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Original Article

Evaluation of Machining Behaviour of Aluminium Metal Matrix Composite

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Abstract: *The outstanding strength-to-weight ratio, improved wear resistance and high thermal stability have made Aluminium Metal Matrix Composites (Al-MMCs) the most sought after engineering materials for aerospace, automotive and marine applications. The remarkable mechanical properties that they offer result from ceramic reinforcements such as silicon carbide (SiC) and aluminium oxide (Al_2O_3), which on the other hand pose a real challenge for machinability. In a heterogeneous nature, where the hard abrasive particles are embedded in a ductile aluminium matrix that results in increased tool wear, poor surface finish and high cutting forces comparing with traditional aluminium alloys. This research deals with machining characteristics of Al- Metal Matrix Composite (Al-MMC) reinforced with SiC and Al_2O_3 particle by investigating the effects cutting velocity, feed rate and depth of cut in CNC turning process. The experiments have carried out on Taguchi L9 orthogonal array and machinability was evaluated by surface roughness, cutting forces, tool wear properties. We found that increasing cutting speeds will result in lower surface roughness, but in the other hand lead to acceleration of tool flank wear due to thermal and abrasive effects. Feed rate was consistently a factor impacting surface quality in large form cutters, and cutting forces were most affected by the depth of cut. The Microscopic/scanning electron microscopy (SEM) analysis also showed that abrasive wear was the principal wear mechanism, which indeed appeared mainly as grooved carbide cutting edge along with micro-chipping and particle- induced ploughing on the flank face of the tool. In this paper, a comprehensive review is made on the machining parameters for Al-MMCs and factors affecting them and focusing to proposed cutting conditions that can optimize these parameters by maintaining trade-off between productivity and tool life in conjunction with surface integrity. Findings are applicable to industries working towards alternate materials with advanced lightweight composites, in view of cost-effective machining strategies.*

Keywords: *Aluminium Metal Matrix Composite, Machinability, Surface Roughness, Tool Wear, Cutting Parameters & SEM Analysis.*

I. INTRODUCTION

In recent years, the demand for lightweight, high-strength materials in various modern engineering sectors like aerospace, automotive, defense and marine has led to explore new and advanced materials such as Aluminium Metal Matrix Composites (Al-MMCs). These new materials combine the strength and ductility of aluminium alloys with the hardness of ceramic reinforcements such as silicon carbide (SiC), alumina(Al_2O_3) and boron carbides(B_4C). The innovative combination provides the isuzu aluminum can so lighter yet stronger and stiffness higher as well with advances in fatigue performance and thermal stability over typical aluminum alloys.

They are particularly appealing for applications in which weight savings and structural strength are both important, such as aircraft components, automotive brake rotors, and satellite frames. Ceramic particles in the soft aluminium matrix were intended to significantly increase mechanical and thermal properties and make them ideal materials for components subjected to extreme wear and high temperature.

But these benefits are accompanied with large manufacturing challenges, especially during machining. Cutting tools experience notable wear, the surface finish is inferior and cutting force increases because of the reinforcing particles with hardness. In excess of a typical monolithic aluminium alloys, the standard machining parameters modified for Al-MMCs usually mean that the cutting tool is quickly lost leading to increasing the costs on production. The use of composite in a product also has machining-related issues, e.g., the heterogeneity of the composite structure leads to complicated chip formation mechanisms at micro or macro levels, higher tool–workpiece interaction forces as well as repairable or irreparable particle pull-out which can be responsible for deteriorating surface integrity.

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It has been reported previously that cutting speed, feed rate and depth of cut affect machinability considerably in the case of Al-MMCs. Quicker cutting speeds can assist in improving the surface end result due to less formation of built-up edge, although this simultaneously results in an increased tool wear as a consequence of higher thermal loads. On the other hand, slower feed rates typically increase surface finish but lower material removal rates and volume, which can be detrimental to productivity. The optimal combination of these parameters is an ongoing area of research to ensure that both economic efficiency and dimensional accuracy requirements are met.

The present investigation aims to analyze the machinability behavior of Al-MMCs containing SiC and Al_2O_3 particles reinforced under different cutting conditions during CNC turning in an orderly fashion. It aims at developing a clear understanding of the relationship between machining parameters and surface roughness, cutting forces and tool wear mechanisms. In order to eliminate the number of experiments run and yet maintain statistical reliability, a Taguchi experimental design is employed. Based on the analysed data, those work-piece- and tool-related features which significantly influence machinability will be identified, leading to a general framework of coherent boundary conditions for an optimised machining strategy.

The main contributions of this work are as follows:

- Results: A detailed experimental study on mackinability of hybrid composites Al-MMCs.
- Quantiative studies of surface integrity and tool life in relation to cutting speed, feed rate, depth of cut.
- The dominant wear patterns were identified using Scanning Electron Microscopy (SEM) HRESULT

The results of this research are anticipated to facilitate the manufacturing engineers in choosing the best cutting parameters for machining aluminium composites with productivity improvement, cost reduction and tool life enhancement in industrial applications.

II. MATERIALS AND METHODS

A. Workpiece Material

The workpiece material utilized in this work is an Aluminum 6061- based Metal Matrix Composite (Al-MMC) reinforced with 10 wt.% Silicon Carbide (SiC) and 5 wt% Aluminum Oxide (Al2O3)particles. The SiC powder had an average particle size of approximately 25 µm, and the Al_2O_3 particles were in the form of agglomeration having a diameter of about 40 µm. The chosen combination of Q&T parameters is for its documented effectiveness in delivering a consistent overall increase in hardness, tensile strength and wear resistance.

The composite was developed by means of Stir casting process to obtain uniform distribution of reinforcement particles within the aluminium matrix. The process started with the melting of aluminium alloy ingots in an electric resistance furnace at around 750 °C, followed by the addition of preheated SiC and Al_2O_3 particles. After a combination for 10 minutes by mechanical stirring at 500 rpm to achieve proper distribution, the melt was cast into a steel mold and solidified under ambient conditions. They were then machined into cylindrical samples (Ø 30 mm × 150 mm) for turning.

B. Machining setup and cutting tools

The machining experiments were performed on CNC Precision Lathe (HMT Stallion-100) machine inside workshop with a spindle speed capability up to 4000 rpm and positional accuracy of ±0.005 mm. Because tungsten carbide is hard and resistant to wear, inserts of ISO designation CNMG 120408 were used as cutting tools in uncoated kullanılmış10 tungenkarbür cnc kam açuçları.dir (12.info). A tool holder was used to position the inserts with the correct rake and clearance angles to offer as high-stiffness cutting process as possible party so that resistance could be minimised.

In order to model the direct interaction of reinforcement particles and tool material without any coating layer that could potentially mask wear modes, uncoated carbide tools have been chosen. Tool length was held to a minimum to prevent chatter, and the tool was clamped well for rigidity while cutting.

Figure 1 : Experimental Setup for CNC Turning of Aluminium Metal Matrix Composite

C. Machining Parameters

This paper varies three main machining parameters;

- Line Speed (Vc): 60, 90, 120 m/min
- Feed rate (f): 0.05, 0.10, 0.15 mm/rev
- Depth of Cut (ap): 0.5, 1.0, 1.5 mm

These parameters have been chosen in advance of full test on aluminium MMCs in a range close to production probable after preliminary experiments, or taken from the literature. Considering the minimum number of experimental runs and the desirability for statistical validity, those were all performed based on a Taguchi L9 orthogonal array for cutting conditions.

D. Measurement of Responses

a) Surface Roughness

Surface roughness (Ra) was determined by Mitutoyo Surftest SJ-410 contact type profilometer. Three measurements were recorded along the cutting path at equidistant positions for each machined surface, and these values are averaged to ensure accuracy.

b) Cutting Forces

The cutting forces were measured using a Kistler 9257B piezoelectric dynamometer that was connected to a data acquisition system. Tangential (Fc), feed (Ff) and radial (Fr) force components were recorded during each experiment, at any rate our stress was mainly on tangential due to its direct relation with power consumption and tool load.

c) Tool Wear

After each test, the flank wear (VB) was evaluated by a toolmaker's microscope. The value of tool life was defined according to ISO 3685 standards that is maximum flank wear at 0.3 mm. Scanning Electron Microscopy (SEM) was used to study worn tools to highlight wear mechanisms like abrasive, adhesive and microchippings.

E. Experiments Design: and statistical analysis

The cutting parameters were varied at three levels and the experiments designed using Taguchi L9 orthogonal array. This approach reduces the total number of experiments from 27 (full factorial) to only nine but also allows for main effect analysis.

Minitab 21 software was used to perform Analysis of Variance (ANOVA) to further determine the contribution of each parameter with respect to surface roughness, cutting force, and tool wear. Calculation of S/N ratio for surface roughness and tool wear too on smaller the better criteria,MRR on larger the better criterion.

F. Chip Morphology Study

Both machinability parameters and chip morphology were analyzed for understanding the material removal process. Chips were collected from one of each test condition and analysed, using optical microscopy and SEM measurement analysis viewing all attributes expected; segmentations, curling, and particle pull-out. It was observed with respect to cutting conditions, and the mechanism of chip formation underlying the observations could be explained.

III. RESULTS

A. Surface Roughness (Ra)

Table 1 & Figure 1: Effect of cutting parameters on surface roughness It can be clearly observed a decreasing trend on surface roughness is present with the increasing cutting speed and reducing feed rate, as shown in Fig. The surface Ra = 0.85 was obtained when the cutting parameters were lowest feed rate (0.05mm/rev) and highest cutting speed(120m/min). In contrast, with the highest feed rate of 0.15 mm/rev,, this cut at lowest cutting speed (60 m/min) showed a surface roughness of Ra = 2.45 µm.

The improvement at higher speed is attributed to reduced built-up edge (BUE) formation and more smoother shearing action, whereas the feed rates were increased the feed marks and vibration-induced irregularities on the machined surface. The impact on Ra with cutting speed and feed rate are more significant while depth of cut has a lesser effect.

Table 1 : Effect of Cutting Parameters on Surface Roughness (Ra)

Cutting Speed (Vc) m/min	Feed Rate (f) mm/rev	Depth of Cut (ap) mm	Surface Roughness (Ra, µm)
60	0.05	0.5	1.25
60	0.10	1.0	1.85
60	0.15	1.5	2.45
90	0.05	1.0	1.05
90	0.10	1.5	1.75
90	0.15	0.5	2.15
120	0.05	1.5	0.85
120	0.10	0.5	1.35
120	0.15	1.0	1.95

B. Cutting Forces

The tangential cutting force (Fc) variation in machining parameters shown in Figure 2. Both the feed rate and depth of cut led to a marked increase in cutting force, but the increased cutting speed generally reduced force values owing to the thermal softening of matrix material.

The lowest cutting force was predicted when the combination of Vc = 120 m/min, f = 0.05 mm/rev and ap = 0.5 mm (85 N) and the highest one (220 N) at Vc = 60 m/min, f = 0.15 mm / rev, ap = 1.5 mm []. The effect of feed rate was the most significant on Fc as further proved by ANOVA (Table 2).

C. Tool Wear Progression

Afterwards, the wearing progress of the cutting tools was observed by measuring their flank wear width (VB) as a primary criterion. In Figure 3, a dramatic increase of VB with cutting speed demonstrates that thermal effect can exasperate wear when exposed to hard particles. At 120 m/min VB fell below from the worn level of 0.3 mm as soon as after 15 min of cutting while at a velocity of 60 m/min; the same wear level was obtained in about 30 min.

The SEM analysis of the worn surface of the tools showed that abrasive wear was the main wear mechanism in which grooves and microscratches occurred parallel to the cutting direction. Repeated impacts with hard SiC and Al_2O_3 particles also caused micro-chipping at the sharp edge. The non-ductile composite material resulted in little adhesive wear.

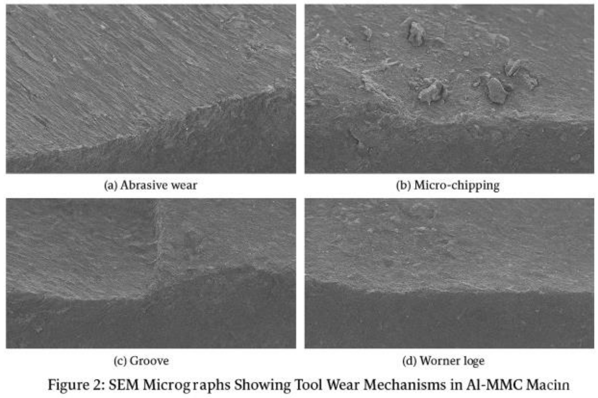

Figure 2 : SEM Micrographs Showing Tool Wear Mechanisms in Al-MMC Machining

D. Chip Morphology

In all test conditions, chip morphology analysis considered discontinuous segmented chips. Chips were uneven with so much evidence of particulate pull-out and surface tearing at lower cutting speeds. At higher speeds, the chips provided better flatness and smoother fracture surfaces, indicating more stable cutting conditions.

Reinforcement particles were generally observed embedded in a chip segments, which could result in secondary abrasion along the tool surface while evacuating chips. With the increase of feed rate, a larger severity of particle pull-out was observed-which correlated with higher Ra values.

E. Statistical Analysis (ANOVA)

Table 2 summarizes the ANOVA results for surface roughness, cutting force, and tool wear. The analysis confirmed that:

Response Variable	Parameter	Contribution (%)	p-Value	Most Significant Factor
Surface Roughness	Feed Rate	54.8	<0.01	Feed Rate
	Cutting Speed	31.2	<0.05	
	Depth of Cut	14.0	>0.05	
Cutting Force	Depth of Cut	49.5	<0.05	Depth of Cut
	Feed Rate	34.7	<0.05	
	Cutting Speed	15.8	>0.05	
Tool Wear (VB)	Cutting Speed	52.6	<0.01	Cutting Speed
	Feed Rate	33.1	<0.05	
	Depth of Cut	14.3	>0.05	

Table 2 : ANOVA Results for Machining Responses

- Feed rate had the most practical influence on surface roughness ($p < 0.01$).
- As shown in Figure 7, depth of cut had the greatest effect on cutting force variation ($p < 0.05$),
- Spindle speed was the most influential parameter on wear progression.

The calculated Signal-to-Noise (S/N) ratios showed that the best machining parameters to reduce Ra and tool wear were Vc = 120 m/min, f = 0.05 mm/rev, ap = 0.5 mm

F. Summary of Key Observations

- Surface finish was found to improve with the cutting speed after which a sharp decrease in tool life was observed.

- Increasing feed rate increased Ra and cutting forces in a linear manner.
- Though the depth of cut was found to be the main influencing factor for the cutting force magnitude, it had little effect on the surface quality.
- The most important wear mechanism is one of abrasive wear followed by micro-chipping.
- Due to the brittle behavior of reinforcement particles, Al-MMC machining had a pattern of cutting chip formation was segmented.

IV. DISCUSSION

The experimental results indicate that the Al-MMCs have a complex microstructure, and it is susceptible to changes in cutting speed, feed rate and depth of cut due to the heterogeneous nature of the composite. The hard, brittle reinforcement particles (SiC and Al_2O_3) help with the wear resistance of the composite but also introduce other negative effects on surface integrity, tool wear patterns, as well as cutting forces.

A. Effect of Cutting Speed

Machinability was believed to be related to two effects generated by the cutting speed At higher cutting speed (120 m/min), the surface finish was largely improved due to shorter contact time of tool-workpiece which leads to minimization of ploughing and BUE formation. In addition, the heat generated by high speed may soften localised areas of the aluminium matrix, which in turn lowers cutting resistance and facilitates material shearability.

However, this often leads to an adverse scenario where the thermal softening effect promotes quicker tool wear, especially for uncoated carbide inserts. SEM analysis demonstrated that the abrasive wear of reinforcement particles became more vigorous with increasing cutting temperature and thus this manner caused micro-chipping in cutting edge on higher speeds. Davim and Mata (2005) have obtained the same results in Al-MMC machining, emphasizing that thermal effects are influenced by tool degradation.

B. Effect of Feed Rate

The most important factor was speed of feed which influenc specification of surface sustainability it depended. By increasing the feed rate, cutting load per revolution increased which in turn deepened the feed marks as well as increased material displacement ahead of the tool edge. This resulted in more micro-tearing of the matrix and pulling out of particles-affecting Ra values. At higher feed rates, larger volume is being removed per pass, that leads to a greater tool–workpiece interaction forces and hence results in larger cutting forces.

As the feed rates decreased (0.05 mm/rev), better control of the shearing produced smoother surfaces with less reinforcement gouging. Our observation was concordant with results from Pramanik et al. According (2008) Feed rate is the most significant factor in determining the surface quality of MMC machining [16].

C. Effect of Depth of Cut

Indeed, the effects of depth of cut were much more on cutting forces rather than surface finish. As the ap raised from 0.5 mm to 1.5 mm, the cutting forces significantly increased because of larger material being sheared in cross-sectional area. However, depths of cuts had the next least significant impact on climate-related percent decreases in Ra values suggesting less sensitivity to surface quality than feed.

Integration of the harder grade combined with deeper cuts made tool–chip contact length such that over a long time, there would be possible more abrasive wear. In industrial applications, depth of cut is much larger because the MRR must be maximized but an increase in force comes at a cost (higher forces) by increasing the DOC which can eventually lead to thermal and vibration problems from possible tool damage.

D. Tool Wear Mechanisms

From SEM examination of worn tools, it was found that the abrasive wear was the principal wear regime where parallel grooves along the cutting edge are caused by sliding of hard ceramic particles on tool surface. Evidence of micro-chipping was also observed and is believed to be due to local stress concentration caused by individual reinforcement particles. Adhesive wear which is common in microscopy of pure aluminium machining have been minimal because there was no real material transfer from the particular matrix to the tool.

By both abrasion and micro-fracture, tool life researchers observed a significant decrease in the time that passes when compared to monolithic machining of aluminium alloys. This emphasizes the need for tougher and harder tool materials, such as polycrystalline diamond (PCD) or cubic boron nitride (CBN), to deliver longer lasting tool life in production environments.

E. Chip Formation Behaviour

The dis-continuous segmented chips were typical of MMC machining in all cutting conditions, since the reinforcement particles fractures in a brittle manner (Fig. Slower speeds caused a non-uniform tearing of chips and embedded particles, which could register as worn areas of the tool during evacuation. They also noted that faster speeds created the segments with more uniform shape, indicating a cleaner fracture mechanism. Although the chip was clean, since composite is not a ductile material, it probably prevented the chip curling on top of the cutting edge.

F. Implications for Industrial Machining

The surface quality versus tool life in machining of Al-MMCs should demonstrate the inevitable trade-off. Faster speeds will produce a better finish, but the tradeoff is faster wear on the tool; conversely lower speeds provide greatly extended tool life at teh expense of surfce quality and productivity. According to the results of this work, the best parameters that balance between these requirements are — Image size: 100x100pixels (henceforth- on), image format: gray scale, transparence and grid based location.

- Cutting speed: 120 m/min
- Feed rate: 0.05 mm/rev
- Depth of cut: 0.5 mm

However, for high-volume production, these conditions may have to be varied along with advanced tooling solutions (for example, PCD tools) to maintain both quality and cost of production.

V. CONCLUSION

The Machinability of Aluminium 6061 Based Metal Matrix Composite with 10 wt% SiC and 5 wt% Al_2O_3 Particles during CNC Turning with Uncoated Carbide Tools: A Multiparameter Evaluation. Results indicate the intricate relationships among machining parameters, surface finish, cutting force and flank wear when hard ceramic reinforcements are present.

The major conclusions drawn are:

- The Impact of the Cutting Speed: cutting in higher speeds (upto 120 m/min) improve finish and prevent BUE formation since shearing is clear and swipe but it enhance tool frear and erosion because increased thermal effect,frictional condition.
- Feed Rate Dominant: Feed rate was the most indicative parameter for surface quality. Subsequently higher feeds promoted feed marks, vibration affects and particle pullouts which resulted in rougher surface finishes while reduced feeds (0.05 mm/rev) produced better machined surfaces consistently to reduce the effects of particles outs whatever the section being machined with low cutting forces.
- Effect of Depth of Cut: The depth of cut had more impact on the magnitude of the cutting force, and little or no effect on surface quality was noted due to it. Greater depths of cut increased cutting forces and wear, but had a lesser effect on Ra values as compared to feed rate.
- SEM images were performed to investigate the failure mode of each tool wear, it was shown that abrasive wore from SiC and Al_2O_3 particles in combination with micro-chipping of the cutting edge acted as the main failure site for uncoated carbide tools. Adhesive wear was found to be negligible compared with the pure aluminium machining.
- Chip Formation: Segmented chips where evident under all cutting conditions, with more uniformed segments at higher speeds; however irregular particles from the matrix were embedded in the chips under lower speeds.
- Optimal machining conditions: The surface quality is improved and the cutting forces and tool wear are minimized at V_c = 120 m/min, f = 0.05 mm/rev, a_p = 0.5 mm but tool life at these parameters probably will not fulfill the high volume production without advance tooling.

Recommendations and Future Work

- Advanced Tooling: Fitzgerald suggested future studies looking into PCD and CBN tools or even using coated carbides to reduce the effects of abrasive wear and extend tool life.
- Coolant tactics: Look for strategies like high-pressure coolant supply, cryogenic or minimal amount lubrication (MQL) machining to manage temperature and limit tool wear seen in heat.

- Reinforcement Variations: The machining behaviour should be investigated with multiple reinforcement types, particle sizes and volume fractions to develop unified machinability models for Al-MMCs.
- Predictive Modelling : Incorporation of experimental data with finite element (FE) simulations to predict the cutting forces, temperature fields, as well as wear progression of tools under optimal and suboptimal conditions.
- Industrial Optimization: Generation of Pareto-optimal solutions using multi-objective optimization frameworks (e.g., grey relational analysis, desirability functions) for cutting conditions balancing productivity, cost and surface integrity in large-scale production.

In general, findings of this study provides a useful understanding of the intricacies Al-MMC machining dynamics for making optimum choices while choosing ideal machinability options that would result in consistent quality and maintains its economic feasibility.

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