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ORIGINAL ARTICLE

Investigations of flank wear, cutting force, and surface roughness in the machining of Al-6061–TiB_2 in situ metal matrix composites produced by flux-assisted synthesis

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Abstract This paper presents the results of an experimental investigation on the machinability of in situ Al-6061–TiB_2 metal matrix composite (MMC) prepared by flux-assisted synthesis. These composites were characterized by scanning electron microscopy, X-ray diffraction, and micro-hardness analysis. The influence of reinforcement ratio of 0, 3, 6, and 9 wt.% of TiB_2 on machinability was examined. The effect of machinability parameters such as cutting speed, feed rate, and depth of cut on flank wear, cutting force and surface roughness were analyzed during turning operations. From the test results, we observe that higher TiB_2 reinforcement ratio produces higher tool wear, surface roughness and minimizes the cutting forces. When machining the in situ MMC 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.

Keywords In situ MMC · Turning operation · Machinability · Tool wear · Cutting force · Surface roughness

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1 Introduction

Composite materials are important engineering materials due to their outstanding mechanical properties. MMCs are one of the widely known composites because of their superior properties such as high strength, hardness, stiffness, and wear and corrosion resistances. These properties are important in automotive and aerospace applications because of the potential for large reductions in weight [1]. 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. The major drawback in the former process involves the difficulties encountered in incorporating the line ceramic reinforcements into the matrices, agglomeration, and poor wetting between particles and matrices. For most applications, a homogeneous distribution of the reinforcing phase is desirable for maximizing the mechanical properties and to improve machinability of the MMCs. To overcome this problem and to increase the bonding strength between the particles and the matrix, in situ composite materials have been developed. The major advantage of the in situ process is that the reinforcement is created by the exothermic reaction so that the particles are formed within the melt and fewer problems are observed with the distribution of the in situ particles. Al-6061 possesses good machinability and weldability that it is used in automobile, aerospace, electronics, and medical industries. The chemical composition of Al-6061 is shown

Table 1 Chemical composition of Al-6061

Component	Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	Al
Amount (wt.)	0.8	0.4	0.7	0.15	0.25	0.15	0.15	0.04	Balance

in Table 1. TiB_2 reinforcement is to provide stiffness and hardness, and more importantly, TiB_2 does not react with aluminum to form a reaction product at the interface of the reinforcement and the matrix. Turning is the most common method for cutting and especially for the finishing machined parts. The objective of the present work is to fabricate, characterize, and investigate the machinability behavior of the in situ A1-6061–TiB_2 MMC.

The reinforcement particles formed in situ routes are very fine, and the dispersion of reinforcement is accomplished by means of exothermic chemical reaction. Many authors [2, 3] have reported that the mechanical properties of an in situ composite are superior to an ex situ composite. Reinforcement particles formed in situ are finer in size and their distribution in the matrix is more uniform. Daniel et al. [4] and Tjong et al. [5] have studied the advantages of the composites reinforced using the in situ route on fabrication, microstructure, and mechanical properties. Particular attention is paid to the flux-assisted synthesis because of its simplicity of manufacturing. Some of the authors [6–8] attempted to fabricate and characterize the Al–TiB_2 reinforcement composite by flux-assisted synthesis. Christy et al. [9] reported that there is 23% improvement in tensile strength and also 15% improvement in yield strength, while adding 10% in situ TiB_2 reinforcements in Al-6061 matrix. Ozcatalbas [10, 11] investigated the machinability behavior of Al_4C_3-reinforced aluminum-based composite produced by the in situ route during turning operations. It was observed that high-volume fraction of Al_4C_3 present in the matrix decreases the build-up edge formation and increases the surface quality at high cutting speed. The machinability behavior of ex situ composites during turning operations is reported in the literatures [12–19]. However, no work addresses the machinability of Al-6061–TiB_2 in situ composite produced by flux-assisted synthesis. An attempt has been made to study the influence of cutting speed, feed rate, and depth of cut on flank wear, cutting force and surface roughness during turning of the Al-6061–TiB_2 in situ MMC produced with different volume fractions was investigated. The contribution of this paper is to study the influence of TiB_2 reinforcements which are formed by in situ chemical reaction on machinability.

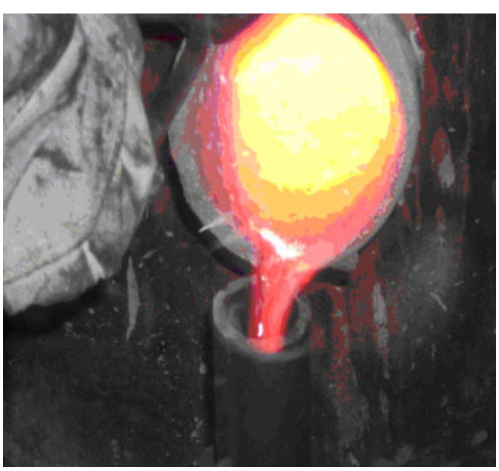


Fig. 1 Casting of Al-6061–TiB_2 in situ MMC

2 Experimental work

2.1 Production of Al-6061–TiB_2 in situ MMC

The production of Al-6061–TiB_2 in situ MMC is a novel low-cost reactive approach, which involves adding Ti- and B-bearing salts to molten aluminum. The reaction between the salts leads to the formation of reinforcing TiB_2 particles in the aluminum matrix. The in situ formed TiB_2 particles are very fine. During the synthesis, mixed salts of potassium hexafluorotitanate (K_2TiF_6) and potassium tetrafluoborate (KBF_4) are introduced into a stirred aluminum melt with an atomic ratio in accordance with TiB_2. Exothermal reactions between the salts and the molten aluminum take place in the crucible. After the reaction stirring is stopped in order to remove the slug containing $KAlF_4$ and K_3AlF_6, the molten composite is cast into a Ø 38×200-mm graphite-coated cast iron mold (Figs. 1 and 2).

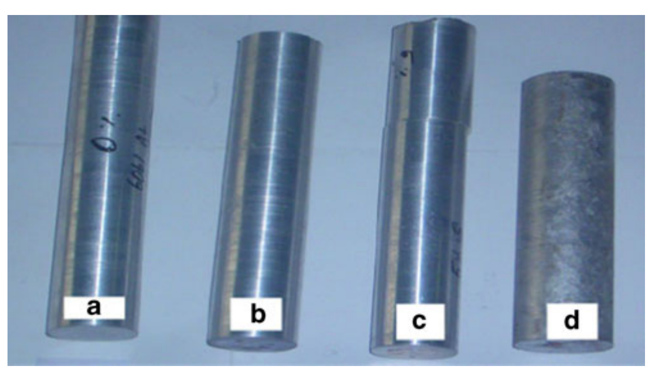


Fig. 2 In situ Al–TiB_2 MMCs (**a** 0% TiB_2, **b** 3% TiB_2, **c** 6% TiB_2, and **d** 9% TiB_2)

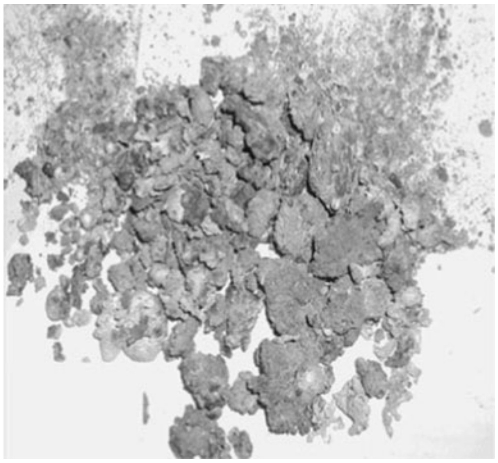


Fig. 3 $KAlF_4$ and K_3AlF_6 slag

The removed slug containing $KAlF_4$ and K_3AlF_6 from mold is shown in Fig. 3.

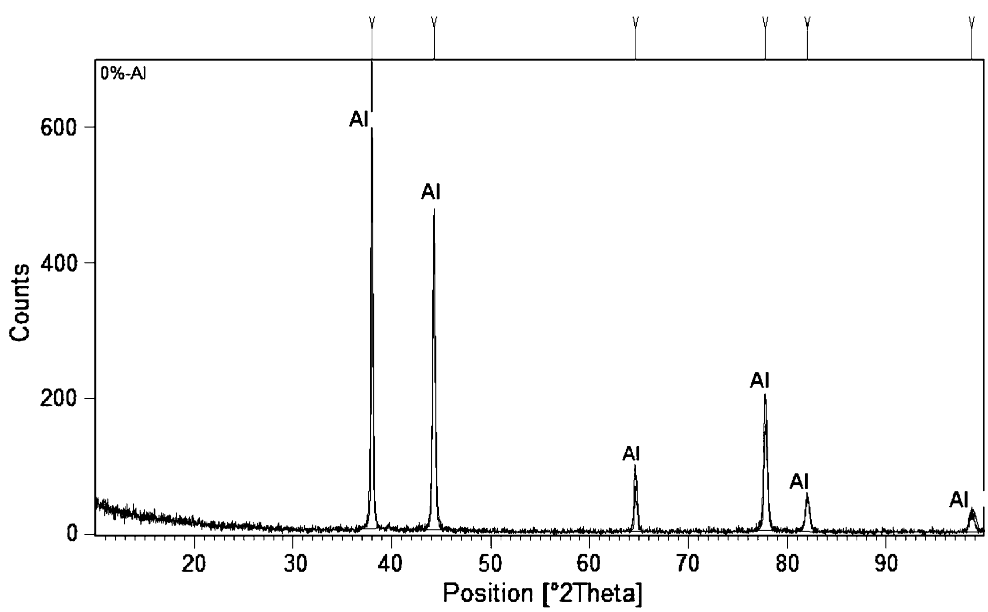
2.2 Characterization of Al-6061–TiB_2 in situ MMC

The fabricated composites are examined under a scanning electron microscopy (SEM) to ascertain the formation of TiB_2 particles and their distribution. SEM micrographs were recorded by a JEOL 6360 LV model. X-ray diffraction (XRD) analysis also used to confirm the presence of TiB_2 reinforcement. Figures 4, 5, 6, and 7 shows the XRD pattern of Al-6061 and MMC with −3%, 6%, and 9% TiB_2 reinforcement particles. A XPERT-PRO X-ray diffractometer was operated using Cu-kα radiation, at a generator setting of 30 mA and 40 kV. Continuous scanning of 1°/min was applied. The peak confirms the presence of aluminum and TiB_2 in the sample. Figures 8 and 9 show the micrographs of MMC with 3% and 9% of TiB_2 reinforcement particulates. The figures reveal the presence of TiB_2 particles in the aluminum matrix. It is observed that TiB_2 particles display a hexagonal shape in Fig. 9. The size of the reinforcement particles are up to 1 μm. These micrographs also show the lack of agglomeration and fine distribution of TiB_2 reinforcements. Effect of addition of reinforcements in the matrix on hardness was investigated by using Vickers micro-hardness tester (MH06 model, Everyone make) at a load of 25 g with 3 s dwell time. Table 2 shows effect of reinforcements increase the hardness of the MMC.

2.3 Experimental work

Machining tests were carried out in Turn master-35 lathe (3 HP, 0.75 KW) supplied by Kirloskar, Mysore, India, which is shown in Fig. 10.The uncoated tungsten carbide inserts were clamped in a rigid tool holder. The specification for insert and tool holders are given in the Table 3. The length of turning is 110 mm. Chip breaker was not used for the experiment. Average flank wear was measured using Mitutoya microscope with ×30 magnification. A stylus type perthometer was used for measuring surface roughness. The cutting force was measured using a Kistler Dynamometer (model 9257B). The data acquisition was carried out by appropriate software Dynaware Kistler. Machining tests were conducted in dry cutting conditions. The selected machining parameters and their ranges were given in Table 3.

Fig. 4 XRD pattern of Al-6061–0% TiB_2 in situ MMC



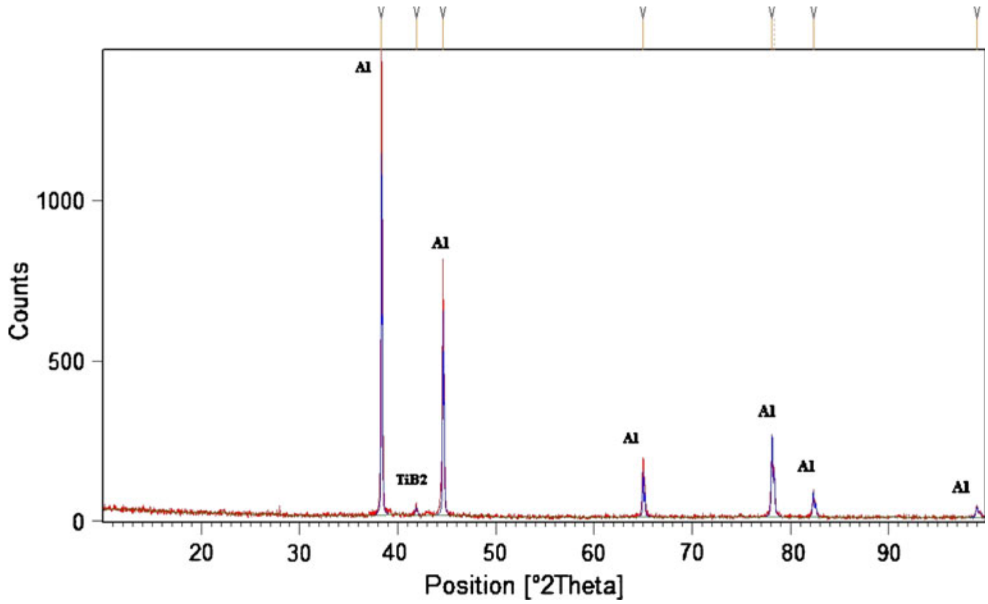


Fig. 5 XRD pattern of Al-6061–3% TiB_2 in situ MMC

3 Results and discussion

XRD spectrum of the in situ composites show that there are no extra peaks due to any impurity phases are identified. It establishes chemical stability of the in situ MMC. Microstructure examination shows that TiB_2 particles display a hexagonal shape with a size of 1 μm. It observed that fine distribution of TiB_2 reinforcements in the aluminum matrix. Micro-hardness analysis show that effect of reinforcements increase the harness of the materials and also indicates that the hardness value of the composite increases by increasing the reinforcement ratio.

In this study, the effects of TiB_2 reinforcement of Al-6061 at different ratios of TiB_2 on the tool wear, cutting force and surface roughness in turning the formed MMC have been investigated in terms of selected cutting speed, feed rate, and cutting depth. During examination of tool wear, the amount of flank wear on the free surface was taken as the reference. Flank wear is due to abrasive action of the reinforcement particles present in the MMC. The harder particles of TiB_2 grind the flank face of the cutting tool similar to a grinding wheel during machining of in situ Al–TiB_2 MMC.

Figure 11 shows the influence of cutting speed on the flank wear during machining of MMC. Turning operations

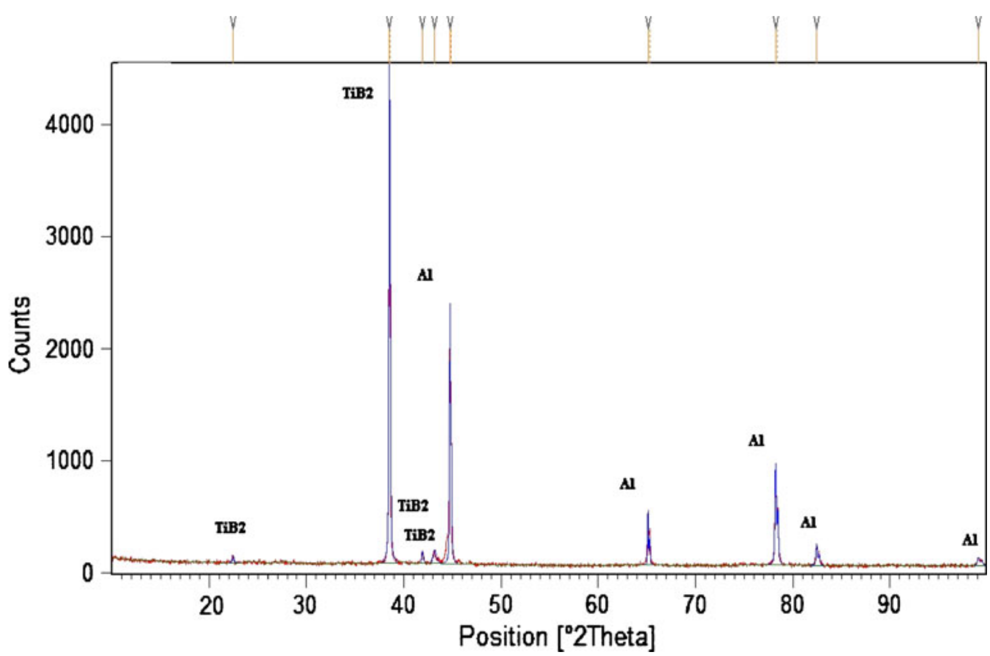


Fig. 6 XRD pattern of Al-6061–6% TiB_2 in situ MMC

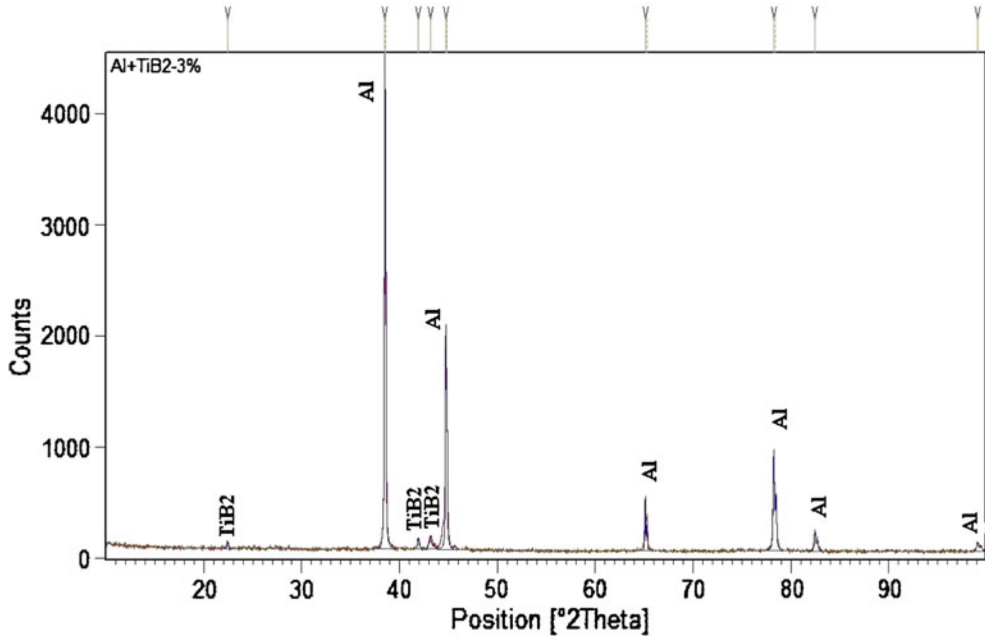


Fig. 7 XRD pattern of Al-6061–9% TiB_2 in situ MMC

were performed considering a constant feed rate of 0.2 mm/rev and a depth of cut of 1 mm, and continuous length of turning of 110 mm. The experimental results revealed that the tool wear at 50–100 m/min, the flank wear is 0.02–0.12 mm whereas at 150 m/min, the flank wear is 0.23. If the cutting speed increases above 100 m/min, the values of flank wear increases rapidly. At high cutting speed, the temperature of the machining interface will increase. High temperature in the machining interface will soften cutting tool. From the figure, it can be observed that the tool wear increases with an increase in the reinforcement ratio.

The influence of feed rate on the tool wear is examined by considering a constant speed of 125 m/min with a cut depth of 1 mm, and a length of turning of 110 mm. Figure 12 shows the effect of an increase in reinforcement evaluated under different feed rates. When constant feed rate was taken into consideration, the flank wear of cutting tool increases as the reinforcement ratio increases. 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 13 shows the effect of the depth of cut on the flank wear during turning of in situ Al-6061–TiB_2 composite without the use of a coolant. Turning operations were performed considering a constant feed rate of 0.2 mm/rev, a constant speed of 125 m/min, and a length of turning of 110 mm. The influence of an increase in reinforcement ratio 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,

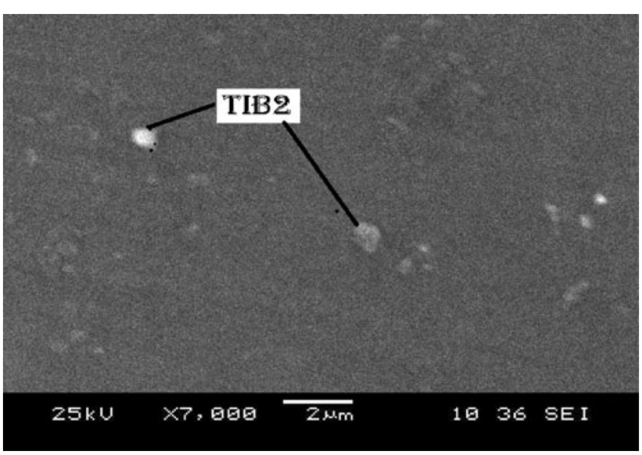


Fig. 8 SEM micrograph for Al-6061–3% TiB_2 in situ MMC

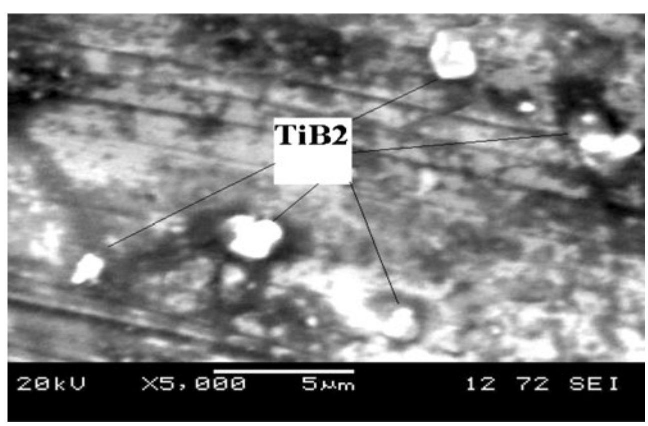


Fig. 9 SEM micrograph for Al-6061–6% TiB_2 in situ MMC

Table 2 Micro-hardness comparison

Material	Trail 1	Trail 2	Trial 3	Average hardness (Hv)	Standard deviation of hardness
Al–0% TiB_2	90	89	100.2	93.07	6.20
Al–3% TiB_2	99.3	104.1	108.9	104.10	4.80
Al–6% TiB_2	112.4	113.1	119.7	115.06	4.02
Al–9% TiB_2	117.5	122.4	129.5	123.13	6.03

flank wear of cutting tool increased as the reinforcement ratio increased. 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.

Figure 14 shows the influence of the cutting speed on cutting force during machining of in situ MMC. The effect of an increase in reinforcement ratio is evaluated under different speeds, at a constant feed rate of 0.2 mm/rev, a depth of cut of 1 mm, and a length of turning of 110 mm. When constant cutting speed was considered, the cutting force is decreased as the reinforcement ratio increases. 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 125 m/min, a depth of cut of 1 mm, and length of continuous turning of 110 mm. When constant feed rate is considered, the cutting force is decreased as reinforcement ratio increases. Figure 15 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 16 shows the influence of the depth of cut on cutting force turning of Al-6061–TiB_2 in situ MMC. The effect of an increase in reinforcement ratio is evaluated under different depths of cut at a constant feed rate of 0.2 mm/rev, cutting speed of 125 m/min, and a length of machining of 110 mm. When constant depth of cut is taken into consideration, the cutting force is decreased as reinforcement ratio increases. At same speed and feed rate values, an increase in the depth of cut causes more cutting force because of excessive area of contact.

Figure 17 shows the effect of cutting speed on surface roughness on machined surface. At the same level of cutting speed Al-6061 with 9% TiB_2 having more roughness value, when compared with Al-6061 with 0% TiB_2. The presence of reinforcement in composite will increase the surface roughness. Increase in cutting speed will improve the surface roughness. When increasing the cutting speed, reduce the build-up edge formation. Therefore deposition of build-up edge material on the machined surface will be minimized.

The influence of feed rate on the surface roughness is shown in Fig. 18. At same level of feed rate the surface roughness value increased when increasing reinforcement ratio. Figure 18 also shows that the increase in feed rate is increase the surface roughness. Figure 19 reveals that the surface roughness value increases by increasing the depth of cut. Increasing in depth of cut causes large size build-up edge because of excessive friction. Deposition of build-up edge on machined surface causes poor surface finish.

The experimental results reveal that an increase in reinforcement ratio increases the tool wear, surface roughness and minimizes cutting force. Figure 20 shows a

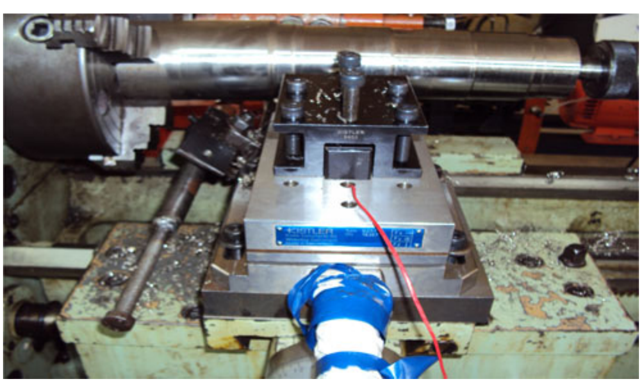


Fig. 10 Photographic view of experimental setup

Table 3 Experimental conditions

Experimental conditions	
Cutting tool	Uncoated tungsten carbide
Cutting tool specification	SNMG12O408 MTTT5100
Tool holder specification	PSBNR-2525M12
Clearance angle (°)	7
Cutting edge angle(°)	75
Nose radius (mm)	0.8
Cutting speed (m/min)	50, 75, 100, 125, and 150
Feed rate (mm/rev)	0.1, 0.2, 0.3, 0.4, and 0.5
Cutting depth (mm)	0.5, 0.75, 1, 1.25, and 1.5
Reinforcement ratio (wt.%)	0, 3, 6, and 9
Cutting condition	Dry

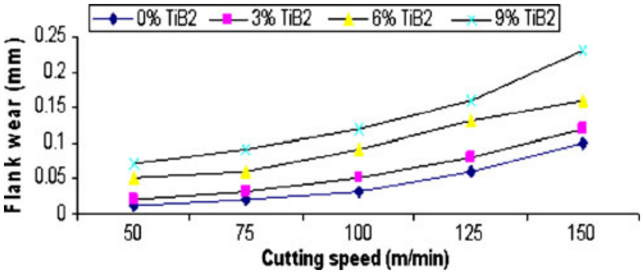


Fig. 11 Effect of cutting speed on tool wear

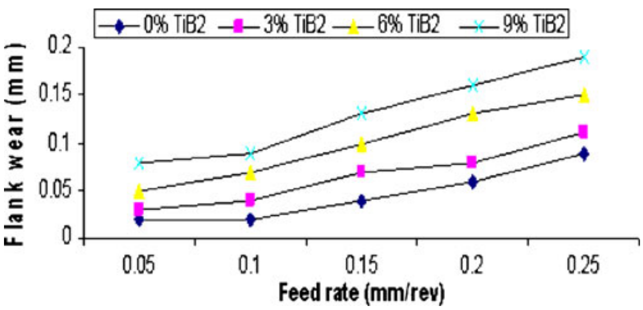


Fig. 12 Effect of feed rate on tool wear

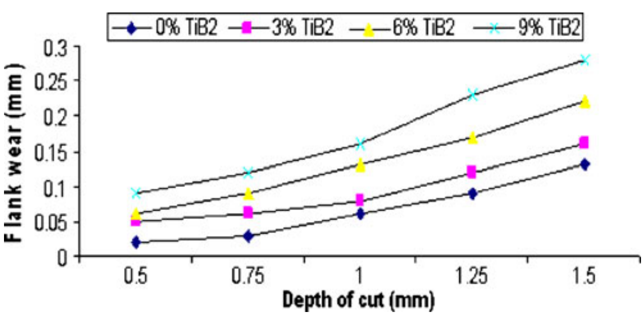


Fig. 13 Effect of depth of cut on tool wear

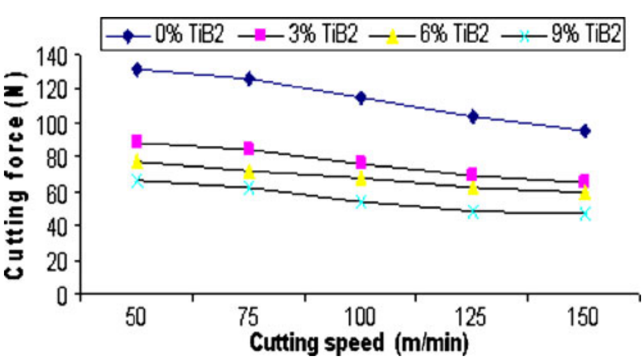


Fig. 14 Effect of cutting speed on cutting force

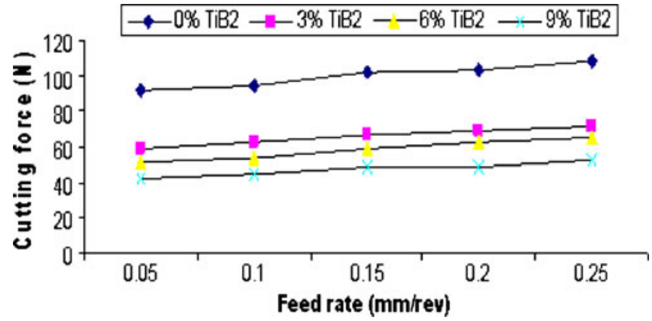


Fig. 15 Effect of feed rate on cutting force

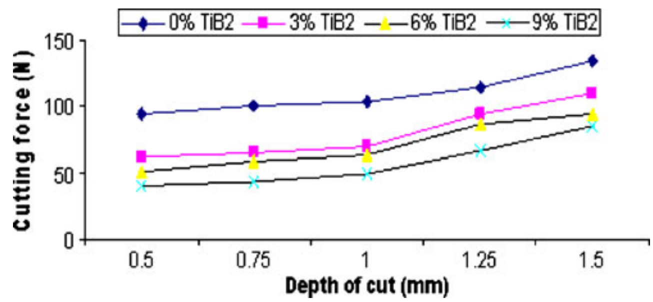


Fig. 16 Effect of depth of cut on cutting force

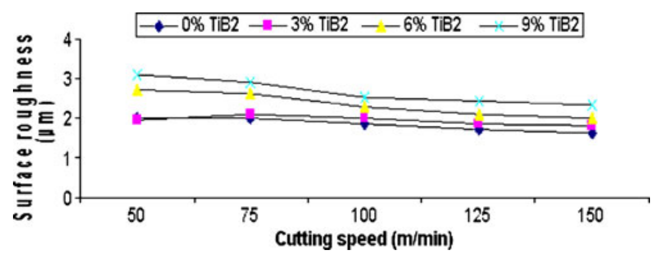


Fig. 17 Effect of cutting speed on surface roughness

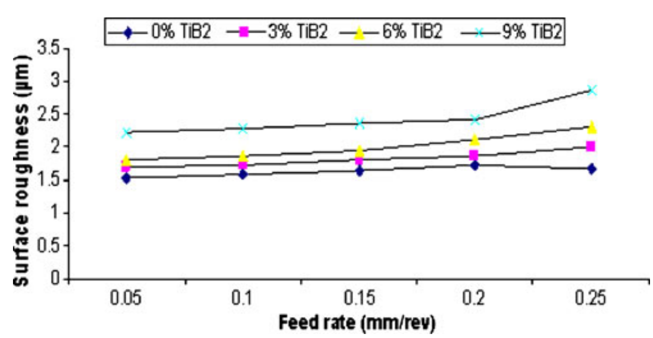


Fig. 18 Influence of feed rate on the surface roughness

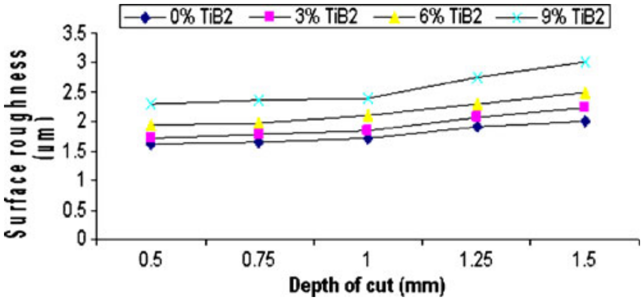


Fig. 19 Influence of depth of cut on surface roughness

microscopic view of build-up edge formation during machining of Al-6061–3%TiB_2 in -situ composite with 100 m/min speed, 0.1 mm/rev feed rate, and 1 mm depth of cut. Generally the build-up edge formation indicates the excessive friction between the tool and work piece interface. The build-up edge formation is less when increasing the cutting speed whereas increase in feed rate and depth of cut causes more build-up edge formation. From our investigations, we observed that high cutting speed machining causes rapid tool wear, minimize build-up edge formation, reduce the cutting force and decrease the surface roughness. The increase in feed rate increases the flank wear, surface roughness, and cutting force. An increase in the depth of cut causes more tool wear and excessive build-up edge formation. Excessive build-up edge increases the rake angle of the cutting tool, which increases the cutting force and surface roughness. Hence, moderate cutting speed, moderate feed rate, and low depth of cut are best suitable for economic machining, which reduce the machining cost while machining in situ Al-6061–TiB_2 MMC. In situ MMC is fine particle reinforcement composite because of its nature of processing. The presence of fine reinforcement particle minimizes the obstruction to the plastic deformation and reduces scrapping on the flank face of the cutting tool during turning of MMC. Due to this reason, low tool wear and surface roughness is recorded while turning with a cutting tool made of uncoated tungsten carbide.

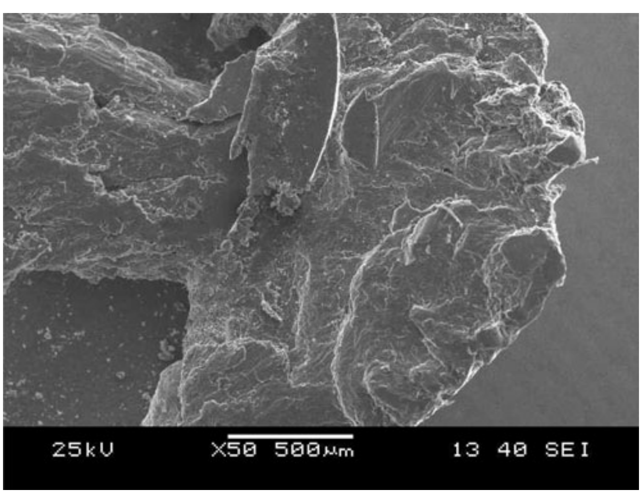


Fig. 20 SEM micrographic view of build-up edge formation

4 Conclusions

In this study, the machinability of TiB_2 reinforced in Al-6061 matrix produced by flux-assisted synthesis was investigated and following results were obtained.

- XRD and micro-hardness analysis confirmed the presence of TiB_2 reinforcements.
- Higher TiB_2 reinforcement ratio produces higher tool wear, surface roughness and minimizes the cutting forces.
- Machinability of in situ MMC is different from traditional MMC, because of the presence of fine and uniformly distributed reinforcement, which reduces flank wear.
- When machining the in situ 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
- 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.

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