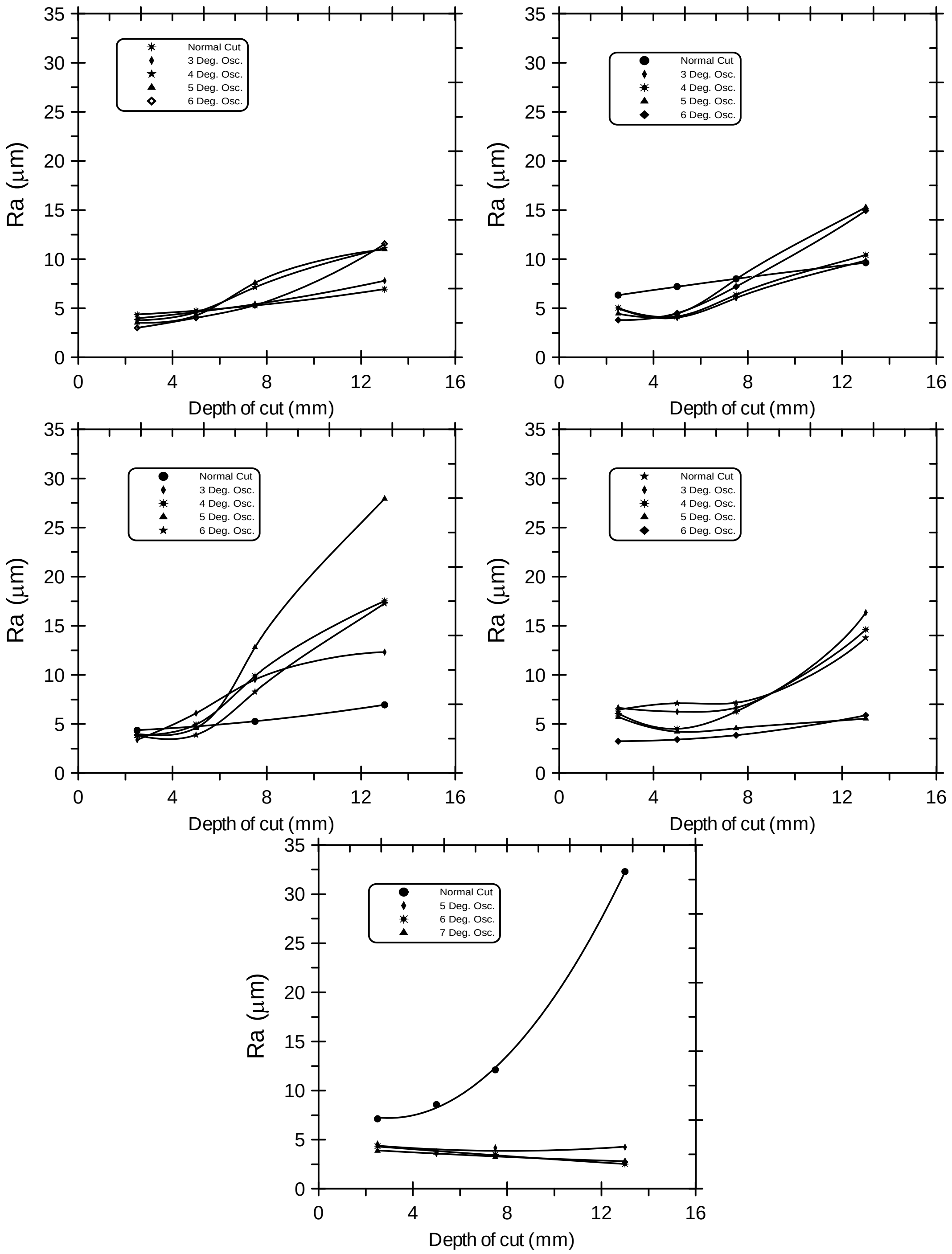
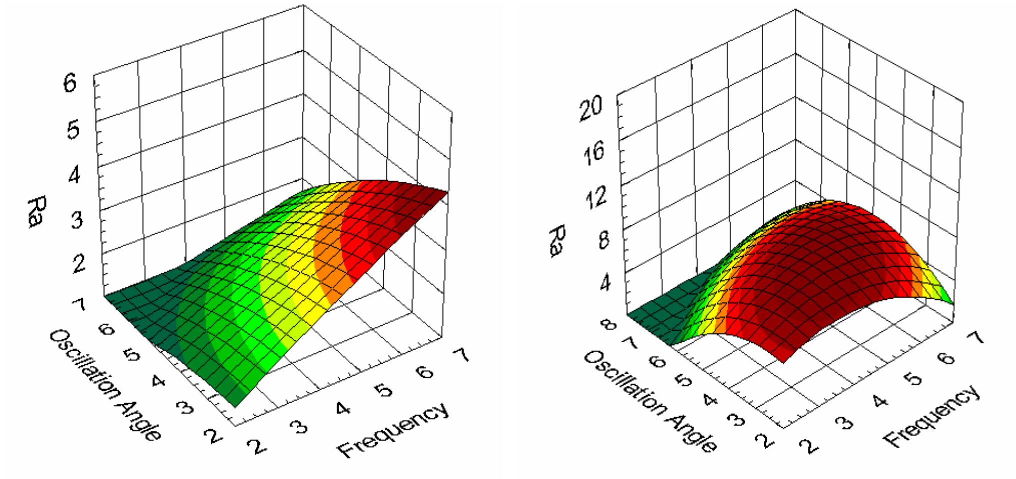
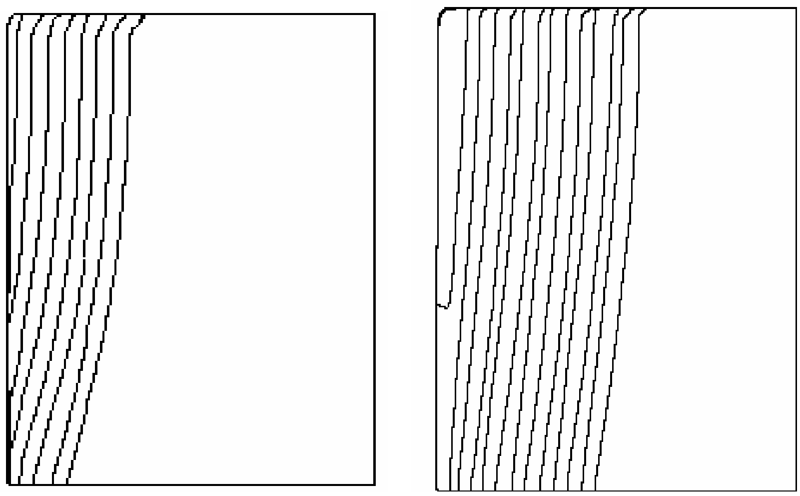


Fig. 6. Oscillation cutting results for Aluminium samples: (a) traverse speed = 150 mm/min. and oscillation frequency = 6 Hz; (b) traverse speed = 180 mm/min. and oscillation frequency = 6 Hz; (c) traverse speed = 150 mm/min. and oscillation frequency = 4 Hz; (d) traverse speed = 240 mm/min. and oscillation frequency = 6 Hz; (e) traverse speed = 300 mm/min. and oscillation frequency = 5Hz.



(a) (b)

Fig. 7. Roughness values as a function of frequency of Oscillations and Oscillation angles; (a) mild steel, (b) aluminium.



(a) (b)

Fig. 8. Abrasive jet and workpiece interface trace profile at traverse speed of 30 mm/min and water pressure of 276 Mpa: (a) traditional AWJ cutting method; (b) with nozzle oscillation at oscillation angle of 2^o and oscillation frequency of 2 Hz.