RESEARCH ARTICLE

RSP Science Hub

International Research Journal on Advanced Science Hub
2582-4376
Vol. 04, Issue 08 August
www.rspsciencehub.com

Check for updates

http://dx.doi.org/10.47392/irjash.2022.051

Challenges, Opportunities and Analysis of the Machining Characteristics in hybrid Aluminium Composites (Al6061-SiC-Al_2O_3) Produced by Stir Casting Method

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Article History

Received: 2 August 2022
Accepted: 23 August 2022

Keywords:

Microstructure;
Machining;
Depth of Cut;
Surface Roughness(SR);
Hybrid Metal Matrix Composite(HMMC)

Abstract

Metal matrix composites of Aluminium are finding increasing applications across a wide range of industries, including the automotive and aerospace industries, amongst others. When a third constituent is added to the metal matrix, the production of the hybrid compound commences. This body of work presents the findings of an investigation into the surface roughness properties of hybrid aluminum metal matrix (Al6061-SiC-Al_2O_3) composites. Some experimental investigations were carried out using a lathe. The stir casting method is a technique employed in the field of liquid metallurgy. In this technique, the base matrix was infused with 4, 8, and 12 percent by weight of SiC and Al2O3 particles, respectively. This allowed for the production of composites. The end-result cast composites were handled with a great deal of care and attention to detail. The parameters such as feed rate, cutting speed, and depth of cut that are known to influence surface roughness were investigated. The findings of the study demonstrated that an increase in feed rate leads to a rise in surface roughness, but an increase in cutting speed leads to a decrease in surface roughness.

1. INTRODUCTION

In the field of materials science, metal matrix composites are one of the more cutting-edge developments in recent history. One of the components of a metal matrix composite(MMC) can be a metal, and the other component can be a different metal or substance, like a ceramic or an organic compound. A MMC always consists of at least two distinct components, and one of those components can be metal. Something that is comprised of at least three distinct materials might be referred to as a "hybrid metal matrix composite." When hybrid matrix metal composites(HMMCs) are being manufactured, the reinforcing material is combined with a metal matrix. During the beginning of the 1980s, a number of automakers carried out extensive research and usability studies on them. In the vast majority of instances, the matrix is made up of a lightweight metal such as aluminum, magnesium, or titanium. Within the matrix is where you'll find the reinforcement material (Monaghan). Reinforcement is not always merely a constructive activity, in the sense that it works to strengthen connections; rather, reinforcement serves the aim of changing the qualities of the material in some way (Singh et al.) . This is not always the case, but there are times when it is. Not only are these innovative materials less heavy than their traditional analogues, but they are also sturdier and more resistant to wear than their predecessors were. In many applications in the aerospace and automotive industries, HMMCs compete with other materials such as super-alloys, ceramics, plastics, and reworked steel parts for the role of the material of choice (Palanikumar and Karthikeyan). HMMCs are very popular in this field because they have all of these desirable qualities and can still work normally at high temperatures. Machining HMMCs is not possible with the use of standard tool materials like high-speed steel because of the rapid pace at which cutting tools become worn out. When working with hard metals, tools will undergo a large amount of wear after just a very short amount of time being machined, and this wear will occur regardless of whether the metal being worked with is blank or coated (Basheer et al.). When it comes to machining MMCs, a number of researchers have found that tools made of polycrystalline diamond (PCD) are the only type of tool material that can guarantee a usable tool life (Boey et al.). This is the case because PCD tools are the only type of tool material that can withstand the high temperatures that are generated during the machining process. PCD is harder than both Al_2O_3 and SiC, and it does not have a chemical tendency to react with the material that makes up the work piece. Diamond particles of a size on the order of microns that are connected to a tungsten carbide substrate make up the PCD cutting tool. This tool is made up of a sintered layer of diamond particles. Experiments were carried out with a variety of cutting speeds, feeds, and depths of cut, and beginning parameters such as surface roughness and tool wear rate were measured. The results of the tests were analyzed and researched in order to explore the influence that a variety of different characteristics had on the processing of HMMC. As seen under a light microscope, the microstructure of the HMMC, Al6061-SiC-Al_2O_3 (wt. 8%) may be seen illustrated in Figure 1.

Extrusion, forging, and rolling are examples of some of the typical metalworking methods that can be used to treat hybrid MMCs. Machining HMMCs using traditional methods is also a possibility; however, PCD tools will almost certainly be required in this process. The objective of these components is to fulfill the function of fortifying this structure, and they are aluminum oxide and silicon carbide. The HMMC composite that was developed for this specific application made use of the liquid state technique, which was one of the three different HMMC manufacturing processes that were available: the solid state, the vapor state, and the liquid state. In this technique, the stir casting method is the one that is utilized. In this technique, reinforcements are stirred into molten metal as the mixture is being mixed (Ranjith et al., "Impact of various reinforcement particles on the density of AA7050 graded aluminium fabricated through stir casting") , and after that, the mixture is left to cool and harden on its own. As can be seen in Figure 2, a hybrid aluminum-MMC called Al6061-SiC-Al2O3 was created with different weight percentages of 2, 4, 6, 8, and 12. For the purpose of this study, we selected weighted samples at the four, eight, and twelfth percent levels.

It is possible to reinforce aluminum composites using particles formed of aluminum oxide (Al_2O_3) or silicon carbide (SiC), but doing so incurs a large cost because of the high machining costs associated with the reinforcements' hardness and abrasive character (Tomac, Tannessen, and O Rasch). MMCs that are reinforced with alumina (Al_2O_3) are notoriously difficult to work with when utilizing standard processing techniques like turning, milling, drilling, and tapping (Durante, Rutelli, and Rabezzana). This is due to the unusually high abrasiveness of these composites. The presence of Al_2O_3 makes aluminum MMCs difficult to machin . This makes the composites tough to machine and leads to quick tool wear, which leads to shorter tool life, which leads to higher tool costs. Another problem is that the combination, once it has been machined, has a surface polish that is not very good. As a consequence of this, the vast majority of research studies investigate the wear behaviors of a variety of tool materials during the machining of aluminum MMCs (C. T. Lane). In order to improve machining, study into the wear characteristics of tools is necessary. This research is vital because research into the wear characteristics of tools is essential. Investigations into machining reveal that the material has a high rate of tool wear, making it difficult to machine. In addition, the quality of the machined surface will deteriorate as a result of tool wear (Sahin, Kok, and Celik). The production cost of tools constructed of cemented carbide that have been coated with titanium nitride

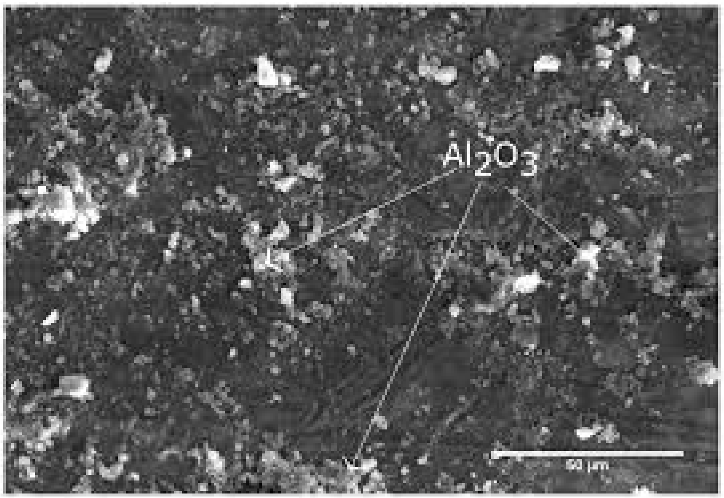

FIGURE 1. **Microstructure of the HMMC (Al6061-SiC-Al_2O_3 (wt.8%))**

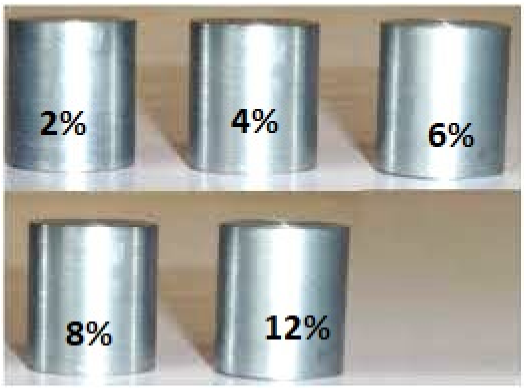

FIGURE 2. **Hybrid aluminium metal matrix composite (Al6061-SiC-Al_2O_3) at different wt.%**

(TiN) or titanium carbide (TiC) is highly costly. This is because the pace at which these tools wear down is relatively high. When utilizing PCD diamond tools, there is less tool wear. Nevertheless, the cost of diamond tools is extremely high. When compared to the performance of PCD inserts of grade 1500, the performance of PCD inserts of grade 1600 offers a greater surface finish (Finn and Srivastava). It is possible for a number of criteria, such as the volume percent, morphology, distribution of the reinforcement phase, and properties of the matrix phase, to have an effect on the overall machining performance (El-Gallab and Sklad). Carbide tools are preferred over HSS tools for roughing, whilst PCD tools are appropriate for finishing work. It is not necessary to use HSS tools. The surface roughness of aluminum metal matrix composites can be significantly affected by three factors: the feed rate, the cutting speed, and the volume percentage of SiC (Yanming and Zehua). A model was developed in order to accurately forecast the level of surface roughness that will be produced by PCD tools during the precise machining of metal matrix composites. This model takes into account the nose radius, as well as the size and amount of reinforcement, the feed rate, and the depth of cut. The coarseness of the machined surfaces is not determined by the feed rate or the cutting edge radius; rather, it is determined by the size of the reinforcements in the composite (Joshi, N. Ramakrishnan, and P. Ramakrishnan). During the machining process, HMMCs produce short cutting chips, the cutting force is mild, and there is a very wide range of machining parameters that may be utilized to mill these materials. In addition, HMMCs generate shorter cutting chips than conventional MMCs. On the other hand, HMMCs are quite abrasive and have the potential to cause rapid tool wear. This can be a problem when working with these materials. The decision made about the PCD grade has the greatest impact on the total life of the tool. Differentiating between different classes of PCD is most commonly accomplished by constructing the PCD layer with diamond particles of varying sizes, measured in microns (Lin, Bhattacharya, and C. T. Lane). This is the method that is most commonly used. The size of the particles ranges anywhere from 2 to 25 micrometers, on average. It has been discovered that the grain size of the diamond has a direct bearing on the density of the diamond. This contributes to an increase in the material's resistance to abrasion (Chandrasekaran and O Johansson). When low-abrasive machining conditions are present, the appropriate PCD grade is chosen by taking into consideration the aspects of tool production and design, in addition to the substance of the workpiece and the machining process itself. The relative stiffness of the reinforcing materials is the key issue that adds to the difficulties of machining HMMCs (Pendse and Joshi). Table 1 gives a quick look at the things that a variety of materials have in common, such as how quickly they can be machined and other things.

After a great deal of investigation, researchers discovered that PCD tools are the only type of tool material that can guarantee a significant amount of service life to the machine operator. PCD has a higher hardness than both Al_2O_3 and SiC (Somu et al., "Synthesis of various forms of carbon nanotubes by arc discharge methods-Comprehensive review") , and it does not have a chemical tendency to react with the material that makes up the work piece. This makes PCD an ideal material for use in cutting and grinding applications. (Kok) The PCD cutting tool consists of a sintered layer of diamond particles with a diameter of a few microns apiece that are bonded to a tungsten carbide substrate. This layer is sintered over a tungsten carbide substrate. The polycrystalline diamond that is used in cutting tools is typically produced in the form of a flat, circular disc. From this disc, pieces of nearly any shape or size can be cut out and brazed to the main body of the cutting tool. Grinding is the process of machining that is done on the PCD in order to acquire the required cutting edge geometry. Sawing, turning, drilling, milling, tapping, reaming, and drilling are only some of the uses for polycrystalline diamond tools. Other applications include milling and reaming. Every one of these implements can be fabricated. PCD can be purchased in a number of different grades, which can be distinguished from one another based on the typical micron size of the diamond particles that are used to construct the PCD layer. When determining which PCD grade to utilize in the majority of instances, factors such as tool life, the quality of the machined surface that is sought, and even, on occasion, certain characteristics of the tool manufacturing process are taken into consideration (Muthukrishnan, Murugan, and Rao). In comparison to PCD tools with a grit size of 10 m, PCD tools with a grit size of 25 m are more resistant to the abrasion that can be induced by micro-machining. An increase in the PCD grain size does not result in an extension of the tool's useful life, but it does result in a significant reduction in the surface quality. The fact that PCD grains with a size of 25 m can be easily dragged out from the cutting edge is the reason why this is the case (C. Lane).

Research that has been done in the past on the machinability of HMMCs has concentrated on studying the impact of machining settings, the properties of HMMCs on tool wear, and the mechanism of tool wear. This was done in order to investigate the difficulties that are associated with machining hybrid MMCs (Singh et al. Joshi, N. Ramakrishnan, and P. Ramakrishnan) . Numerous scholars have done studies and investigations into numerous aspects of the machinability of hybrid MMCs, and as a result, they have arrived at a number of different conclusions as a result of their labors. When turning Al-SiC MMCs (Ranjith et al., "Integrated Taguchi cum Grey Relational Experimental Analysis (GREAT) for Optimization and Machining Characterization of Cryogenic Cooled AA6063 Aluminium Alloys") with PCD and coated tungsten carbide tools, it was discovered that high cutting speeds lower tool life because they cause excessive flank wear. This was the case because high cutting speeds cause PCD and coated tungsten carbide tools to break down. When the speed was slowed down, this impact became more noticeable. They carried out a study on the subject and discovered that raising the feed rate to a higher setting helps reduce the amount of tool wear that occurs over time. When the feed rate of the machine (Singh et al.) is raised, there is a corresponding rise in temperature in the cutting zone. This leads to a weakening of the metallic matrix, which makes it much simpler to extract the SiC particles that are lodged in the work piece as a result of the fact that the matrix has been weakened. It was found that the cut depth affects the life

TABLE 1. **Properties of different materials (courtesy: supplier's data)**

Material	PCD	Al_2O_3	SiC
Elastic modulus (GPa)	800	370	475
Coefficient of thermal expansion (10^{-6} /K)	4.0	6.7	4.2
Thermal conductivity (W/mK)	500	35	120
Density (g/cm^3)	4.1	3.9	3.2
Hardness (GPa)	74	21	29

of PCD cutting tools in a bad way.

A number of studies have come to the conclusion that PCD is an outstanding cutting material that can be utilized in the efficient fabrication of hybrid aluminum MMCs. PCD tools have exhibited higher wear resistance and offered superior surface finishes as compared to carbide or aluminum oxide tools. This is due to the fact that diamond tools possess an extraordinarily high level of hardness and a low affinity for MMC material (Boccaccini et al.). The grain size of the cutting tools used in MMC machining has a significant bearing on the amount of tool wear that occurs during the process (Pravin et al.) . When a tool with a coarse grit has the high abrasiveness that is required for good performance, increasing the grit size can cause the fracture toughness to decrease, which in turn affects the tool's overall performance. This is because the larger the grit size, the more likely it is that the tool will fracture.

In the current study, the researchers are interested in the machining properties of HMMC with PCD cutting tools, as well as the surface roughness and tool wear that occur as a result of machining operations. Alumina (Al_2O_3) has a low thermal expansion coefficient on the order of 6.5-8$\times10^{-6}$/K and a hardness that ranges from 18-23 GPa. Both of these properties are indicative of the material's exceptional strength. The matrix material's hardness, resistance, and density are all increased when Al_2O_3 particles are incorporated into the matrix material (Ganesh and Gupta). This addition also provides dimensional and thermal stability to the matrix material. The best material for the matrix was decided to be Al6061, and the formula called for SiC and Al_2O_3 to be used as dispersoids.

2. EXPERIMENTAL PROCEDURE

2.1. Composite Preparation

The use of a liquid metallurgical process has allowed for the production of cast composites that have improved wettability as well as particle distribution. Before being melted in a graphite crucible, the Al6061 alloy was first in the shape of bars. These bars were subsequently broken into smaller pieces and then placed in the crucible. The percentages of the various chemical components that make up Al6061 are listed in Table 2, which can be found here. A piece of the matrix material was brought up to the required temperature within the crucible, and then it was uniformly agitated by a motor-driven stirrer. Because the temperature was first raised above the liquidus temperature of the aluminum alloy, and then gradually dropped below the liquidus temperature of the matrix material, melting occurred between the solidus and liquidus temperatures. The reason for this is that the temperature was first raised above the liquidus temperature of the matrix material, and then gradually raised above the liquidus temperature of (semi-liquid state). After that, the semi-liquid melt is blended by hand while hot mixtures of SiC and aluminum oxide particles are added to the stage (Somu et al., "A novel Cu-Gr composite electrode development for electric discharge machining of Inconel 718 alloy") . If you combine it first, then it will be much simpler to distribute it uniformly throughout the batter. Following an adequate amount of hand mixing, the molten substance needs to be heated to a temperature that is greater than the temperature at which it becomes liquid. At this point, the mixture needs to be stirred for around 20 minutes at a pace of approximately 500 revolutions per minute on average. Following this step, the slurry is poured into a cast-fixed mold that has already been heated. Multiple iterations of the technique were conducted, each with an increasing wt% disparoid of SiC and Al_2O_3 (two, four, six, eight, and twelve wt%). The apparatus used in the studies to create HMMC is seen in Figure 3, which may be found here (Al6061-SiC-Al_2O_3).

TABLE 2. Chemical composition analysis of Al6061 aluminium

Aluminium 6061alloy (Al6061)	Fe	Si	Mg	Cu	Cr	Mn	Zn	Ti	Others	Al
Composition	0.70%	0.68%	0.85%	0.22%	0.06%	0.32%	0.07%	0.05%	0.15%	Balance

FIGURE 3. The experimental set up for production of hybrid MMC (Al6061-SiC-Al_2O_3) composites

2.2. Experiment

Throughout the course of the investigation, cylindrical MMC hybrid samples were utilized. These samples were mixed with an equal quantity of aluminum oxide (Al_2O_3) and varying amounts (four, eight, and twelve weight percent) of SiC particles, respectively. The following are some instances to take a look at from Table 3. Sample II was chosen for research out of the three HMMC samples (I, II, and III) because the quality of the work piece degrades and machining becomes more difficult when the weight percentage of these elements reaches a certain limit. This limit was determined by the fact that Sample II was the middle of the three samples. As a direct result of this, it was agreed that sample B would be the one to be scrutinized as the source material. The experiment was conducted using three distinct levels of cutting speed; more specifically, the chosen sample was machined on the lathe using a different cutting speed for each of the levels. A 1600 PCD insert was used as the cutting tool during this machining process. Machining was carried out with a number of parameters, the most important of which were cutting speed, feed rate, and depth of cut. During the machining experiments that were carried out under dry machining conditions, a self-centering lathe served as the tool of choice. When we were turning the composite, we used three different cutting speeds that ranged from 15 m/min all the way up to 45 m/min. The feed rates varied from 0.3 to 0.9 mm for each turn of the machine. Machining calls for a depth of cut of 0,5 millimeters, 0.75 millimeters, or 1 millimeter, respectively. We were able to measure the level of surface roughness that the machined component possessed by making use of a "Mitutoyo surface roughness tester." This instrument was quite helpful. For sample II, the average surface roughness value, which was given the number Ra, was found for each processing condition.

3. RESULTS AND DISCUSSION

3.1. Cutting Speed and Average Surface Roughness

Figures 4, 5 and 6 show the change in average surface roughness at different cutting speeds for different depth feeds of 0.50 mm, 0.75 mm and 1.0 mm respectively.

When the cutting speed is raised, there is a general tendency toward a smoother overall average surface roughness of the hybrid material. This occurs despite the fact that the surface of the hybrid material is being roughened. According to the findings of the current study, the SR of the HMMC is at its

TABLE 3. Specimens and their compositions

Specimen	Compositions
I	4% SiC + 4% Al_2O_3 + Al6061 aluminium alloy (rest)
II	8% SiC + 8% Al_2O_3 + Al6061 aluminium alloy (rest)
III	12% SiC + 12% Al_2O_3 + Al6061 aluminium alloy (rest)

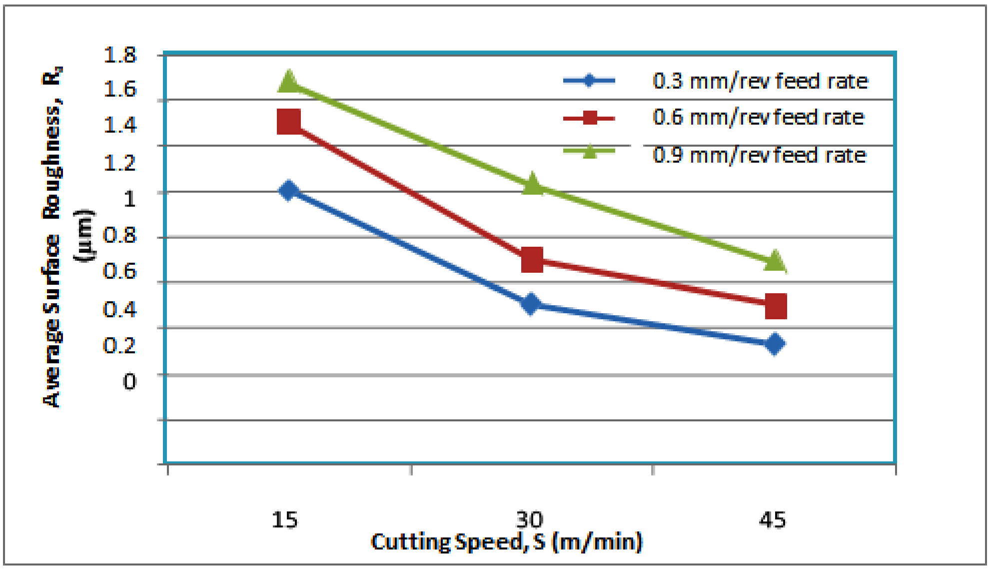

FIGURE 4. R_a Vs Cutting speed at Depth of Cut of 0.50 mm

worst when the cutting speed is set to 15 meters per minute. This is true even when the cutting depth of 0.50 mm is taken into account. The value of the surface roughness starts to decrease when the cutting speed is increased to 30 meters per minute, and it continues to decrease until it reaches its lowest point when the cutting speed reaches its greatest point, which is 15 meters per minute. The surface roughness of the HMMC that was evaluated can be significantly reduced by machining the sample at a feed rate of 0.3 mm/rev and a cutting speed of 45 m/min, assuming a depth of cut of 0.50 mm. This can be seen in Figure 4, which shows that this can significantly reduce the surface roughness of the HMMC that was evaluated, Figure 5 illustrates an abrupt improvement in the surface smoothness when the feed rate was 0.90 mm/rev and the cutting speed was 30 m/min. A feed rate of 0.3 mm/rev results in a surface roughness that is also low. As shown in the previous figure, when the cutting speed goes up, the roughness of the surface goes down.

Figure 6 Demonstrates very clearly that a feed rate of 0.3 mm/rev results in a significant reduction in the surface roughness. After raising the cutting speed to well over 30 meters per minute, there is a discernible improvement in the surface's smoothness. Because of this, the graphs below Figures 4 through 6 show that the average surface roughness can be made a lot better by slowing down the feed rates and speeding up the cutting speeds at the same time.

3.2. Feed Rate and Average Surface Roughness

At a depth of cut of 0.50 mm, it can be shown in Figure 7 that the surface roughness Ra gets worse as the feed rate gets higher. In addition, the surface roughness is greater when cutting at a speed of 15 m/min as opposed to 45 m/min, which results in a lower cutting speed.

Figure 8 depicts the fluctuation of Ra and F at a depth of cut of 0.75mm. This demonstrates that the surface roughness of the hybrid MMC grows almost sharply as the feed rate is increased. In addition, the surface roughness is greater when the cutting speed is 15 meters per minute, but it is lower when the cutting speed is 45 meters per minute. This demonstrates, once more, that the surface roughness rises as the feed rate rises, but it falls when the cutting speed rises.

Figure 9 also displays the variation in average surface roughness across a variety of feed rates, all with

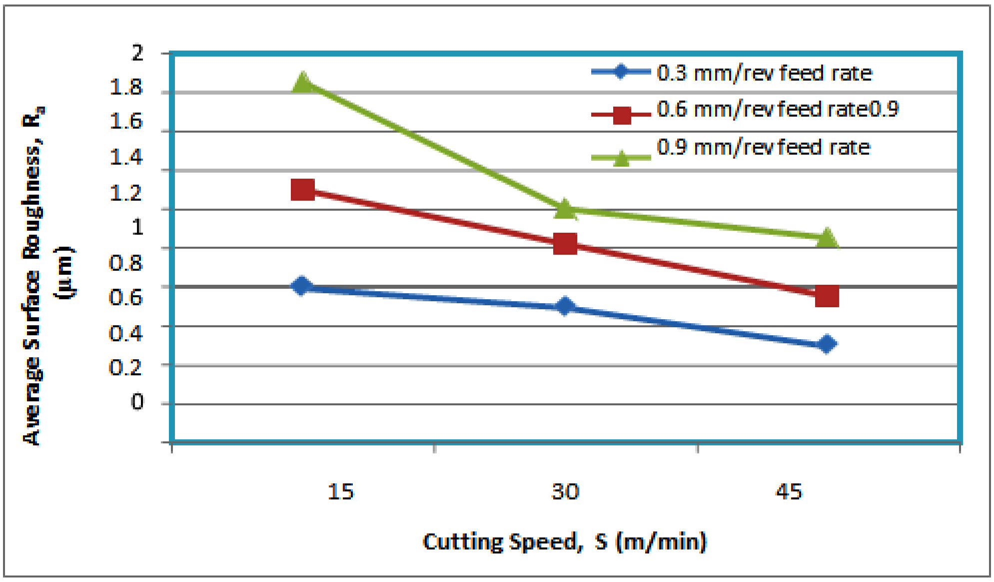

FIGURE 5. R_a **Vs Cutting speedat Depth of Cut of 0.75mm**

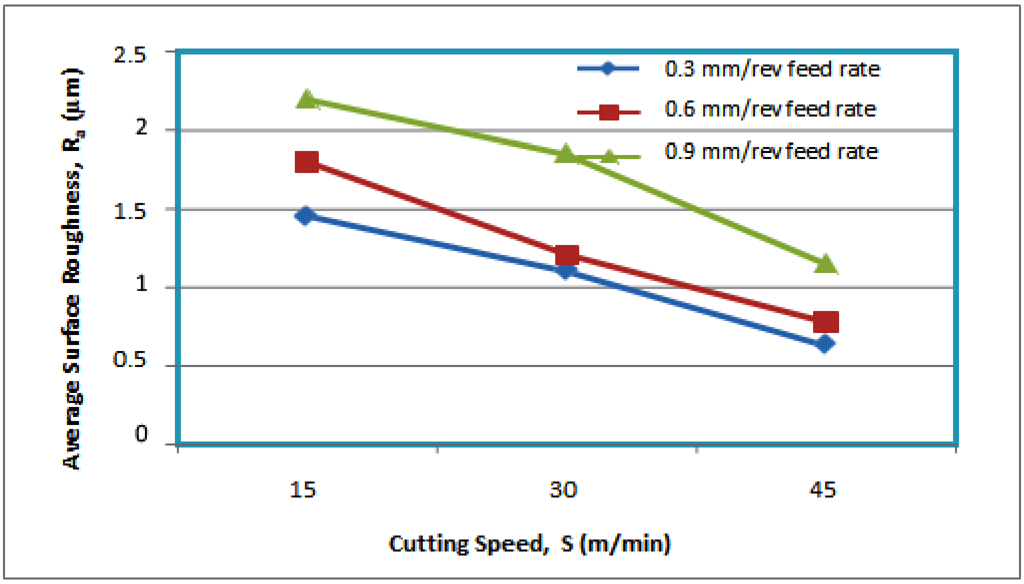

FIGURE 6. R_a **Vs Cutting speedat Depth of Cutof 1.0 mm**

a depth of cut of 1 mm. This graph also demonstrates that the Ra value is at its minimum when the feed rate is set to 0.3 mm/rev and the cutting speed is set to 45 m/min. As a result, it is possible to draw the obvious conclusion that faster cutting speeds and lower feed rates are preferable with less surface roughness, thanks to the diagrams found under Figures 7 to 9.

3.3. Opportunities and Challenges

The demand for materials that have been engineered is the primary impetus behind the development of more advanced materials such as super alloys, ceramics, and composites. Among these more modern materials, composites stand out thanks to their unique characteristics, which include an increased resistance to wear, a high specific strength, a specific strength and cost ratio. Because of this, researchers are encouraged to develop composites employing an aluminum matrix with a variety of different reinforcements. The application of the optimal mode that was found through this research has the practical advantage of enhancing the surface of hybrid composites in terms of their resistance to wear and their mechanical properties. The microstructures of each surface hybrid composite demonstrated that the reinforcing particles (SiC and Al_2O_3) are distributed

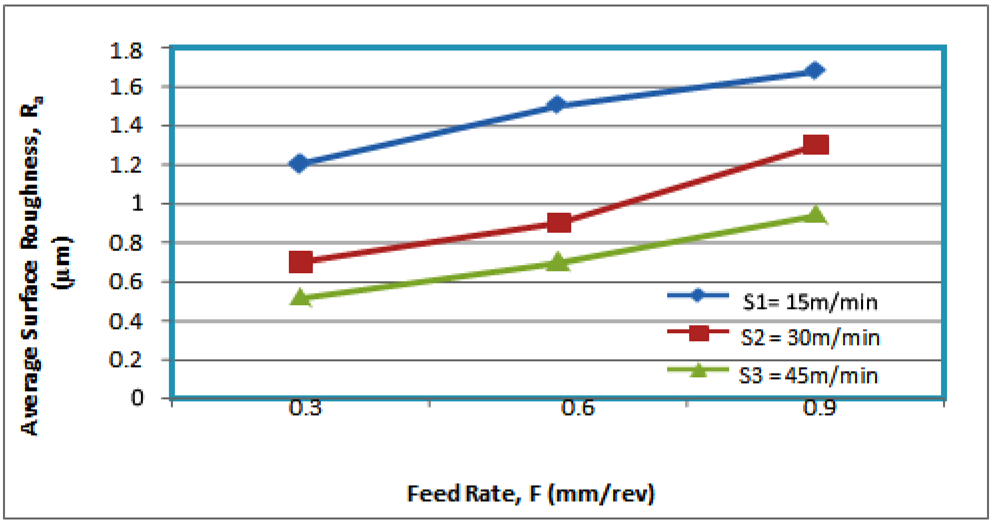

FIGURE 7. **R_a Vs F at Depth of Cut of0.50 mm**

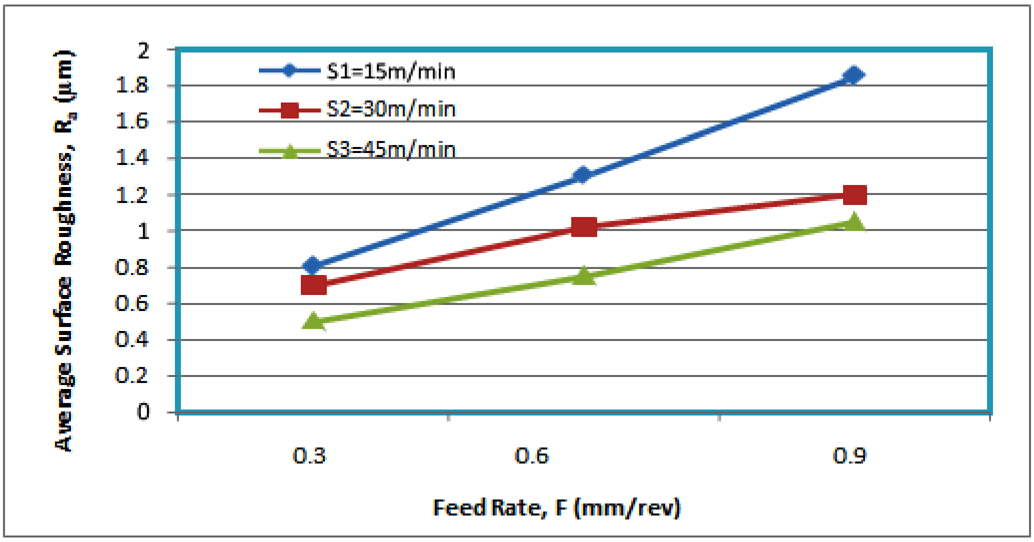

FIGURE 8. **R_a Vs F at Depth of Cut of0.75 mm**

uniformly across the nugget zone. A rise in microhardness under ideal conditions was also discovered, which can be attributed to the presence of solid particles composed of SiC and Al_2O_3, which have a pinning effect. It was discovered that the reinforcing particles (i.e., SiC and Al_2O_3) were reduced in size compared to the original particles (less than 5 micrometers). Microstructures were found to have a correlation with both the wear that was detected and the mechanical qualities. Because of their high strength-to-weight ratio, wear resistance, cost-to-strength ratio, and other desirable properties, hybrid composites are used in many industries, such as the aerospace, marine, defense, and automotive industries.

A number of reinforcements, including SiC and Al_2O_3, have already been added, and others are currently in the process of being added. There have been efforts directed toward the creation of HMMCs. In order to manufacture composites via stir casting, it is necessary to distribute harsh abrasives in a homogeneous manner across the metal matrix. One can't say enough about how important it was that the speed and length of stirring affected how the particles were spread out in the cast MMC.

4. CONCLUSION

When machining HMMCs, various experiments are carried out in order to investigate the impact of cutting settings on the SR of the finished product. The following are some of the inferences that can be made based on the findings of the experiment:

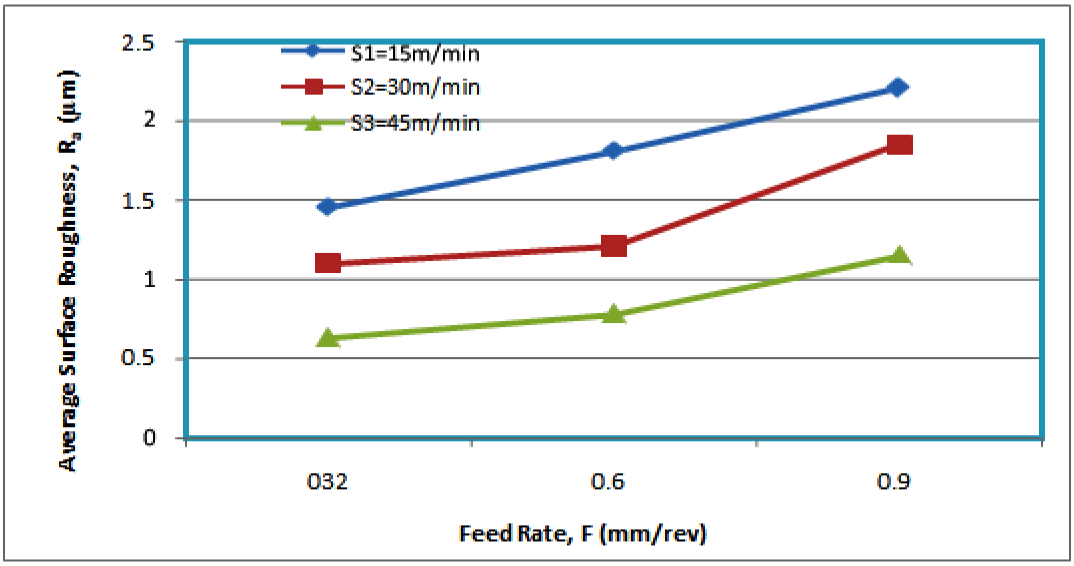

FIGURE 9. R_a Vs F at Depth of Cut of1.0 mm

• When the cutting speed goes up to 45 meters per minute (m/min), the average SR of the evaluated HMMC sample II goes down.

• The SR is reduced when the cutting speed is increased, and the opposite is true when the cutting speed is decreased.

• When HMMCs are being machined, the feed rate is an extremely critical aspect that plays a role in determining the SR. The findings demonstrated that an increase in the feed rate caused a corresponding rise in the SR.

• The greatest results can be achieved by cutting at a speed of 45 meters per minute with a feed rate of 0.3 millimeters per revolution and a depth of cut of 0.5 millimeters. This combination of settings will produce the best possible results.

• A surface with a low average roughness can be achieved by using a medium cutting speed, a moderate feed rate, and a shallow depth of cut. These settings should be used in conjunction with one another.

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Embargo period: The article has no embargo period.

To cite this Article: Syed, Shoeb Ahmed, Steve Ales, Rajesh Kumar Behera, and Kamalakanta Muduli. "**Challenges, Opportunities and Analysis of the Machining Characteristics in hybrid Aluminium Composites (Al6061-SiC-Al_2O_3) Produced by Stir Casting Method**." International Research Journal on Advanced Science Hub 04.08 August (2022): 205–216. http://dx.doi.org/10.47392/irjash.2022.051