Determination of Optimum Cutting Parameters for Surface Roughness in Turning AL-B_{4}C Composites

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Abstract. Many materials such as alloys, composites find their applications on the basis of machinability, cost and availability. In the present work, machinability of Aluminium 1100 and Boron carbide (AL+ B_{4}C) composite material is examined by using lathe tool dynamometers (BANKA Lathe) by varying the cutting parameters like spindle speed, Depth of cut and Feed rate in 3 levels. Also, surface roughness is measured against the weight % of reinforcement in the composite (0, 4 and 8 %). From the study it is observed that the hardness of a composite material increases with increase in weight % of reinforcement material (B_{4}C) by 26.27 and 66.7 % respectively. The addition of reinforcement materials influences the machinability. The cutting force in both X and Z direction were also found increment with the reinforcement percentage.

Key words: Machinability, Lathe tool dynamometer, B_{4}C, surface roughness, AL-1100, DOE.

1. Introduction

Now days metal matrix composites play a very important role in the development of components in different applications. In metal matrix composite (MMC), aluminium alloy based composite are used to improve the strength to weight ratio with enhanced mechanical properties. Introducing a hard reinforcement materials such as ceramics, strength and wear resistance of aluminium alloys could be significantly improved. Among different cutting parameters affected by the final properties of the composites [1] Boron carbide is a second hardest material. It has low density (2.51 g/cm3), excellent chemical resistance and is extremely hard. Additionally, boron carbide (B_{4}C) has a high neutron absorption capacity and is being used in the development of nuclear applications [2, 6]. Conventional materials being used for a large number of structural applications such as those in the aeronautical/aerospace, transportation, defence and sports industries because of their superior properties. The addition of reinforcement material in conventional material further increases the mechanical properties. Therefore excellent mechanical properties such as high specific strength, specific modules, damping and wear resistance can be expected. The large number fabrication technique are being used in the manufacturing of metal matrix composite materials (MMC). Some of the techniques being used are: stir casting, squeeze casting, liquid processing, powered metallurgy and extrusion etc. [3]. A large number of fabrication techniques currently used to manufacture the MMC materials according to the type of reinforcement used. The 1100 Aluminium alloy is the best “cosmetic” alloy. This alloy is typically used in a lightweight components which are being in defence and aeronautics parts. The pure aluminium (AL-1100) basically heat treatable alloy. This alloy combines very high corrosion resistance and has an excellent formability for use in many applications.
2. Experimentation

2.1. Material

2.1.1 Aluminum (AL-1100)

In this work the AL-1100 is considered as matrix material [5].

| Table 1. Chemical composition of AL-1100 alloy [5] |
|---------------------------------|---|---|---|---|---|---|---|---|---|
| Elements | Si +Fe | Cu | Ni | Cr | Mg | Mn | Zn | Each | Total | AL |
| Percentage | 0.095 | 0.05 | - | - | - | - | 0.10 | 0.05 | 0.15 | Balance |

2.1.2 Boron Carbide (B$_4$C)

| Table 2. Properties of Boron Carbide (B$_4$C) |
|---------------------------------|---|
| Density | 2.52 g.cm$^{-3}$ |
| Melting Point | 2445 °C |
| Hardness | 2900-3580 Kg.mm$^{-2}$ |
| Fracture Toughness | 2.9 - 3.7 MPa*m$^{1/2}$ |
| Young's Modulus | 450 – 470 GPa |
| Thermal Expansion Co-eff. | 5 x10$^{-6}$ °C$^{-1}$ |

2.2 Experimentation

In this work commercially available AL-1100 is selected as a matrix material and B$_4$C having average size of 45µm as a reinforcement material due to its attractive properties, including high strength, low density, extremely high hardness, good chemical stability and neutron absorption capability [3]. With varying weight % of reinforcement (B$_4$C) from 0 to 8% with increment of 4%, the mixture is melted in the electrically charged resistance furnace. In order to increase the wettability of a reinforcement the K$_2$TiF$_6$ (wetting agent) added to the reinforcement which is pre-heated at temperature of 300°C. Al - 1100 is taken in a graphite crucible which kept in a furnace. After eight minutes the mixture of B$_4$C and K$_2$TiF$_6$ is added to the Aluminium. The mixture is continuously stirred manually for about 2-3 minutes, to distribute reinforcement particles uniformly aluminium alloy matrix. Electrical furnace of 5 Kg capacity is used for casting the composite materials. The furnace is set to a temperature of 850°C. The temperature rate of the furnace should be controlled at 830 ± 10 °C in final mixing process. The degasser is also added to mixture to remove trapped gases and to ensure that the heat from mixture in the graphite crucible should not be transferred easily to atmosphere. From each casting 10 specimens were produced. Die is prepared for the casting of specimen as per ASTM E8 standards. For each composition, Al-1100 metal matrix and B$_4$C reinforcement material with 4% and 8% are used for preparation of samples. Apart from the above compositions, the aluminium alloy is alone consider for the casting of specimens.
Figure 1 shows resistance furnace which is used for casting of specimens, specification for the electrical resistance furnace shown in table 3.

| Specifications     |            |
|--------------------|------------|
| Capacity           | 5 kg       |
| Operating temperature range | 1100 °C   |
| Power Rating       | 7.5 KW     |
| Heating element    | Silicon carbide |

Figure 2 shows the hot liquid in graphite crucible which contains the mixture of AL-1100 and B₄C. Specification for the crucible are given in table 4.

| Parameter       |            |
|-----------------|------------|
| capacity of crucible | 1 Kg      |
| Material        | Graphite   |
| Parameter       | Diameter-20cm, Length -25cm |
Figure 3 shows the die to which material mixture is pouring. It consists of two cavities and hence two specimens can be produced at a time. Specifications for the die are given in Table 5.

| Table 5. Die Specifications |
|-----------------------------|
| Diameter | 22 mm |
| Length  | 180 mm |
| Material | Cast iron |

Figure 4 shows the casted specimens as per the measured dimensions. Table 6 shows the dimensions for the specimen.

| Table 6. Specimen Dimensions |
|------------------------------|
| Diameter | 20 mm |
| Length  | 150 mm |

3. Testing

3.1 Hardness test
In Rockwell hardness tester, 1/16 inch steel ball indenter is used and a load of 100 kgf is applied for about 20 seconds. The testing is repeated at 5 different locations on specimens and average result is tabulated.

3.2 Machinability
The machinability test is conducted in computerized BANKA lathe machine. Tool dynometer is attached to tool post in order to measure the cutting forces. In the machining of composite materials, the parameters like speed, feed, depth of cut and reinforcement are considered and there are varied in 3 levels. The three levels for these parameters are tabulated in Table 7.

| Table 7: Parameter used in Machinability Test |
|-----------------|-----------------|-----------------|-----------------|
| Parameter       | Level 1 | Level 2 | Level 3 |
| Reinforcement   | 0%     | 4%     | 8%     |
| Speed (rpm)     | 175     | 263     | 395     |
| Feed (mm/min)   | 0.067   | 0.111   | 0.167   |
| Depth of cut (mm) | 0.2     | 0.4     | 0.6     |

Surface roughness (Ra) of the machined surface of a specimen is measured in Pro table surface roughness device (Mitutoyo SJ201) according ISO 4287 standards.

4. Design of Experiments
In this research work, depth of cut, feed and speed were observed to determine the effects of machinability parameters on the cutting force and the surface roughness. The full factorial experimental cutting parameters like speed, depth of cut, feed and reinforcement (0%, 4% and 8% weight percentage) involve 64 experiment results. Increase in the experimentation results high cost and more time consumption. Using Taguchi design of orthogonal array to examine the full parameter with number of trails, the number of experiments will significantly be reduced. Furthermore, it gives an easy, systematic and efficient approach to identify the most favourable cutting parameters in the
manufacturing process [8, 9]. The Taguchi’s technique quality loss function approach was performed to calculate the deviation between the optimal cutting values and the experimental values. Based on the S/N ratio function, the further regeneration of cutting parameters and signal to noise ratio (S/N) is to be considered. The S/N ratio indications can be separated into 3 groups: the nominal-the-best, larger-the-better and the smaller-the-better. In this study we aimed to optimize the surface roughness (µm) and cutting forces. Table 8 shows L9 standard orthogonal array.

Table 8. L9 Orthogonal Array

| Sl. No | Cutting speed (rpm) | Feed rate (mm/sec) | Depth of cut (mm) | Weight % of B₄C |
|-------|---------------------|--------------------|------------------|-----------------|
| 1     | 175                 | 0.067              | 0.2              | 0%              |
| 2     | 175                 | 0.111              | 0.4              | 4%              |
| 3     | 175                 | 0.167              | 0.6              | 8%              |
| 4     | 263                 | 0.067              | 0.4              | 8%              |
| 5     | 263                 | 0.111              | 0.6              | 0%              |
| 6     | 263                 | 0.167              | 0.2              | 4%              |
| 7     | 395                 | 0.067              | 0.6              | 4%              |
| 8     | 395                 | 0.111              | 0.2              | 8%              |
| 9     | 395                 | 0.167              | 0.4              | 0%              |

5 Result and Discussion

5.1 Microstructure of samples
Uniform distribution of B₄C particles were observed from the obtained micrographs as shown in figure 5. b and c. It is also observed that boron carbide particles have got good wettability with the addition of K₂TiF₆ salt. Agglomeration of reinforcement particles were also found in certain area of micrographs.

Figure 5: a) Base metal AL-1100. b) 4% B₄C+AL-1100+1100. c) 8% B₄C+AL-1100

5.2 Hardness
The hardness test is conducted on 3 different specimen, each specimen is having 0%, 4%, and 8% as B₄C with load of 100kg, using the 1/16 inch ball indenter, and the time taken for indention was 20 second and measuring B scale. Five readings were considered of different locations. The average value for all the specimen were tabulated in table 9
Figure 6 shows hardness v/s weight % of reinforcement

![Figure 6. Hardness of Specimen for Different Compositions](image)

From figure 6 we can observe that with increase in weight % of reinforcement (B₄C) to the base alloy AL-1100, the hardness increases by 26.27 and 66.7 %

### 5.3 Machinability

#### Table 10. Surface Roughness Readings.

| Sl. No. | Speed (rpm) | Feed (mm/min) | Depth of cut (mm) | Surface roughness (Ra) |
|---------|-------------|---------------|------------------|-----------------------|
|         |             |               |                  | 0% | 4% | 8% |
| 1       | 175         | 0.067         | 0.2              | 0.81 | 1.10 | 1.42 |
| 2       | 263         | 0.111         | 0.4              | 1.81 | 2.86 | 2.26 |
| 3       | 395         | 0.167         | 0.6              | 1.18 | 2.46 | 2.68 |
| 4       | 175         | 0.111         | 0.6              | 1.88 | 2.55 | 1.24 |
| 5       | 263         | 0.167         | 0.2              | 1.26 | 3.68 | 2.12 |
| 6       | 395         | 0.067         | 0.4              | 2.75 | 2.21 | 2.31 |
| 7       | 175         | 0.167         | 0.4              | 3.44 | 2.89 | 2.21 |
| 8       | 263         | 0.067         | 0.6              | 3.36 | 2.91 | 2.02 |
| 9       | 395         | 0.111         | 0.2              | 3.40 | 2.10 | 2.14 |
5.4 Residual Plot

![Residual Plots](image)

**Figure 7.** Residual Plots

| Level | Speed (Rpm) | Feed (mm/min) | Depth of cut (mm) | Material variance |
|-------|-------------|---------------|-------------------|-------------------|
| 1     | 2.4100      | 1.2500        | 1.3333            | 1.4000            |
| 2     | 1.5800      | 1.5833        | 1.4800            | 1.8100            |
| 3     | 0.7233      | 1.8800        | 1.9000            | 1.5033            |
| Delta | 1.6867      | 0.6300        | 0.5667            | 0.4100            |

**Table 11.** Analysis Variance

From the figure 7, straight line is dividing the points into two equal parts and hence our experimental data meeting the normality assumptions (model adequacy). Also, figure shows our experimental data roughly obey the constant variance assumption. The observation order v/s residual plot shows that experiments are done randomly.

![Main Effects Plot](image)

**Figure 8.** Main Effects Plot v/s S/N Ratio
Based on plots shown in figure 8 for S/N ratio to identify optimum variance of the each variables, the material at 4% of B₄C of having the maintained speed 175, feed 0.167 or 0.111 and depth of cut 0.4.

To validate the above result the analysis of variance is being considered.

**Table 12. Analysis Variance Value Table**

| Source         | DOF | Adj SS | Adj MS  | F-Value | P-Value |
|----------------|-----|--------|---------|---------|---------|
| Speed(rpm)     | 1   | 4.2200 | 4.2200  | 57.96   | 0.001   |
| Feed(mm/min)   | 1   | 0.5898 | 0.58975 | 8.10    | 0.036   |
| Depth of cut(mm) | 1   | 0.4817 | 0.48167 | 6.62    | 0.050   |
| Error          | 5   | 0.3641 | 0.07281 |         |         |
| Total          | 8   | 5.6555 |         |         |         |

Table 12 shows the results of ANOVA for surface roughness. From the table, it can be observed that the p-value of feed and speed are less than significant level i.e., 5%. Hence, these factors have significant effect on response variables i.e., surface roughness. Hence depth of cut is not significance variable levels. Therefore, Speed and feed are significance variables and response variable (Ra).

\[ Ra = 0.868 - 0.2108 \text{Mt} + 0.002815 \text{S} + 5.75 \text{F} + 0.258 \text{D} \]

R² and R adjective square greater than the 85% hence model is fit.

### 6 Conclusion

In this experimental work, Aluminium 1100 alloy based metal matrix composite reinforced with 45 µm of boron carbide particles were successfully fabricated by stir casting method. The B₄C particles were uniformly distributed in matrix material which were examined in optical microscope. Rockwell hardness test was done on all the specimens as per ASTM Standards. Later the machinability carried out as per ASTM standards to measure the surface roughness by Mitutoyo SJ201 tester. The following conclusions obtained in experimental study:

- The hardness of the AL-1100 metal matrix composites with the addition of 4% and 8% of B₄C particles increases by 26.27 and 66.7% respectively.
- The machinability of MMC is different from base material because of the presence of boron carbide reinforcement particles. After conducting the turning operation at different feed rates and speeds, it is observed that the surface roughness decreases on increase in speed. On increasing the weight % of B₄C the surface roughness of MMC increases. However, with the addition of 8% B₄C content results in better surface finish when compared to base metal.

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