IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

Studies on Tool Wear, Cutting Forces and Chip Morphology During High-Speed Milling of Al-Si-Mg- Fe Alloys

S.Madhava Reddy[*1], **A.Chennakesava Reddy**[2]
[*1] Associate Professor, Dept. of Mechanical Engg., MGIT, Hyderabad-500075, India
[2] Professor of Mechanical Engineering, JNTUH, Hyderabad- 500 088, India
smrmech@gmail.com

Abstract

This paper investigates the High speed end milling of Al-Si-Mg-Fe alloy for aerospace and automotive industry. High speed machining has received important interest because it leads to an increase of productivity and a better workpiece surface quality. At high cutting speeds, the tool wears increases dramatically due to the high temperature at the tool-workpiece interface. The cutting force depends upon the cutting speeds, depth of cuts and feed rates. The behavior can be attributed to the precipitation hardening in the alloy on account of the formation intermetallic compounds. The cutting force increases with increase in feed rate and depth of cut. The machining parameters with the highest influence on tool wear progress are cutting speed and feed/tooth. Tool wear impairs the surface finish and hence the tool life is reduced. The cutting speed range was up to 1800 m/min. The feed rate used was up to 5000 mm/min. Cutting speeds of up to 1800 m/min are feasible and will greatly improve the milling process productivity and to implement this range of cutting velocity in industrial applications, new cutter designs should be developed.The adhesive tool wear mechanism and adhesion activated surface quality deterioration are revealed. Chip management is indicates that up to a cutting speed of 1800 m/min, a continuous chips are generated and cause surface degradation.

Keywords: Surface quality; High-speed machining; wear mechanism; chip morphology

Introduction

Machinability is the term used to describe how easily a material can be cut to the desired shape (Surface finish and tolerance) with respect to the tooling and machining processes involved in a machining operation tool life achieved, metal removal rate, component forces and power consumption, surface finish generated and surface integrity of the machined component as well as the shape of the chips can all be used to measure machinability. Machining productivity can be significantly improved by employing the right combination of cutting tools, cutting conditions and machine tool that will promote high speed machining without compromising the integrity and tolerance of the machined components[1]. The need to reduce the manufacturing cost has led to higher demand for increased manufacturing productivity. High-speed machining (HSM) is now recognized as one of the most important manufacturing technologies for higher productivity, especially when the machining time is a significant fraction of the total cycle time. Moreover, due to reduction of the cutting force and the temperature of machined surfaces, HSM has the potential to produce certain part configurations, such as thin webs, that are not easily obtainable by conventional machining. One obvious benefit of HSM in general is that at high spindle speeds the feed can be increased proportionally for the same chip-load as in conventional machining. However, many issues related to tooling and machine tool design must still be addressed especially in speed ranges above 600 m/min. High-speed is a relative term varying from one work material to another making the definition of such a concept rather difficult. According to Ref. [2], ‘high-speed machining for a given material can be defined as that speed above which shear-localization develops completely in the primary shear zone’.

Advanced manufacturing technology of high silicon aluminum alloys has been identified as one of the manufacturing processes most in need of new developments to obtain the required improvements for a new generation of vehicles. The advantage of using high speeds in machining aluminum alloys stems from the fact that their melting points fall well below the temperature at which modern tool materials experience thermal softening. The potential for increasing high speeds in machining aluminum alloys at speeds up to 1800 m/min is real and represents one order of magnitude increase over the current common practice in the automotive industry [3]. Clearly, such a drastic increase in cutting speeds would result in significant productivity gains. Nevertheless, several key research issues must be addressed before the widespread industrial application of this new technology can be fully implemented. According to Kannatey [4], there are two major types of gradual tool wear in metal cutting namely: temperature activated— diffusive and mechanically activated— adhesive, abrasive and fatigue. The particular type of wear that prevails in a specific machining operation depends on the cutting tool material, the workpiece material being machined, and the cutting conditions.

From a materials viewpoint, high-speed machining is a relative term, since different materials should be machined with different cutting speeds to insure acceptable tool life. Because of this difference and the fact that cutting speed determines whether a material will form continuous or segmented chips, one way to define high-speed machining is to relate it to the chip formation mechanism. High-speed machining for a given material can be defined as a speed above which shear localization develops completely in the primary shear zone. However, this definition is not very useful in practice. Therefore, high-speed machining has been arbitrarily defined quantitatively in terms of specific cutting speed ranges [5]:

- High-speed machining (600 to 1800 m/min)
- Very high-speed machining (1800 to 18000 m/min)
- Ultra high-speed machining (18000 m/min and above).

Salomon led the way in breaking new ground in machining at high speeds. He conducted a series of experiments in the late 1920's on nonferrous metals such as aluminum, copper and bronze at speeds up to 16,500 m/min. Salomon claimed that the cutting temperature reached a peak at a given cutting speed and as the cutting speed was further increased the temperature decreased. With this statement he presented the possibility that better cutting conditions could be achieved at high speeds. It was not until the late 1950's that research in high-speed machining was reborn and doubts arose about Salomon's theory. From that time to the mid 1980's, the interest in high-speed machining was driven by the assumption that very high speeds could lead to local melting in the chip and subsequently reduced forces, stresses and wear on the tool. However, further research showed that most metals, including soft aluminum alloys, begin to machine with segmented chips at high cutting speeds, which results in a deleterious fluctuating fatigue type loading on the cutting edge leading to tool damage [6].

In recent years, the development of new tool materials along with high-speed machining spindles and the need throughout the machining industry for cost reduction and increases in productivity have contributed to new interest in high-speed machining. As a result, focus has been given to:

- Increasing the cutting speed
- Controlling chip segmentation
- Reducing product distortion due to stress generation during material processing and subsequent machining.

High-speed machining is used in the defense, aerospace and automobile industries. Most aerospace manufacturers have implemented high-speed machining in end milling using small-size cutters, and since the most common work material is aluminum, there is no tool wear limitation, especially when carbide cutters are used [7]. Also, in the aerospace industry, the main application of high-speed machining has been in thin walled structures. It is more economically advantageous to produce thin walled components by using high-speed machining to remove large amounts of material from bulk aluminum, instead of by casting, assembly or other manufacturing methods.

In high-speed, very high-speed and ultra-high-speed machining, it can be concluded that all the energy associated with the cutting process is devoted to either plastic deformation in the shear zone, friction along the tool rake face or the change in momentum of the chip material. Generally, the shear energy and the frictional energy end up as a thermal energy. In machining, the following parameters can change the amount of thermal energy produced during the cutting process:

1. An increase in the cutting speed and the feed rate causes an increase in the temperature
2. The temperature in the primary shear zone and tool/work interface would decrease with an increase in the tool rake angle.
3. An increase in the undeformed chip thickness causes an increase in the thermal energy [8].

Machining Aluminum Alloys

When normal Al-Si alloys are treated after simple melting with an alkali fluoride or with sodium or potassium, so-called ‘modified’ alloys result. In the case of the normal alloys, the silicon occurs as relatively large plates and needles, while in the modified ones the silicon is in a state of high dispersion. Now it is well established that the Al-Si eutectic can exhibit either of two morphologies an unmodified and a modified morphology. The unmodified morphology is typically coarse and flaky and is usually observed in slowly cooled foundry alloys when no chemical modifiers are added.

The microstructure of an unmodified Al-Si eutectic is shown in Figure1.1a. In chemically modified alloys or at relatively fast cooling rates, such as in chill casting, the Al-Si eutectic is much finer and the silicon assumes fibrous morphology as shown in Figure1.2b. It should be noted however that the growth mechanism of silicon in the chemically modified alloy is quite different from that in the chill cast alloy [9].

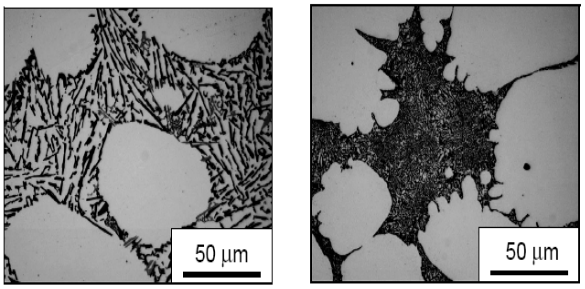


Figure1.1 Effect of modification (a). Unmodified Al-Si eutectic (b) Sr-modified Al-Si eutectic.

In 1987 Lu and Hellawell conducted detailed TEM studies on impurity modified silicon fibres in order to document their growth mechanism [10]. Lu and Hellawell observed significant twinning in the flake morphology and the impurity modified fibres, but not in the quench modified fibres. Moreover, they observed that twinning in the impurity modified fibres was more frequent than in the silicon fibre with flake morphology. Based on these observations they concluded that silicon in the flake morphology grows predominantly by the layer mechanism illustrated in figure 2.

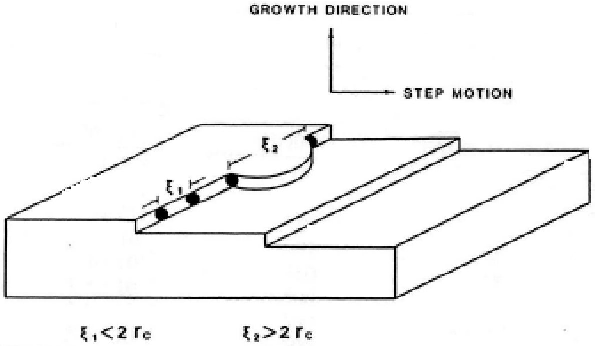


Fig. 2. Schematic representation for adsorbing of impurity atoms at monolayer steps on a growth interface, r_c is some critical dimension for layer extension [10].

According to the impurity induced twinning theory [11], chemical modifiers are impurities that poison already growing atomic silicon layers by becoming adsorbed onto surface steps and kinks thus preventing the attachment of silicon atoms to the crystal. Furthermore, the adsorbed impurity atoms induce twinning by altering the stacking sequence of atomic layers as the newly added layers seek to grow around the adsorbed impurity atom. Several metallurgical factors can influence machinability of Al–Si alloys. The relative machining performance can be related directly to the size, shape and distribution of the abrasive silicon phase in the alloy. Silicon, as a major alloying element, in either eutectic or primary form, is much harder than any other phase of an alloy's microstructure. The fundamental information for understanding the mechanism of abrasion of carbide tools by silicon particles was given in Ref. [12].. It was found that the quartz elements considered for the experiments have an effective hardness of 71–87 BHN. This is approximately the same hardness as silicon particles in the Al–Si alloys which makes it a soft abrasive relative to most centered carbides with hardness of approximately 140BHN.

At all cutting speeds, aluminum forms continuous chips under normal conditions. Contrary to earlier claims, the shear angle and chip thickness ratios are not unusually high in HSM. A continuous chip will be formed in HSM of all aluminum alloys at all cutting speeds, recent research has found that the heat treatment (age hardening) influenced the chip formation [13]. The experiments conducted under carefully controlled conditions have shown a change in the chip shape from continuous to segmented as a function of age hardening and cutting speed [14]. The main results of the research published by B. F. von Turkovich define the cutting speed for HSM of aluminum alloys in the range from 600 to 1800 m/min. In this research, relationship between the specific removal rate (cm^3/min kW), cutting speed, and feed rate were presented. It was concluded that cutting speeds of between 600 and 1800 m/min and feed rates of 1000 and 5000 mm/min were the optimum. The resulting surface roughness obtained with HSM was much better than that achieved by conventional machining, and is less than 2 mm at cutting speed of 1800 m/min and feed rate of 1000 mm/min.

In a relatively recent work, Reilly [15] clearly outlined the advantages of using high-velocity machining (HVM) in milling of thin walled aluminum parts and experimentally defined the preferred working envelope for HVM. The authors have found that the dominant variables influencing the tool wear and tool life are: microstructure, silicon content, in homogeneities (non- metallic inclusions, etc.), and interrupted regime of cutting. At lower cutting speeds, the difference in silicon content plays an insignificant role in tool wear. As the cutting speed rises, the wear promoting effect of higher silicon content becomes more pronounced; therefore, the use of poly- crystalline diamond (PCD) tools for HSM of alloys with higher silicon content is recommended. Use of PCD tools for high-speed milling leads to up to 100-times tool life increase compared with the carbide tool life, yields excellent surface quality and extremely low burr formation. The main finding was that a positive tool geometry and sharp cutting edge are considered optimal when using PCD and/or carbide tooling when coupled with a stable, vibration-free machining system[16].

This paper presents the effect of the cooling environment on the modes of chip morphology and the characteristics of the surface produced during machining Al-Si-Mg-Fe alloys at high cutting speed.

Experimental Setup and Procedure

High-speed end milling tests were performed on Al-Si-Mg-Fe alloys castings at cutting speeds of up to 1800 m/min. The objective of the experimental investigation was to determine the effect of different process parameters, in particular the cutting environment on tool wear, cutting forces and surface quality when end milling aluminum alloys.

The tests were performed using uncoated and diamond- coated carbide inserts and three different coolant environments: flood coolant (CM2 coolant), Minimum Quantity Lubricant (MQL) (synthetic phosphate ester BM2000 with extreme pressure additives), and dry cutting. The MQL was applied at rate of 30 ml/h. Two different carbide insert grades and one type of diamond-coated insert were used. The performance of regular uncoated carbide grade THM was compared to the micro grain, high polished inserts THM-U and to the diamond-coated THM.

Straight flute end milling cutters are generally used for milling either soft or tough materials. In order to develop monitoring functions, displacement sensors are installed on the spindle unit of a high precision machining center. The machine used in the study is a vertical type- 3 axis machining center (figure 3).

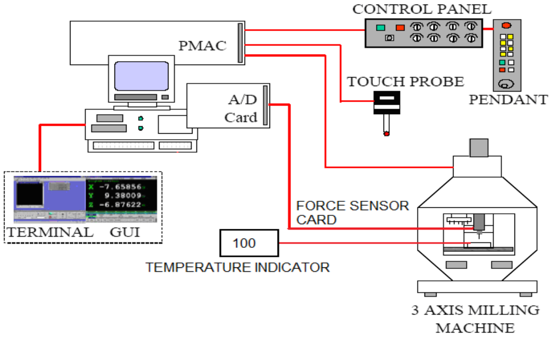


Fig.3. High speed vertical milling center

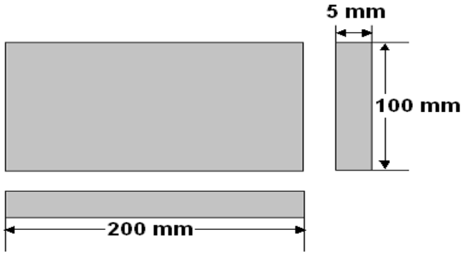


Fig.4. The dimensions of workpiece used high-speed milling

The PCD end-milling cutter having four straight flutes was used in this investigation. High-pressure coolant jet was employed for cooling and lubrication of the high-speed machining operations. The spindle has constant position preloaded bearings with oil-air lubrication, and the maximum rotational speed is 20,000 rpm. The dimensions of the work piece used in the high-speed milling are shown in figure 4. The temperature of the work piece material was measured using thermocouple.

Tool wear was measured during each machining test using a toolmakers microscope. High-resolution optical and scanning electron microscopy was then used in order to analyze and illustrate the modes of tool wear after reaching the end of tool life. The surfaces of the high-speed machined test samples were examined in scanning electron microscope (SEM) to determine the surface morphology. The samples for SEM observation were obtained from the machined specimens by sectioning parallel to the machined surface and the scanning was carried in IICT (Indian Institute of Chemical Technology) S-3000N Toshiba shows Scanning Electron Microscope Figure 5.

Fig.5. S-3000N Toshiba Scanning Electron Microscope.

Four eddy-current displacement sensors are installed on the housing in front of the bearings to detect the radial motion of the spindle (figure 6).

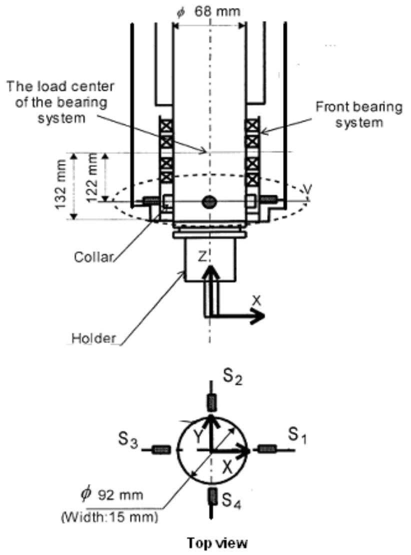


Fig.6. Arrangement of sensors on the spindle

The specifications of the sensor are as follows: the diameter is 5.4mm and the length is 18mm; measurement range is 1mm; nominal sensitivity is 0.2mm/V; dynamic range is 1.3 kHz; linear sensitivity is ±1% of full scale. Figure shows the sensor locations. The two sensors S_1 and S_3 are aligned opposite in the x-direction, and the other two S_2 and S_4 are aligned in the Y-direction. The temperature of the workpiece material was measured using thermocouple. The experiments were conducted on a 3-axis CNC vertical milling machine fitted with a 5KW motorized high-speed spindle. The maximum speed limit of the spindle is 40,000 rpm. Polycrystalline diamond tool having helical teeth on the periphery was used for end milling operations. The diameter of end mill cutter is 20 mm. The Kistler dynamometer with control unit was used to measure the cutting forces. The temperatures generated in the workpiece were measured using the thermocouple. Chips were collected after each machining test. In order to examine the chips cross-section, the chips were mounted in epoxy resin molds, ground, polished and subsequently etched for about 1 min in a solution containing 0.5% HF acid. The specimens were then examined and photographed using inverted microscope.

Workpiece material

The workpiece material used for all machining tests is Al-Si-Mg-Fe alloys ‘as cast’, an aluminum–silicon alloy, widely used in automotive industry. This alloy structure contains silicon particles and intermetallic compounds ($Fe_2Si_2Al_9$, Mg_2Si) crystallized in the aluminum matrix. The high hardness intermetallic compounds considerably increase the material strength, but also decrease its machinability. The chemical composition of Al-Si-Mg-Fe alloys is presented in Table 1.

Table-1: Chemical composition of alloys

Alloy	Composition determined spectrographically, %						
Element	Al	Si	Mg	Fe	Cu	Mn	Cr
%	85.22	9.0	2.0	3.5	0.01	0.25	0.02

Results and Discussion

Tool wear mechanisms

Workpiece material adhesion on the cutter surfaces was always observed, the method of lubricant application plays significant role in quantifying the volume of adhered material. During Machining at cutting speed of 1800 m/min using coated carbide tools, the adhesion to the tool has the highest rate in dry cutting. A significant amount of workpiece material is bounded to the flank, clearance, and rake surfaces. Adhesion levels were reduced when flood coolant has been used. In case of MQL application, areas of moderate adhesion were found on the flank, rake, and clearance surfaces. The high volume of material adhesion observed during this stage of the experimental program can be related to the tool geometry and the large nose radius.

Fig. 7(a) and Fig.7(b) illustrates a comparison between typical wear mechanisms recorded at cutting speeds of 1200 and 1800 m/min using MQL. It can be noted that the higher cutting speed had no negative influence on the wear mechanisms; moreover the amount of adhered workpiece material was reduced at 1800 m/min compared to 1200 m/min while no chipping or edge deformation occurred. The rake face view shows again similar wear mechanisms, with more edge rounding and a larger degree of crater wear formation for the inserts used at the higher cutting speed. As no severe detrimental effect of cutting speed on tool wear mechanisms was recorded, it can be concluded that the higher cutting speed range is a viable option that merits further investigation.

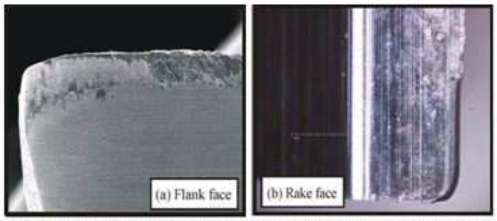


Fig.7 (a) Effect of cutting speed on the mode tool wear (V= 1200 m/min)

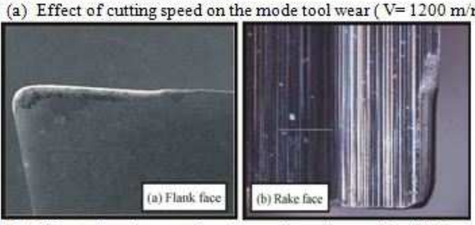


Fig.7 (b) Effect of cutting speed on the mode tool wear (V= 1800 m/min)

After the chemical removal of the adhered material layers, two wear mechanisms were observed namely: abrasive wear at the tool tip and adhesive wear along the remainder of the length of contact of the tool/chip/work- piece interface. Along the chip–tool contact area, the normal stress magnitude is substantially higher when compared to the shear stress. The normal stress is at its maximum at the tool cutting edge. With the increase in distance from the cutting edge, the normal stress decreased in an exponential trend, whereas the shear stress showed a plateau distribution along an area where the chip sticks to rake face. All the examined cases in this investigation indicate that workpiece material adhesion does not appear on the tool tip. However, it was present a little distance away from the tool tip along the rake and clearance face. A possible explanation of the workpiece material adherence on the tool rake face can be found by recalling the normal stress distribution on the rake face of the tool.

Cutting forces

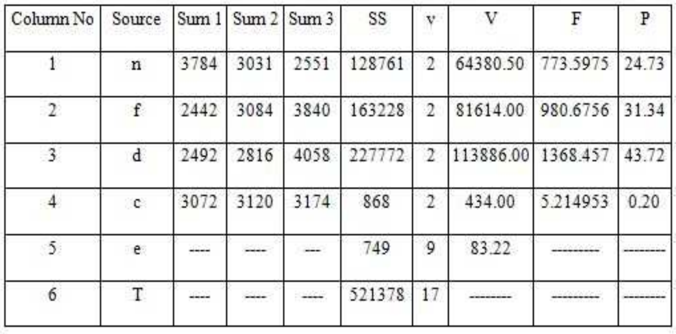
The cutting forces under various combinations of machining variables are given in Table 2. The summary of ANOVA (analysis of variance) for cutting force is shown in Table3. According to the analysis of variance, there are three strong variables, which influence the cutting force.

Table-2 Experimental results of cutting forces

Treat No.	Cutting force, N	
	Trial-1	Trial-2
1	407	401
2	570	576
3	900	930
4	353	346
5	652	641
6	515	524
7	475	460
8	320	325
9	483	488

Looking at the ANOVA table, variable d (depth of cut) has the largest effect (43.72%), variable f (feed rate) the second largest effect (31.34%), variable n (cutting speed) the third largest effect (24.73%), and variable c (type of casting) has no effect.

Table-3: ANOVA summary of cutting forces



Column No	Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
1	n	3784	3031	2551	128761	2	64380.50	773.5975	24.73
2	f	2442	3084	3840	163228	2	81614.00	980.6756	31.34
3	d	2492	2816	4058	227772	2	113886.00	1368.457	43.72
4	c	3072	3120	3174	868	2	434.00	5.214953	0.20
5	e	----	----	---	749	9	83.22	--------	--------
6	T	----	----	----	521378	17	--------	--------	--------

The effect of cutting speed on the cutting force is shown in figure 8. It is observed that the cutting force decreases with increase in cutting speed. This may be owing to low friction coefficient at high cutting speeds. The direction of the friction force is closely related to the direction of the chip flow angle. The cutting force increases with increase in feed rate and depth of cut (figure 9 and 10). The amount of material to be removed from the workpiece increases with increase in depth of cut and feed rate. The thickness and width of chip depend upon the amount of depth of cut and feed rate. Hence, higher depth of cuts and feed rates result in greater cutting forces. This behavior is analogous to the cutting force with increasing feed rate in oblique cutting operations previously reported by Ezugwu.

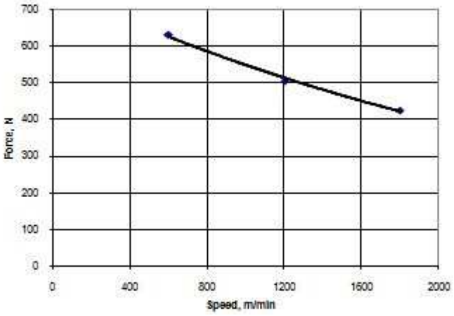


Fig.8. Variation of cutting force with speed

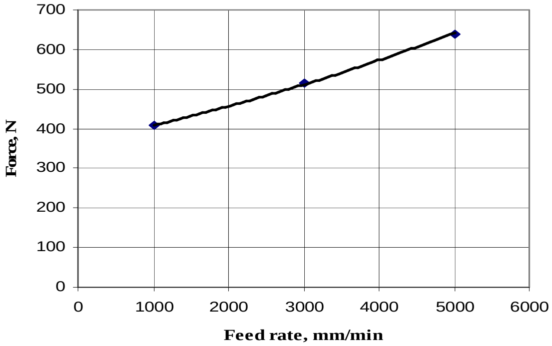


Fig.9. Variation of cutting force with feed rate

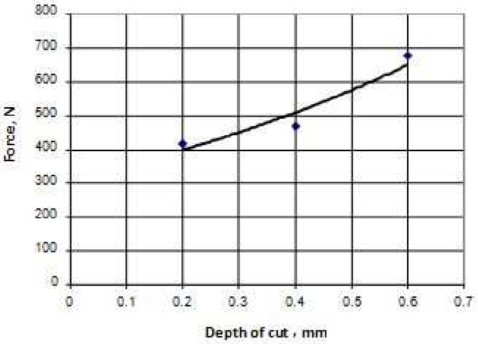


Fig.10. Variation of cutting force with depth of cut

The cutting force depends upon the depth of cuts and feed rates. The behavior can be attributed to the precipitation hardening in the alloy on account of the formation intermetallic compounds. The presence of the precipitate phase is expected to impart thermal stability to the micro structured metallic matrix in addition to enhancing strength.

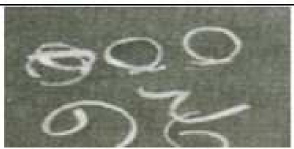
Part surface quality

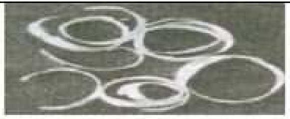
Cutting speed was not a factor in the occurrence of the described phenomena but did affect its severity. As the cutting speed increases, higher cutting temperature is generated in the tool/chip/workpiece interface, which increases the volume of materials adherence to the machined surface and cutting edge. By increasing the clearance angle and radius of the cutting edge and the volume of lubricant, the existence of the adhered layer could be minimized. Further study is required to completely quantify this phenomenon and to identify its causes and prevention methods. Upon completion of the experimental tests, all work- pieces were examined for the burr formation. Based on visual examination of the parts, it can be concluded that the severity of the burr formation is a direct function of the cutting speed and the progress of tool wear.

Chip morphology

The chip formation involves elastic-plastic deformation, work hardening of material ahead of the cutting edge due to plastic deformation followed by fracture/shearing of material along the shear plane that requires the minimum energy. Since ductile materials are known to produce longer chips than the hard materials, average chip length can be used as an indirect measure of ductile/brittle fracture while machining. The size and shape of chips are given Table-4.

Table-4: Size and shape of chips

Size and shape of chips


Depth of cuts and feed rates influence the characteristics of chips to the great extent. Thick and wide chips are resulted on account of deep depth of cuts, large feed rates, and moderate cutting speeds. Thin and narrow chips are produced with the combination of fine depth of cuts and feed rates. The effect of casting condition is negligible on the characteristics of chips.

The TEM micrographs of the chips are shown in figure 11. The formation of progressively refined, highly misoriented subgrains is observed about mid-way through the deformation zone (figure 11a). The continued refinement of the microstructure is revealed in the deformation zone closer to the chip (figure 11b) and the final microstructure of the chip is shown in figure 11c. The TEM study of the evolution of the microstructure across the deformation zone indicates a progressive refinement of the microstructure over a region tens of micrometers thick.

The Al-Si-Mg-Fe alloy gives curled or easily broken chips (Table 4). As the chips tend to curl considerably, the Al-Si-Mg-Fe alloy experiences the plane strain machining conditions.

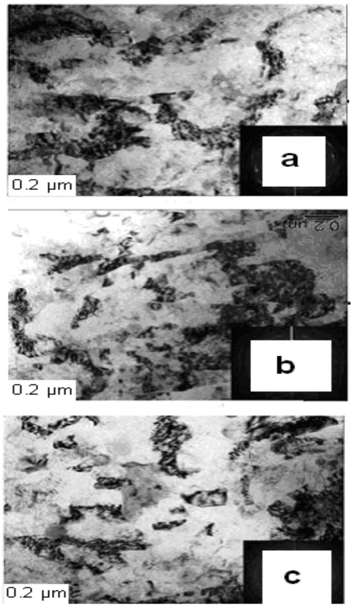


Fig.11 TEM micrographs of partially detached chip showing progression of microstructure across the deformation zone

Conclusions

Based on the experimental finding the following conclusions were made:

- Due to the content of silicon in the Al-Si-Mg-Fe alloy, the main wear mechanisms encountered were abrasive wear at the tool tip region, and adhesive wear on the flank and rake faces away from the tool tip.
- The cutting force depends upon the depth of cuts and feed rates. The behavior can be attributed to the precipitation hardening in the alloy on account of the formation intermetallic compounds.
- The severity of the burr formation is a direct function of the cutting speed and the progress of tool wear
- Cutting speeds of up to 1800 m/min are feasible and will greatly improve the milling process productivity; to implement this range of cutting velocity in industrial applications, new cutter designs should be developed and implemented.
- Chip management is also an open issue that needs further investigation; the results indicates that up to a cutting speed of 1800 m/min, a continuous chips are generated and cause surface degradation.

References

[1] E.O Ezugwu, High speed machining of aero engine alloys, J. of the Braz. Soc. Of Mech. Sci & Engg, Vol.XXVI, No.1 (2004)
[2] C. Muller, R. Blumke, Influence of heat treatment and cutting speed on chip segmentation of age hardenable aluminium alloy, Material Science and Technology (2001) 17.
[3] M. Schultz, et al., Limits for the application of long protruding tools regarding the process stability and safety, Proceedings of the Second International Seminar on Improving Machine Tool Performance, La Baule, France, 2000.
[4] E. Kannatey-Asibu, A transport diffusion equation in metal cutting and its application to analysis of the rate of flank wear, Journal of Engineering for Industry 107 (1) (1985) 81–89.
[5] B. F. von Turkovich, Influence of very high cutting speed on chip formation mechanics, Proceedings of NAMRC-VII, pp.241-247, 1979.
[6] E. M. Trent and P. K. Wright, Metal Cutting. Butterworth Heinemann, Boston, fourth edition, 2000.
[7] J.R.Davis, High-speed machining, Metals Handbook. ASM, Vol.16, pp.597-606, ninth edition, 1989.
[8] M. C. Shaw. Metal Cutting Principles, Oxford University Press, Inc., New York, second edition, 2005.
[9] T.E. Benawy, and H. Fredíksson, Solidification mechanism of unmodified and strontium modified Al-Si alloys, Materials Transactions, Vol. 41, No.4, pp.507-515, 2000.
[10] S.Z Lu, and A. Hellawell, Growth mechanism of silicon in Al-Si Alloy, Journal of Crystal Growth, Vol.73, pp. 316-328, 1985.
[11] S.Z Lu, and A. Hellawell, The mechanism of silicon modification in aluminium-silicon alloys: impurity induced twinning, Metallurgical Transactions A, Vol.18A, No.10, pp. 1721-1733, 1987.
[12] J. Larsen-Basse, E.T. Koyanagi, Abrasion of WC–Co alloys by quartz, Journal of Engineering for Industry 101 (1979) 208–211.
[13] J.P. Kottenstette, Ultra-high speed machining experiments, Proceed- ings of 10th NAMRC, Dearborn, MI, 1982, pp. 263–270.
[14] S. Siems, R. Dollmeier, G. Warneke, Material behaviour of aluminium 7075 and AISI 1045 steel in high speed machining, Transactions of NAMRI/SME 28 (2000) 101–106.

[15] R. O’ Reilly, Back and watch the chips fly, Machine Design October (1999) 21.
[16] W. Konig, D. Erinski, Machining and machinability of aluminium cast alloys, Annals of the CIRP 32/2 (1983) 535–540.
[17] H.A. Kishawy, M. DumitrescuE,G. Ng, M.A. Elbestawi, Effect of coolant strategy on tool performance, chip morphology and surface quality during high-speed machining of A356 aluminum alloy.
[18] G.Boothroyd, Knight, W.A, Fundamentals of Machining and Machine tools. Marcel Dekker, Inc, New York, 2nd Edition, 1989.
[19] T.J Drozda, C.Wick, Editors, Machining SME vol.1, 1983.