# Machinability of Al-2024 reinforced with $Al_2O_3$ and/or $B_4C$

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**Abstract** This paper presents the results of an experimental investigation on the machinability of Al-2024 reinforced with $Al_2O_3$ and/or $B_4C$ (MMC) prepared by stir casting. These composites were characterized by micro-hardness analysis. The effect of reinforcements ( 20 wt % $Al_2O_3$, $B_4C$, and the combination of $Al_2O_3$ and $B_4C$ ) and machining parameters such as cutting speed, feed rate, and depth of cut on flank wear, surface roughness, and cutting force were analyzed during turning operations. From the test results, we observe that $B_4C$ reinforcement added produces higher tool wear, surface roughness and minimizes the cutting forces then the hybrid of $Al_2O_3$ and $B_4C$ in second degree and finally $Al_2O_3$. When machining the $MMC_s$ with high speed causes rapid tool wear due to generation of high temperature in the machining interface. The rate of flank wear, surface roughness , and cutting force are high when machining with a higher depth of cut. An increase in feed rate increases the flank wear, cutting force and surface roughness.

**الخلاصة**

يقدم البحث الحالي النتائج العملية حول قابلية تشغيل سبيكة الألمنيوم( 2024 ) المقواة بنسبة وزنية مقدارها 20% من دقائق الالومينا $Al_2O_3$ ، كاربيد البورون $B_4C$ و 10% لكل من الالومينا و كاربيد البورون كمزيج أو هجين إذ حضرت هذه المواد بطريقة السباكة بالمزج. مُيزت هذه المتراكبات بواسطة الفحص المجهري للصلادة. أجريت التجارب لمعرفة تأثير مواد التقوية ومتغيرات قابلية التشغيل مثل ( سرعة القطع ، معدل التغذية ، عمق القطع ) على البلى الخلوصي وخشونة السطح وقوة القطع بواسطة عملية الخراطة. لوحظ من النتائج أن إضافة $B_4C$ يسبب بلى لأداة القطع وخشونة سطح عاليين ويخفض من قوة القطع ثم يأتي الهجين المتراكب في الدرجة الثانية من حيث التأثير وأخيرا تأتي الالومينا . عند تشغيل هذه المتراكبات بسرعة عالية يحدث بلى سريع لأداة القطع نتيجة لتوليد درجات حرارة عالية في السطح البيني بين العدة والمشغولة . تكون معدلات البلى وخشونة السطح وقوة القطع عالية عند التشغيل بأعماق قطع عالية . بزيادة معدل التغذية يزداد كل من البلى الخلوصي وخشونة السطح وقوة القطع.

**KEYWORDS:** Metal Matrix Composites; Machinability ; Tool wear; Surface roughness : Cutting force**.**

## Nomenclature

BUE built up edge
*d* Depth of cut in mm
*f* Feed rate in mm/rev
$F_Y$ main cutting force in N
HSS high speed steel
MMCs Metal matrix composites
PCD polycrystalline diamond
*Ra* Surface roughness value in μm
$V_c$ Cutting speed in m/min

# 1. Introduction

Composite materials are multiphase materials obtained through the artificial combination of different materials in order to attain properties that the individual components by themselves cannot attain[ Deborah, 2010].Metal matrix composites (MMCs) are advanced composite materials that exhibit tremendous potential for a number of important applications in all sectors [Sornakumar and Kumar, 2008] and when Compared to monolithic metals, MMCs have higher strength-to-density ratios, better fatigue resistance, better elevated temperature properties (such as high strength and low creep rate), lower coefficients of thermal expansion, high thermal conductivity, good damping characteristics, excellent wear properties and flexibility in design attributes[Zhu and Kishawy, 2005]. Some of the typical applications of these MMCs are bearings, automobile pistons, cylinder liners, piston rings, connecting rods, sliding electrical contacts, turbo charger impellers, space structures, etc. [Seeman et al.,2010]. The properties of MMCs are influenced by their matrix, reinforcement, and interface properties. Matrix materials are usually lightweight materials, and especially ceramic reinforcements are added to get high specific strength. Ceramic reinforcements have been used in the form of particulates, whiskers, or continuous fibers. Currently, most of processes employed in the synthesis of MMCs involve the incorporation of ceramic particles such as carbides and borides into the matrices via casting and powder metallurgy methods [Anandakrishnan and Mahamani, 2011]. Compared with powder metallurgy, melt processing has important advantages, e.g., better matrix particle bonding, easier control of matrix structure, simplicity and low cost of processing [Joshi et al. 1995].

It is possible to produce high-quality $MMC_s$ components to near-net shape through various manufacturing techniques, but additional machining is unavoidable to achieve the desired surface quality and dimensional tolerance for efficient assembly [Hung et al.,1996].where the machining of composite materials different from conventional metals and its alloys [Shafaie, 2003]. and it is found that the morphology, distribution, and volume or weight fraction of the reinforcement phase, as well as the matrix properties, are all factors that affect the machining process[Zhou, 2011]. In view of the growing engineering applications of these composites, a need for detailed and systematic study of their machining characteristics and machinability is envisaged. It is important to understand the turning process in MMCs for choosing suitable tool material and producing quality surfaces.

Several researches done experimantals on machining of $MMC_s$.[Manna and Bhattacharayya, 2005] have investigated the effect of machining parameters on the surface roughness and tool wear when turning 10% SiCp/Al composites. Results indicated that higher cutting speeds result in relatively better surface finish, but resulting in increased flank wear. [Pramanik et al., 2006] developed the analytical model extending the classical Merchants theory, Slip line theory and Grifith's theory of brittle fracture to the machining of ceramic particle reinforced MMCs. This model predicted the cutting forces and was validated experimentally. The authors also contend that the classical metal cutting theories are by and large valid of understanding the machining of MMCs also. [Davim, 2007]. investigated to evaluate the chip compression ratio, shear angle, shear strain, shear strain rate, normal stress and shear stress using merchant theory on particulate metal matrix composites used K20 carbide cutting tool in radial turning. He concluded that normal stress and shear stress decreased with the increase of feed rate [Basheer et al., 2008] developed a model to predict surface roughness in precision machining of metal matrix composites using PCD tools with respect to size and volume of reinforcement, tool nose radius, feed rate and depth of cut. They have concluded that the size of reinforcements in the composite material influences roughness of the machined surfaces significantly when its magnitude is comparable to that of the feed rate and tool nose radius employed during machining of the composite. [Seeman et al.,2010] have studied tool wear and surface roughness in machining of particulate aluminum metal matrix composite .it is revealed that the formation of BUE significantly affects the tool wear at low speeds whereas thermal softening plays important role at higher speeds and feed rates. Surface topographies of the tool indicate that the main wear mechanism of cemented carbide tool is abrasive and adhesive wear. Also The optimal machining parametric combination is obtained using desirability function. Cutting conditions such as cutting speed 50 m/min, feed rate 0.05 mm/rev, depth of cut 0.84 mm, and machining time 2.4 min can be used to achieve the minimumflank wear of 0.283mmand minimum surface roughness of 1.8075 μm. [Anandakrishnan and Mahamani, 2011] observe that higher TiB2 reinforcement ratio produces higher tool wear, surface roughness and minimizes the cutting forces. When machining the in situ Al-6061–TiB2 with high speed causes rapid tool wear due to generation of high temperature in the machining interface. The rate of flank wear, cutting force, and surface roughness are high when machining with a higher depth of cut. An increase in feed rate increases the flank wear, cutting force and surface roughness. However, no work addresses the machinability of Al-2024–$B_4C$ or Al-2024-$Al_2O_3$-$B_4C$ as hybrid composite produced by stir casting. Hence, the main objective of the present work is to study the effect of reinforcements (20 wt% $Al_2O_3$, $B_4C$, and the combination of $Al_2O_3$ and $B_4C$) and machining parameters such as cutting speed, feed rate, and depth of cut on flank wear, surface roughness, and cutting force were analyzed during turning operations.

## 3. Experimental procedure

### 3.1 Preparation of composite material

The $MMC_s$ comprises 2024 aluminum alloy as matrix and $Al_2O_3$, $B_4C$, and the combination of $Al_2O_3$ and $B_4C$ were added to the alloy as reinforcement. Initially, master alloy was prepared by melt a pure aluminum (99.99%) with a(3.33 wt% Cu) according to center of vortex and mixing for (5 min.) by (Heidolph Mixer type /Germany) with speed 420 rpm . Table 1 gives the chemical composition of the master alloy.

After the initial master alloy was prepared, samples of the composites were prepared by stir casting route. Master alloy 2024 was preheated at 450°C for 3 hours before melting. The $Al_2O_3$, $B_4C$, and the combination of $Al_2O_3$ and $B_4C$ particles were also preheated at around 1000°C to make their surfaces oxidized. The $Al_2O_3$ particles size ranges from 56 to 185 μm, whereas the $B_4C$ from 67 to 178 μm. The preheated master alloy was first heated above the liquidus temperature to melt them completely. They were then slightly cooled below the liquidus to maintain the slurry in the semisolid state. This procedure has been adopted while stir casting aluminum composites [ Pandey et al., 2007 ]. The preheated reinforcements ( 20% $Al_2O_3$, 20% $B_4C$, and 10% $Al_2O_3$ and 10% $B_4C$ hybrid ) were added and mixed. The composite slurry was then reheated to a fully liquid state, and mechanical mixing was carried out for about 10–15 min at an average mixing speed of 150–300 rpm. The final temperature was controlled to be within 750°C±10°C, and pouring temperature was controlled to be around 720°C. After thorough stirring, the melt was poured into steel molds of 25 mm diameter and 30 cm in length and allowed to cool to obtain cast rods.

### 3.2 Hardness test

Effect of addition of reinforcements phases in the matrix on hardness was investigated by using Vickers micro-hardness tester (Microhardness tester, China, HV-1000 model) at a load of 25 g with 3 sec. dwell time. Table 2 shows effect of reinforcements increase the hardness of the MMC.

### 3.3 Machinability tests

In order to achieve the objective of this experimental work, A Harrison/England medium duty lathe with 2.2 KW spindle power was used to perform the experiments. The insert(cemented carbide/sandvik) used had an ISO shaped – designation of CNMA 120408 TN 010 02 PF, the inserts were clamped mechanically in a rigid tool holder of PCLNR 25 25 M12 type. The used tool geometry was as follows: Top rake angle $0^{\circ}$, nose radius 0.8mm. All machining tests were carried out without coolant. The workpieces are machined at five different cutting speeds ranging from 40 to 200 m/min with five feed rates ranging from 0.03 to 0.15 mm/rev and depth of cut ranging from 0.5 to 2.5 mm. Experimental parameters are given in Table 3. The average surface finish (*R*a) in the direction of the tool movement was measured in five different places of the machined surface using a surface roughness tester, Taylor Hobson measuring instrument. surface mean roughness (*R*a) in microns value of the five locations was considered for the particular trial. After each test, the worn cutting tool is measured with the optical microscope to determine the degree of flank wear on the one hand, and on the other hand, the test samples for microstructures investigations were prepared by standard metallographic techniques. Microscopic examinations of the specimens were carried out using a optical microscope itself. The microstructures of the master alloy (Al -2024) and composites are shown in Fig. 1.Special design instrument (mechanical dynamometer ) was used to measure the vertical deflection of the cutting tool during machining . After that calibration of dynamometer is attached to instron machine, main cutting force ( $F_Y$ ) calibration in *Y*-axis direction . Load is applied on the cutting tool present in dynamometer . Then, dial gauge is recorded the deflection values, these values of deflections as a reflection of the main cutting force.

## 4. Results and discussion

### 4.1 Tool wear

In this study, the effects of $Al_2O_3$, $B_4C$,and the combination of $Al_2O_3$ and $B_4C$ of Al-2024 on the tool wear in turning the formed MMC have been investigated in terms of selected cutting speed, feed rate, and depth of cutting . During examination of tool wear, the main wear pattern physically observed on the cutting tool was the primary flank wear. the amount of flank wear on the flank surface was taken as the reference. This observation confirm the primary role of the abrasive action of the phase reinforcement present in the metal matrix composite. The harder particles of reinforcement grind the flank face of the cutting tool similar to a grinding wheel during machining of $MMC_s$ [Manna and Bhattacharayya, 2003]. The abrasive wear happening in the primary flank of the cemented carbide inserts can be of two types, two bodies abrasive wear and three bodies abrasive wear. The two body abrasive wear is caused by the abrasive action of the $Al_2O_3$, and $B_4C$ particles held by the aluminum matrix moving at high speed. The three body abrasive wear is caused by the released hard particles, entrapped between the tool and the workpiece [Lin et al., 1995].

Figure 2 shows the influence of cutting speed on the flank wear during machining of MMC. Turning operations were performed considering a constant feed rate of 0.06 mm/rev and a depth of cut of 1 mm, and continuous length of turning of 120 mm. The experimental results revealed that the tool wear at 40–120 m/min, the flank wear is 0.025 – 0.125 mm whereas at 200 m/min, the flank wear is 0.255. At( 40-120) m/min of cutting speeds, the formation of built up edge (BUE) was significant. This was one of the important reasons for the increased tool life at this cutting speed. The relatively stable BUE formed acted as a protective cap on the cutting edge preventing it from undergoing wear. However, as it can be seen latter the presence of BUE adversely affected the surface roughness.

As the cutting speed was increased (above 120 m/min) the tool wear rate was much higher. This could be seen from the steep nature of the curves corresponding to the cutting speeds 160 m/min and 200 m/min. It was also because of the absence of any form of BUE. The increased temperature at high cutting speeds reduced the adhesion characteristics thereby eliminating the formation of BUE. The specific power consumed is very likely to reduce at higher cutting speeds, but the tool wear will determine the maximum cutting speed, that would result in a reasonable tool life. From the figure, it can be observed that the tool wear increases with an increase in the hardness.

The influence of feed rate on the tool wear is examined by considering a constant speed of 120 m/min with a depth of cut 1 mm, and a length of turning of 120 mm. Figure 3 shows the effect of phase reinforcement under different feed rates. When constant feed rate was taken into consideration, the flank wear of cutting tool increases as the phases reinforcement ($Al_2O_3$ , the combination of $Al_2O_3$ and $B_4C$ , $B_4C$) respectively. At the same time, an increase in the values of feed rate caused an increase in tool wear. If the feed rate increases the friction between the tool and work increases.

Figure 4 shows the effect of the depth of cut on the flank wear during turning of MMCs without the use of a coolant. Turning operations were performed considering a constant feed rate of 0.06 mm/rev, a constant speed of 120 m/min, and a length of turning of 120 mm. The influence of a reinforcement is evaluated under different values of the depth of cut. With an increase in the depth of cut, keeping the cutting speed and feed rate constant, the tool wear was measured. When constant depth of cut was taken into consideration, flank wear of cutting tool increased as the phase reinforcement ($Al_2O_3$ , the combination of $Al_2O_3$ and $B_4C$ , $B_4C$) respectively. At the same cutting speed and feed rate, an increase in the value of depth of cut caused an increase in tool wear. Increase in depth of cut will increase the area of contact and temperature in the machining interface, which increase the tool wear.

The end shape of the cemented carbide at constant machining parameters and different reinforcement phases is shown in fig. 5

## 4.2 Surface roughness

The experiments were employed to study the effects of reinforcement phases and cutting parameters on surface roughness of the materials when machining $MMC_s$ workpiece .

Figure 6 shows the effect of cutting speed and reinforcement on surface roughness. The experimental results revealed that the surface roughness at 40–120 m/min, the surface roughness is 9.6 – 5.4 µm whereas at 200 m/min, the surface roughness is 4.5 µm. This mean the surface roughness (Ra) decreases as the cutting speed increases. At low cutting speed, the unstable larger BUE is formed and also the chips fracture readily producing the rough surface. As the cutting speed increases, the BUE vanishes, chip fracture decreases, and, hence, the roughness decreases [Palanikumar and Karthikeyan, 2007]. Though these phenomena of improved surface finish at higher cutting speeds can be observed in machining conventional materials also, the effect is more pronounced here because removal of hard $2^{nd}$ strengthen particles from the Aluminum matrix becomes easier at higher cutting speeds.

The influence of feed rate on the surface roughness is shown in Fig. 7. At same level of feed rate the surface roughness value increased when increasing phase reinforcement. Figure 7 also shows that the increase in feed rate increases the surface roughness (Ra). With the lower feed rates, the BUE forms readily and is accompanied by feed marks resulting in increased roughness. With the increase in feed rate beyond 0.12 mm/rev, the rate of increase in surface roughness (Ra) is less due to the reduced effect of BUE [Choudhury and El-Baradie, 1998]. The best surface finish was achieved at the lowest feed rate and highest cutting speed combination.

The effect of depth of cut on the surface roughness (Ra) is shown in Fig. 8. The depth of cut low as 0.5–1 mm less surface roughness observed. But increase in depth of cut beyond 1 mm, results in high normal pressure and seizure on the rake face and promotes the BUE formation. Hence, the surface roughness (Ra) increases along with increase in depth of cut [Kannan and Kishawy, 2006].

### 4.3 Cutting force

Figure 9 shows the influence of the cutting speed and reinforcement on cutting force during machining of MMC. The effect of an increase in reinforcement is evaluated under different speeds, at a constant feed rate of 0.06 mm/rev, a depth of cut of 1 mm, and a length of turning of 120 mm. When constant cutting speed was considered, the cutting force is decreased as the reinforcement added. The presence of reinforcement will minimize the build-up edge formation, which reduce the cutting force. It can be observed that the increase in cutting speed will reduce the chip tool contact length therefore cutting force is reduced.

The effect of feed rate on cutting force is examined by considering a constant speed of 120 m/min, a depth of cut of 1 mm, and length of continuous turning of 120 mm. When constant feed rate is considered, the cutting force is decreased as reinforcement added. Figure 10 shows that the cutting force was increased when increasing the feed rate. At constant speed and depth of cut, an increase in feed rate causes excessive friction between the tool and work piece, which increases the cutting force.

Figure 11 shows the influence of the depth of cut on cutting force turning of master alloy and $MMC_s$. The effect of an increase in reinforcement added is evaluated under different depths of cut at a constant feed rate of 0.06 mm/rev, cutting speed of 120 m/min, and a length of machining of 120 mm. When constant depth of cut is taken into consideration, the cutting force is decreased as reinforcement added. At same speed and feed rate values, an increase in the depth of cut causes more cutting force because of excessive area of contact.

## 5. Conclusion

The results of turning studies on $Al_2O_3$, $B_4C$, and the combination of $Al_2O_3$ and $B_4C$ particles-reinforced aluminium alloy composites using cemented carbide tool were presented. The effect of cutting parameters and reinforcements on tool wear, surface roughness, and cutting force were measured. The following conclusions have been drawn:

1- the microhardness is increased as reinforcement added ($Al_2O_3$, the combination of $Al_2O_3$ and $B_4C$, and $B_4C$) respectively

2- Addition of $B_4C$ as reinforcement to the master alloy produces higher tool wear, surface roughness and minimizes the cutting forces.

3- When machining the master alloy and MMCs with high speed causes rapid tool wear due to generation of high temperature in the machining interface. At high cutting speed machining will minimize chip tool contact length and build-up edge formation, which reduce the cutting force and surface roughness.

4- The rate of flank wear, surface roughness, and cutting force are high when machining with a higher depth of cut.

5- An increase in feed rate increases the flank wear, surface roughness, and cutting force.

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**Table 1 – Chemical composition of the master alloy**

| Component | Cu | Mg | Si | Mn | Zn | Fe | Al |
|---|---|---|---|---|---|---|---|
| Amount (wt) | 3.33 | 0.71 | 0.73 | 0.55 | 0.14 | 0.09 | Balance |

**Table 2 – Microhardness comparison**

| Material | Trial 1 | Trial 2 | Trial 3 | Average hardness (HV) |
|---|---|---|---|---|
| Al- without reinforcement (Master alloy) | 81 | 87.3 | 79.6 | 82.63 |
| Al-20% $Al_2O_3$ | 97.3 | 103.1 | 108.1 | 102.83 |
| Al-20% $B_4C$ | 120.4 | 128.5 | 118.7 | 122.43 |
| Al-10% $Al_2O_3$ -10% $B_4C$ | 111.4 | 113.1 | 117.4 | 113.96 |

**Table 3 – Experimental parameters**

| | |
|---|---|
| Machine tool | Harrison/England medium duty lathe with 2.2 KW |
| Tool insert | CNMA 120408 TN 010 02 PF (cemented carbide) |
| Tool holder | PCLNR 25 25 M 12 |
| Machining parameters | Cutting speed: 40, 80, 120, 160, and 200 m/min.<br>Feed rate: 0.03, 0.06, 0.09, 0.12, and 0.15 mm/rev.<br>Depth of cut: 0.5, 1.0, 1.5, 2.0, and 2.5 mm |
| Surface equipment | Taylor Hobson |
| Cutting force instrument | Special design dynamometer |
| Coolant | Dry machining |

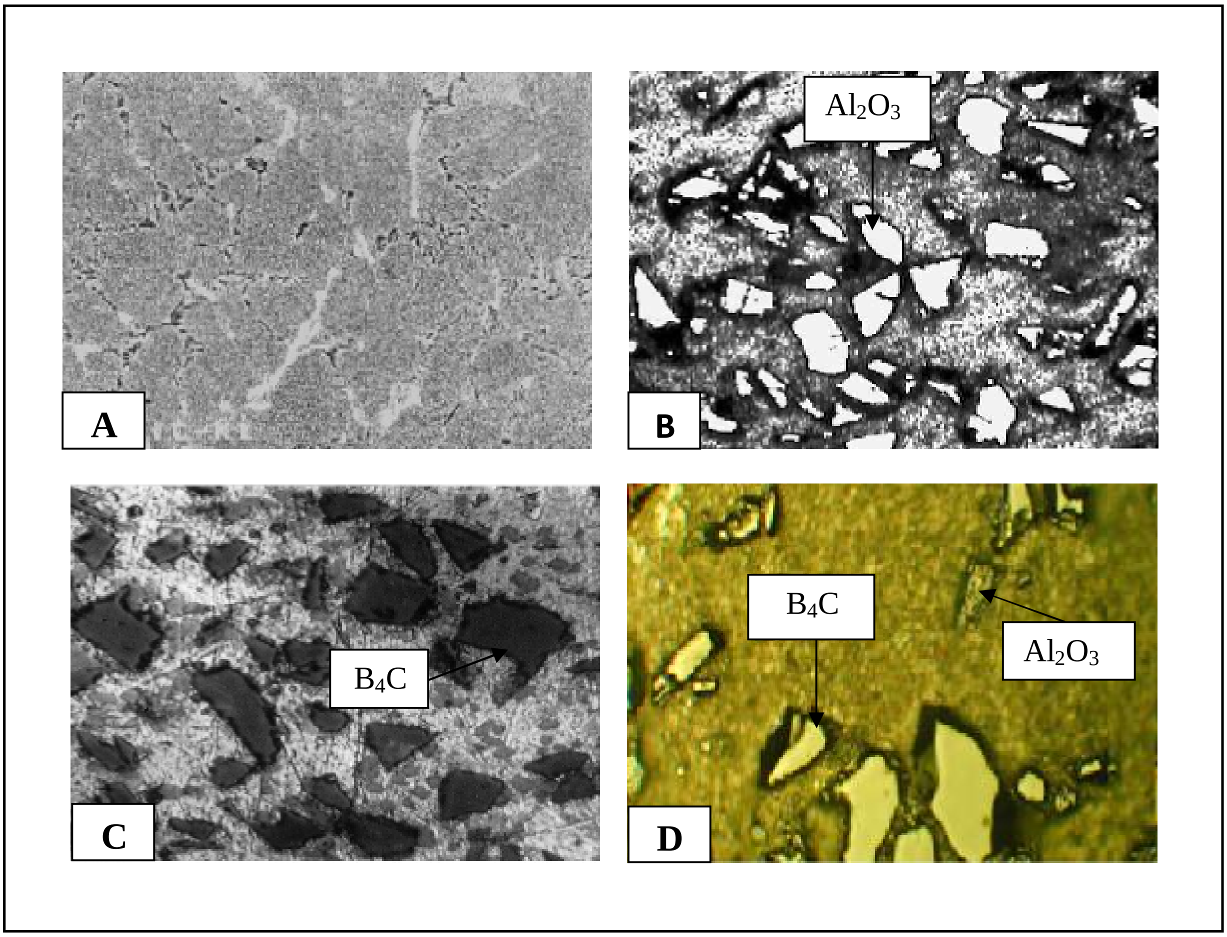


**Fig.** ( 1 ) Optical microstructure of the master alloy and $MMC_s$ at 200X
(**A**:Master alloy, **B**:Al-20%$Al_2O_3$, **C**:Al-20%$B_4C$, **D**:Al-10%$Al_2O_3$-10%$B_4C$)

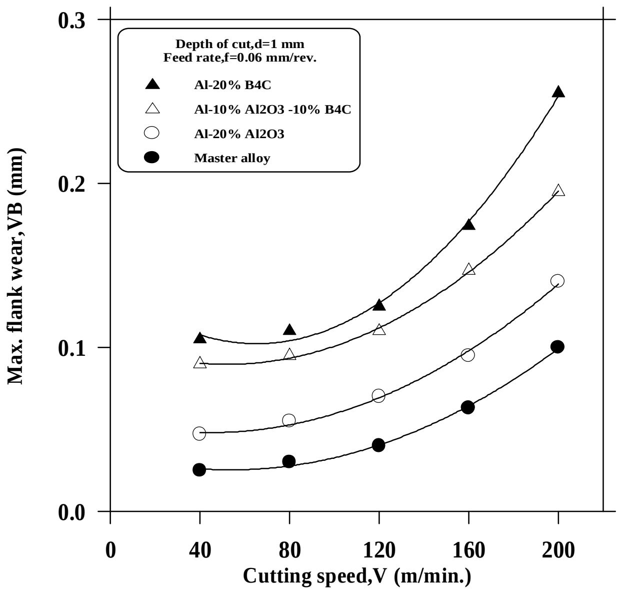


**Fig.**( 2 ) Effect of cutting speed on tool wear

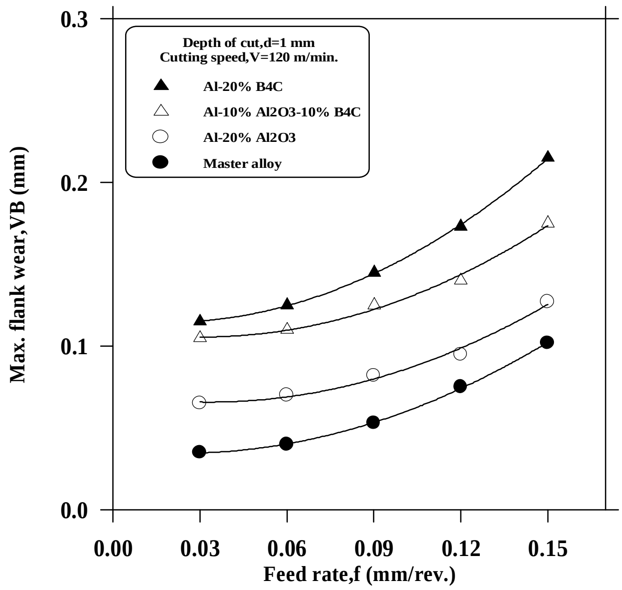


Fig.( 3 ) Effect of feed rate on tool wear

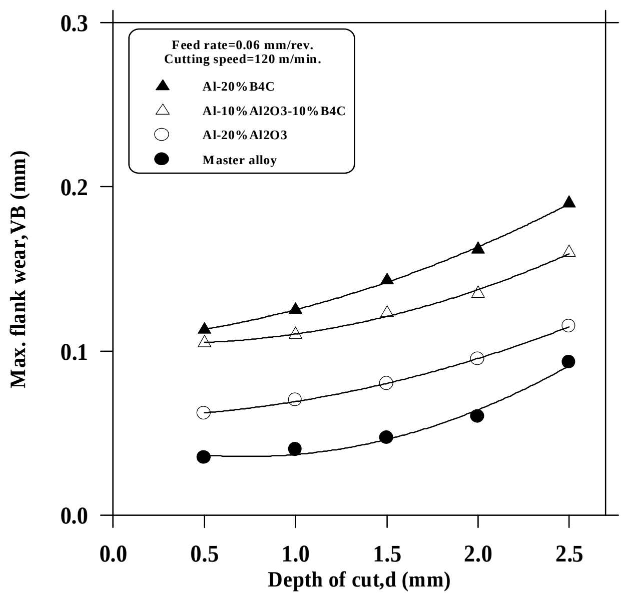


Fig.( 4 ) Effect of depth of cut on tool wear

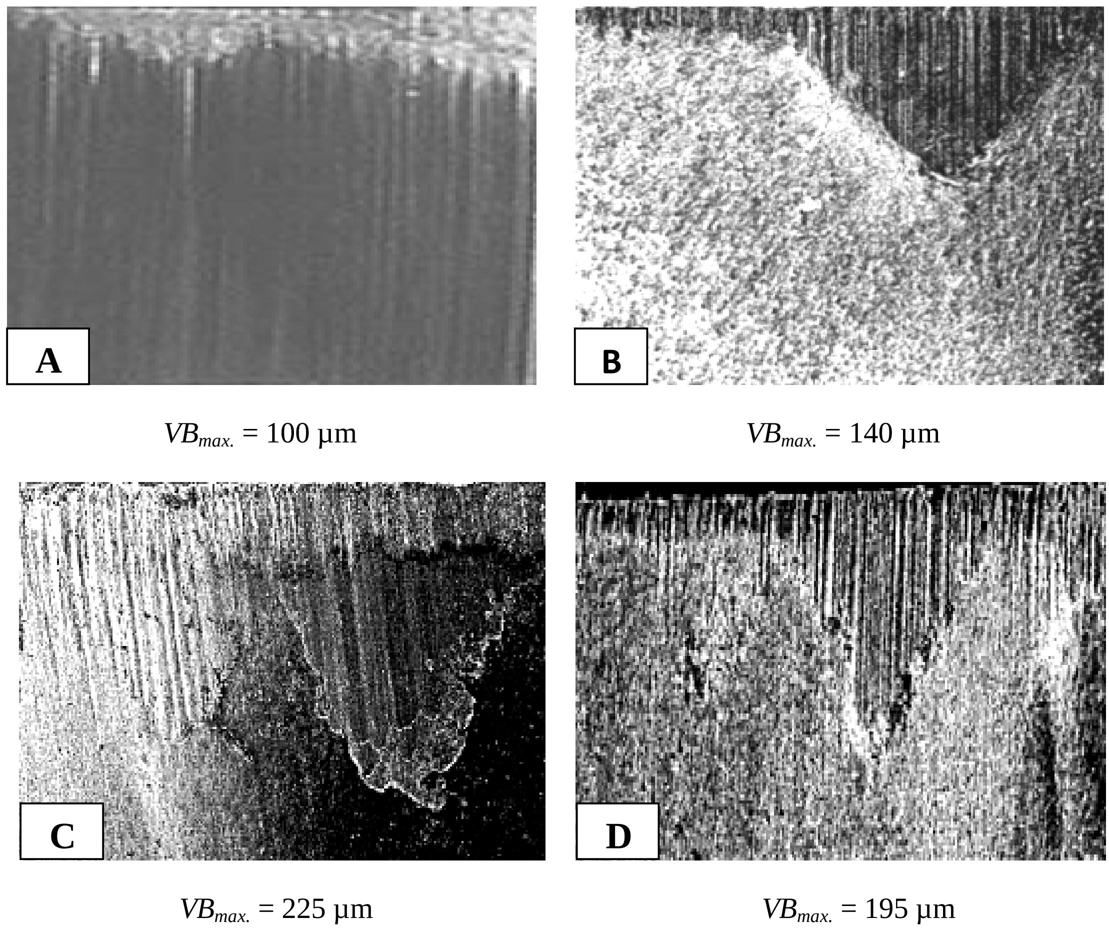


Fig.(5) photographs of tool wear at 100X

Cutting conditions ( $V$= 200m/min., d=1mm, $f$= 0.06mm/rev., and L=120 mm)

(**A**:Master alloy, **B**:Al-20%$Al_2O_3$, **C**:Al-20%$B_4C$, **D**:Al-10%$Al_2O_3$-10%$B_4C$)

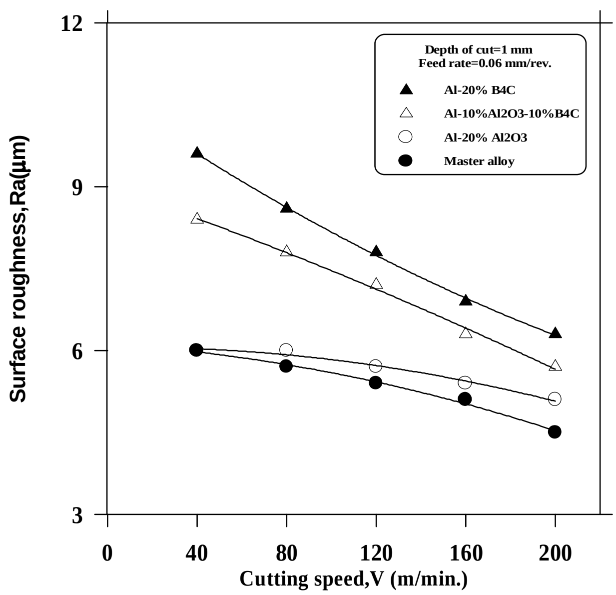


Fig.( 6 ) Effect of cutting speed on surface roughness

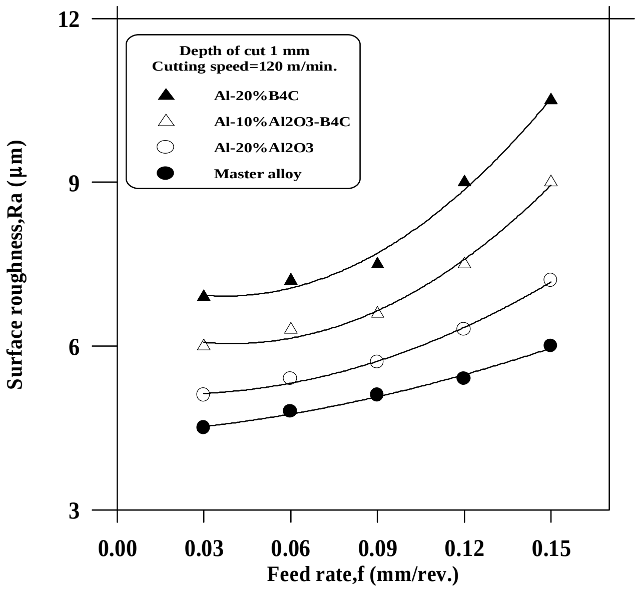


Fig.( 7 ) Effect of feed rate on surface roughness

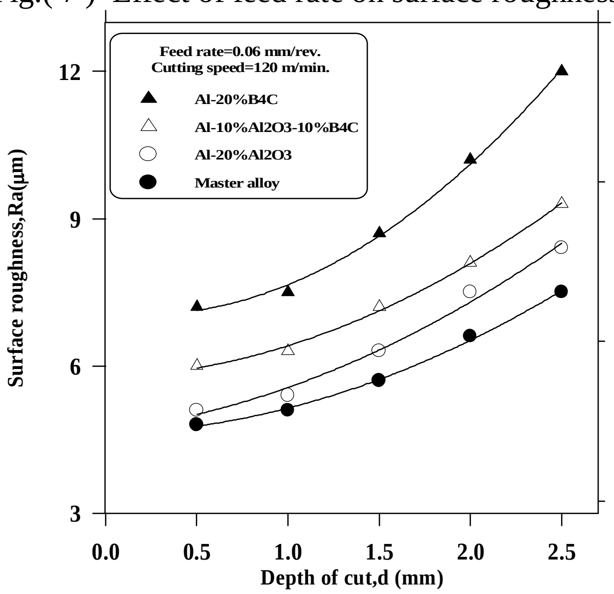


Fig.( 8 ) Effect of depth of cut on surface roughness

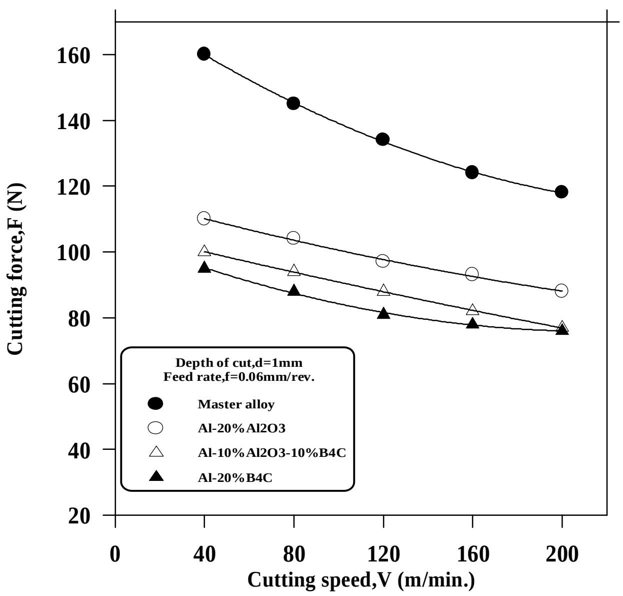


Fig. ( 9 ) Effect of cutting speed on cutting force

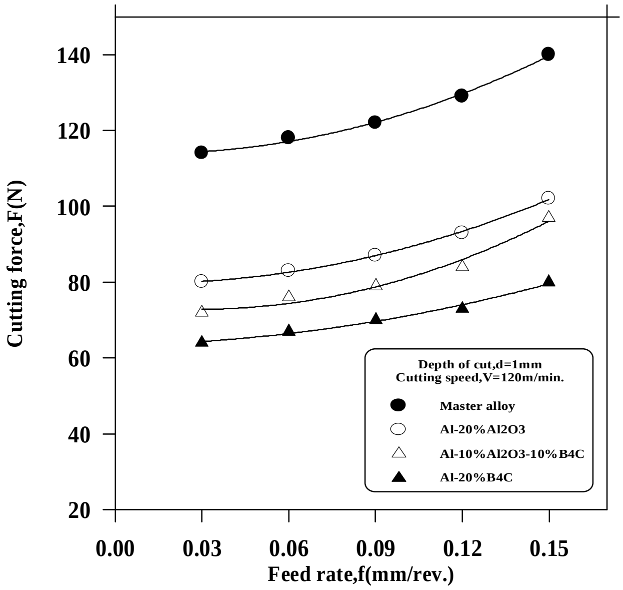


Fig. ( 10 ) Effect of feed rate on cutting force

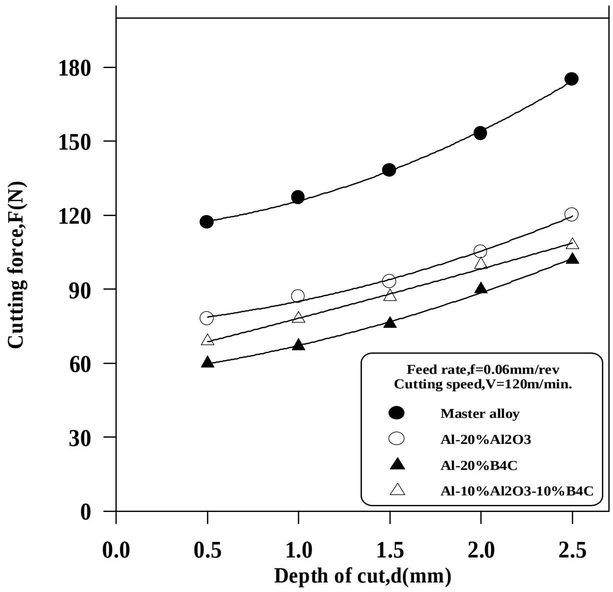


Fig. ( 11 ) Effect of depth of cut on cutting force