Experimental analysis of orthogonal micro-machined surface features and chip morphology of AISI1215 steel by using EBSD method

S. Yadav[1*], R. Waikar[2],R. Pawade[3], S. Joshi[4]

[1]UG Student, [2]PG Student, [3]Associate Professor, Dr. Babasaheb Ambedkar Technological University, Lonere, India
[4]Professor Indian Institute of Technology Powai, Mumbai, India
{spyadav@dbatu.ac.in}

Abstract: In this work analysis of fundamental aspects of orthogonal microcutting was carried out in terms of variables like shear angle, chip thickness, chip morphology as a function of cutting speed, depth of cut, tool rake angle and heat treatment provided to the work specimen. Analysis of results shows that the material flow pattern at low cutting speed is highly inhomogeneous, which affects segmented chip formation. As the uncut chip thickness approaches the minimum chip thickness, chips are formed by shearing of the workpiece, with some elastic deformation still occurring.At the highest depth of cut of 100 µm, shear angle is fairly dependent on the rake angle. AISI 1215 steel heat treated at 1200°C, shows the lowest shear angle at all the depths of cut at 5° or 10° of rake angle. Analyses of chip segment per unit length show that, the number of segments reduces as the rake angle increases for all the four work materials that were heat treated at the various temperatures.

Keywords: ***Micromachining, Chip formation, Cutting force, AISI 1215 steel***

1 Introduction

The principles of micro-cutting are similar to those of conventional cutting operations. The surface of the workpiece is mechanically removed using micro-tools. Unlike conventional macro-machining processes, micro-cutting displays different characteristics due to its significant size reduction. Trend of miniaturization of products and consequently its components nowadays can be evident in almost every production field. To accomplish requirements imposed by miniaturization, micromachining has proved to be a satisfied manufacturing technique. Masuzawa and Tonshoff [1] have defined the range of uncut chip thickness for micro-cutting as 0.1 to 200 µm. Larger uncut chip thickness is normally used in “rough” machining operations to increase the material removal rate. Smaller uncut chip thickness is normally used in finishing operations. A number of features can be used to characterize and define the scope of micro cutting such as uncut chip thickness, dimensions and accuracy of micro parts or features, cutting tool geometry, underlying cutting mechanics, application area.

According to Dornfeld et al., [2] crystalline grain size of most work-piece materials is of the same order as the depth of cut in micro-cutting, so that chip formation normally takes place by the breaking up of the individual grains of a polycrystalline material. Most polycrystalline materials are thus treated as a collection of grains with random orientation and isotropic properties [2]. The crystalline graphic-orientation affects the chip formation, the surface generation, and the variation in the cutting forces [3]. There is a distinct difference between micro-cutting and conventional cutting, where the material can be treated as isotropic and homogeneous. To et al. [4] demonstrated the effects of crystallographic orientation and depth of cut on the surface roughness in diamond turning of single-crystal aluminium rods. Moriwaki et al. [5] conducted in situ machining experiments inside a SEM on single-crystal copper in various cutting direction at depths of cut ranging from 0.1 to 5 mm and a cutting speed of 120 mm/min. They found that the crystallographic orientation influence the chip formation process in terms of magnitude of the shear angle and the cutting forces. The shear angle was found to reach values as high as 60°.

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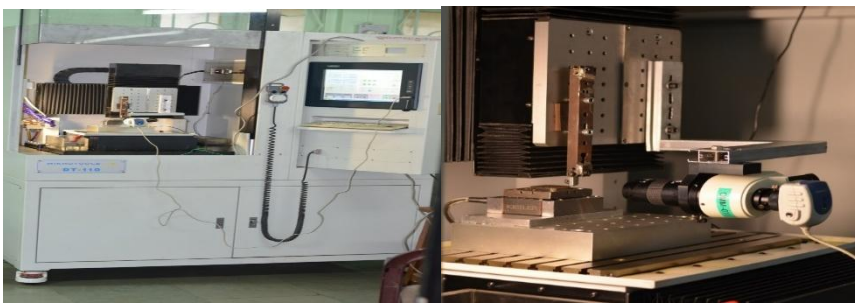
Liu et al. [6] demonstrated that there is elastic-deformation of the workpiece during micro-cutting process.Moriwaki et al. [5] used the Finite Element (FE) method to analyse orthogonal micromachining with the effect of tool edge radius. FE model showed good agreement with experimental cutting of copper with a sharpdiamond tool. Vogler et al. [7] determined the minimum chip thickness of steel by using an FE simulation tool. They reported the critical chip thickness as 0.2 and 0.3 times the edge radius for pearlite and ferrite, respectively. Lo [8] developed the elastic-plastic finite element method to investigate the effect of the tool rake angle on the chip and machined workpiece during precision cutting process.

With an increase in tool rake angle from 5^0 to 15^0, the changes in the above-mentioned physical phenomena are more pronounced. In contrast, the increase of tool rake angle from 15^0 to 20^0 hardly brought about any changes to these physical phenomena. Thus, reducing the cutting force in micromachining operations significantly improves material removal productivity, decrease tool deflection and tool wear, delay tool failure, and narrow workpiece tolerance limits. Pawade and Joshi [9] performed scanning electron microscopy of chips which revealed that the cracks extend from tool nose side up to 1/2 to $3/4^{th}$ width of the chips. The rest of chip thickness was removed by ductile-type deformation. It was also observed that at 125m/min, the chip thickness ratio (t/t_c) was higher which was attributed to thinner chips that was produced during machining of Inconel 718. The works done by Ernst [10] and Merchant [11] previously were based on the concern of forces in the shear plane and on the tool–chip interface. The development of theory of plasticity resulted in various slip-line models of orthogonal cutting.

Lee et al [12] studied the material anisotropy which plays an important role in the formation of shear angle in metal cutting. Crystallographic textures contribute to an important source of material anisotropy. The most likely shear angle is the one at which the Taylor factor is minimum. A good agreement was found between the predicted shear angle in machining a polycrystalline OFHC copper and the experimental data reported. Pawade et al. [13] observed that as the cutting speed increases from 60 m/min to 120 m/min, the chip thickness ratio decreases by small value. However, further increase in the cutting speed to 180 m/min causes increase in the chip thickness ratio. It is observed from their work that at lower and medium cutting speed of 60 m/min and 120 m/min respectively, the chip thickness ratio follows the decreasing trend, which agrees to the fundamentals of metal cutting [13]. Simoneau et al. [14] concluded that microstructure has a significant effect on micro- scale cutting. They analysed the effect of grain size and orientation during micro-cutting of AISI 1045 steel. Thus it is clear that the work on analysing the chip formation in micromachining is not adequate. Thus to understand the effect of machining parameters in microcutting, the present work is planned.

2 Experimental Work

The experiments were carried out on a three-axis multipurpose miniature machine tool, developed for high precision micromachining. The machine tool has dimensions of 560 mm × 600 mm × 660 mm and the maximum travel range in X-210 mm, in Y-110 mm and 110 mm in Z direction. Each axis has an optical linear scale with resolution of 0.1 µm, and closed loop feedback control ensures accuracy to submicron dimensions. The positioning resolution of machine is 0.1 µm and the accuracy is ± 1 µm. Fig. 1 shows the experimental setup.



(a) (b)

Fig. 1. (a) Machine Tool, and (b) machining set-up

The effects of the cutting parameters on machining process responses of low carbon steel (AISI1215) and medium carbon steel (AISI1045) have been studied via a full factorial experimental design. The mechanism of cutting in terms of shear angle has been studied quantitatively whereas chip morphology qualitatively. A full factorial design yielded 48 runs (for each material AISI1215 and AISI1045, a total of 96 runs) and each run was replicated to characterize the experimental scatter in the data. Table 1 shows the factors and their levels selected.

Table 1 Factors and their levels

Level	Rake Angle (Deg)	Depth of Cut (DOC) (μm)	Cutting Speed (V) (m/min)	Materials
0	-5	25	1	AISI1215
1	0	50	2	AISI1045
2	5	75	3	-
3	10	100	-	-

The samples used for the experiments were heat treated at 3 different temperature i.e 950^0, 1050^0 and 1200^0 to study the effect of microstructure on the microcutting processes.

3 Results and Discussion

The mechanism of micro cutting is analyzed in terms of shear angle for AISI 1215 steel with the non-heat treated AISI 1215 steel and heat treated AISI 1215 steel at 950°C, 1050°C and 1200°C. The chip thickness measurement is performed and the chip thickness ratio (r_c)is determined using eq. (1).

$$rc = \frac{t_0}{t_c} \quad (1)$$

The governing equation for shear angle in a machining process is as given below:

$$Tan\ \emptyset = \frac{r_c \cos \propto_n}{1 - r_c sin \propto_n} \quad (2)$$

Where,

t_o = Uncut Chip Thickness

t_c = Measured Chip Thickness

r_c =Chip Thickness ratio

α_n = Rake angle

ϕ = Primary Shear Angle

During micro-cutting experiments, chips were collected using magnetic collector and used further for chip thickness measurement. Two chips of each experiment were inspected under the microscope; the images of the chips for various cutting parameters are shown in the fig. 2.

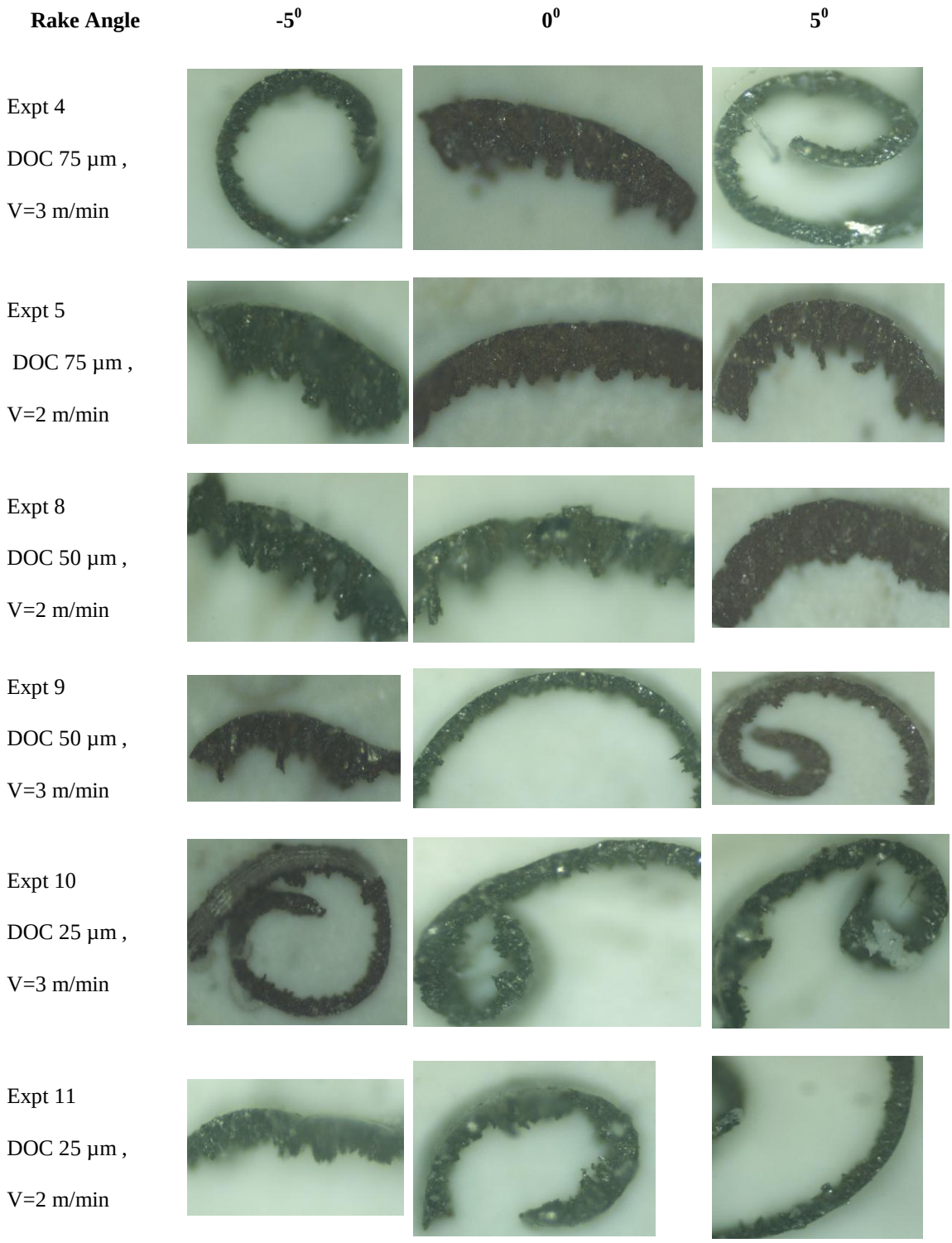


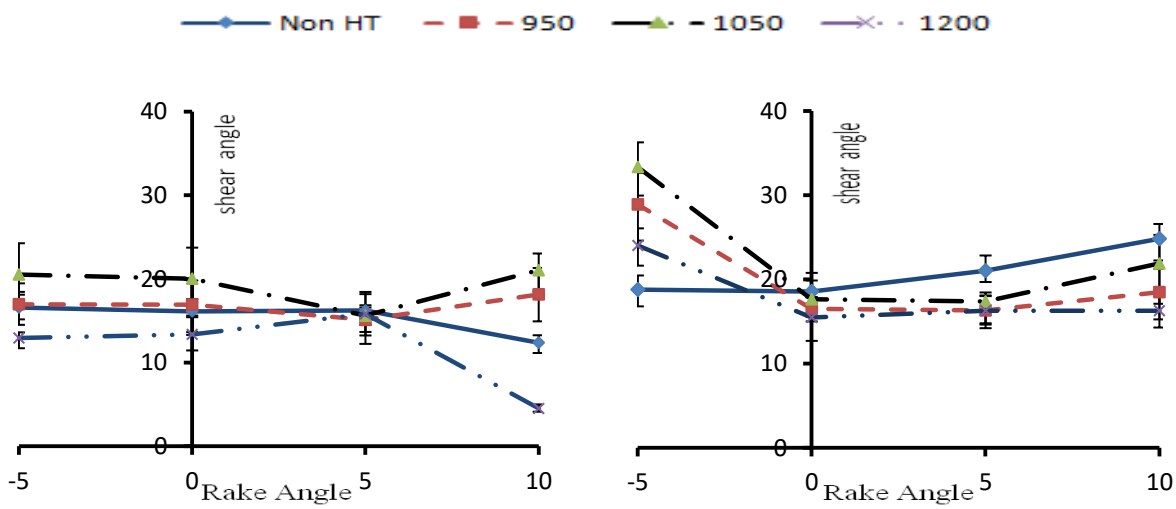
Fig. 2. Various forms of micro cutting chips

A variation of shear angle as a function of depths of cut varying from 25 µm to 100 µm for four different materials at a cutting speed of 3 m/min is shown in fig. 3 (a-d). Similar plots have been prepared for the cutting speeds 2 m/min see fig. 4 (a-d).

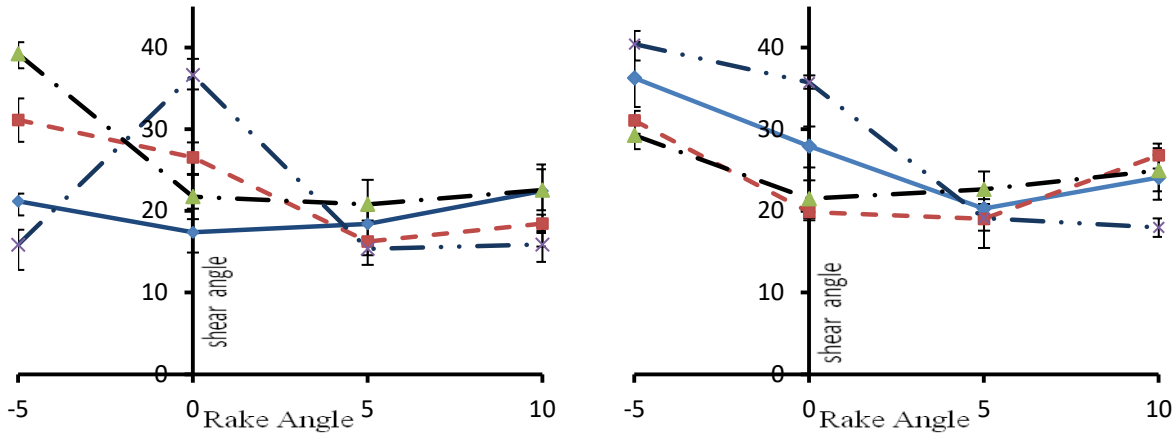
Among the four materials chosen for this work, AISI 1215 heat treated steel at 1050°C shows the maximum shear angle at negative rake angle of -5° as the depth of cut changes from 25 µm to 75 µm. On the other hand, AISI 1215 steel heat treated at 1200°C shows the lowest shear angle at all the depths of cut at 5° or 10° of rake angle as shown in fig. 3 (a-c).

At 25 µm depth of cut, as the cutting speed decreases from 3 m/min to 2 m/min, it is observed that the shear angle shows similar variation as the rake angle changes from -5° to 10° which can be seen in fig. 3(a) and 4(a). AISI 1215 heat treated steel at 1050°C, shows the highest shear angle at the cutting speeds of 3 m/min whereas the lowest shear angle is evident in the case of AISI 1215 heat treated steel at 1200°C, at higher cutting speed as shown in fig. 3. In general, at 25 µm depth of cut, the shear angle is found to lie between 15° to 20°.
At 25 µm depth of cut, the shear angle varies for all materials between an average value of 19° to 25° for the rake angles of 0° to 10°. The shear angle seems to be increasing at -5° negative rake angle, at 50 µm depth of cut. As the cutting speed is decreased from 3 m/min to 2 m/min for 50 µm depth of cut it is observed that the average shear angle varies between 15° to 30° for all four materials which is prevelant from fig. 3(b) and 4(b). AISI 1215 heat treated steel at 1200°C shows the lowest shear angle for all the rake angles from 0° to 10° at 50 µm depth of cut.

At 75 µm depth of cut with cutting speed 3 m/min, the shear angle shows a large variations at -5° and 0° rake angles. However, for 5° and 10° rake angles, the shear angle varies between 15° to 25° as observed in fig. 3(c). As the cutting speed decreases to 2 m/min, it is observed that at 75 µm depth of cut, the shear angle shows an average value of 18° to 30° which can be witnessed from fig. 4(c).
At 100 µm depth of cut the shear angle varies from 25° to 40° at negative rake angle of -5° and 0° but average value of 20° to 25° of shear angle is seen at 5° and 10° rake angle. As the cutting speed decreases to 3m/min and 2m/min, it is observed that at 100 µm depth of cut, the shear angle shows a high variation as the rake angle changes from -5° to 10° as observed in fig. 3(d) and 4(d).

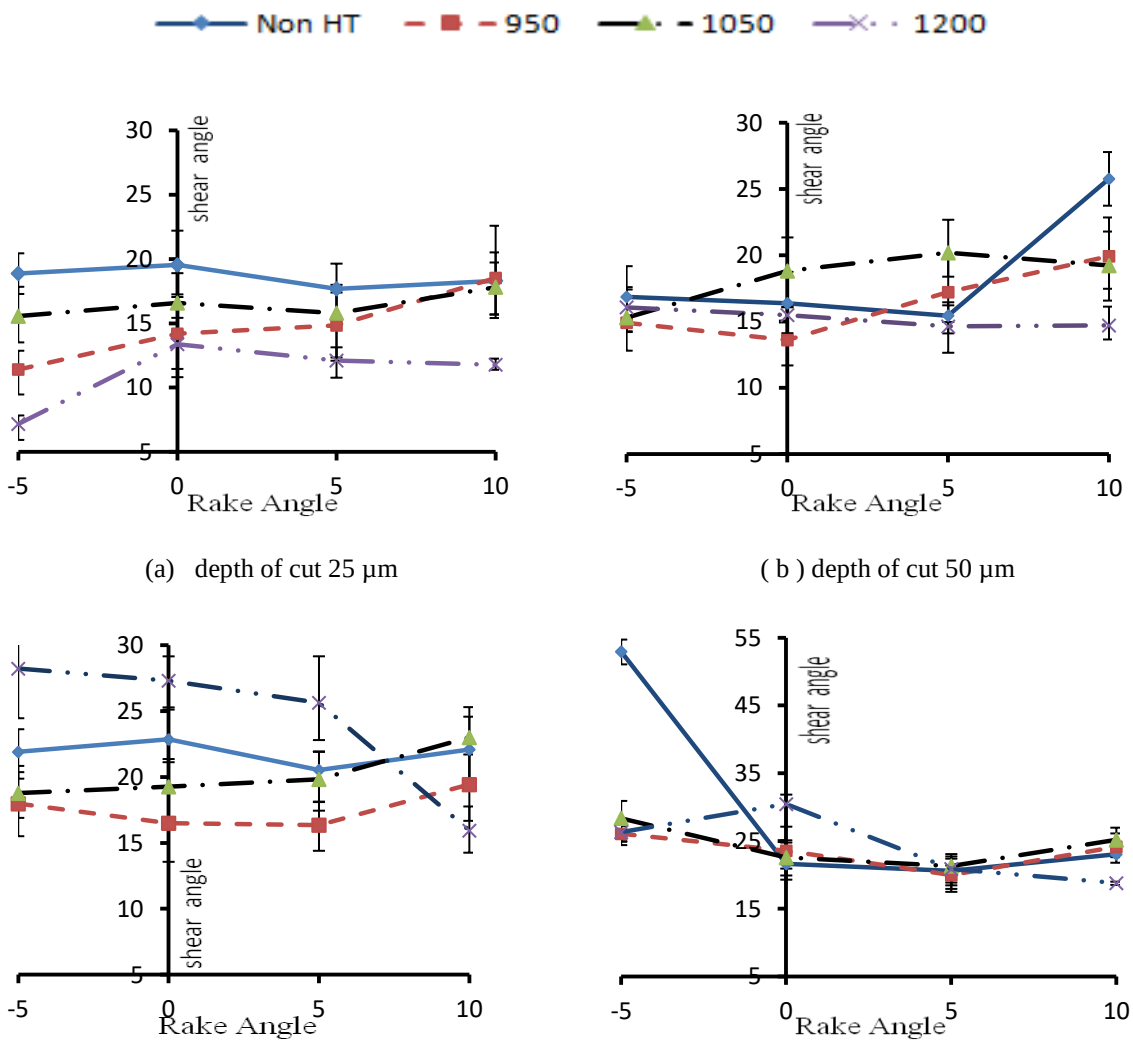


(a) depth of cut 25 µm (b) depth of cut 50µm



(c) depth of cut 75 µm (d) depth of cut 100µm

Fig. 3. Shear angle vs rake angle at 3 m/min cutting speed



(a) depth of cut 25 µm (b) depth of cut 50 µm

(c) depth of Cut 75 µm (d) depth of cut 100 µm

Fig. 4. Shear angle vs rake angle at 2 m/min cutting speed

4 Conclusions

Following conclusion can be drawn based on this work.

- At the rake angle of 10°, chips are by and large continuous. The chip segments appear to be joined together, though the line joining the segments borders can be easily observed.
- The chips do not show the formation of distinct saw tooth profile on the chip outer surface.
- The chips show minor serration along the chip outer surface. This indicates that, at 10° rake angle, the chip thickness is by and large uniform for all four materials at lower cutting speed of 2 m/min.
- It is observed that the shear angle is larger at higher depths of cut of 75 µm than at 25 µm. At 25 µm depth of cut the shear angle varies from 7° to 18°, whereas at 75 µm depth of cut the shear angle varies between 15° to 28°. This shows that machining could be difficult at lower depths of cut.
- At 3 m/min by and large continuous chips are observed at both the rake angles of -5° and 10°.
- Analyses of chip morphology shows that, the shear angle is larger at higher depths of cut of 75 µm than at 25 µm. At 25 µm depth of cut, the shear angle varies from 7° to 18°, whereas at 75 µm depth of cut the shear angle varies between 15° to 28°. This shows that machining could be difficult at lower depths of cut.
- Analyses of chip segment per unit length show that, the number of segments reduces as the rake angle increases for all the four work materials that were heat treated at the various temperatures.
- AISI 1215 non heat treated steel has good machinablity at negative rake angle whereas AISI 1215 steel heat treated at 1200°C, shows the lowest shear angle at all the depths of cut at 5° or 10° of rake angle, for all cutting speeds. This indicates that, this material has relatively lower machinability.

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