Developing hybrid composites of Al5083-carbon nanotubes and fly ash by friction stir processing: machining studies

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Abstract. In the present work, hybrid composites of Al5083-reinforced with CNT and fly ash were produced by friction stir processing (FSP) successfully. The microstructural observations indicated bands like structure in the stir zone. Higher hardness was noticed for the composites due to the grain refinement resulted from FSP and also due to the presence of reinforcements (CNT and fly ash). The variations were observed as higher within the measured hardness for the composites which can be claimed to the variations in the concentration of the reinforcements across the stir zone. Machining studies were done by carrying drilling experiments on the composites as well as on base material. Higher cutting forces were recorded for the composites. Additionally, decreased cutting forces were observed for both the base material and the composite with increase in the cutting speed. The overall observations suggest that Al5083-CNT-fly ash hybrid composites can be successfully developed by FSP which exhibit better mechanical properties and machining behaviour.

Keywords: FSP, MMCs, hybrid composites, machining, hardness.

1. Introduction

Metal matrix composites (MMCs) are a category of modern engineered materials in which matrix is a metal dispersed with suitable fibre materials in the form of continuous or discontinuous phase [1]. MMCs exhibit better properties than their constituting phases. Several properties are influenced by the type of dispersing phase, quantity, size and shape of the reinforcement. Mechanical properties, wear and corrosion properties, machining behaviour are the important bulk properties of MMCs influenced by the reinforcements [2]. If more than one dispersing phase is used in developing composites, such materials are called as hybrid composites. Each reinforcement phase serves a specific purpose and when combined with another dispersing phase, hybrid properties can be achieved.

H. Patle et al. [3] reinforced Al7075 alloy with B2C and MoS2 to develop hybrid composite by FSP (friction stir processing) and demonstrated improved mechanical properties and wear properties.
Particularly, presence of MoS\textsubscript{2} reduced the coefficient of friction due to the lubrication effect attained in the hybrid composite. Zayed et al. [4] developed hybrid composites of Al5083 dispersed with SiC and Al\textsubscript{2}O\textsubscript{3} phases. Improved hardness up to 30% was measured for the hybrid composite and higher wear resistance was observed with the composite containing 50% SiC and 50% Al\textsubscript{2}O\textsubscript{3}. Similarly, Heiderpour et al. [5] also produced surface composites of Al5083-Al\textsubscript{2}O\textsubscript{3}-TiO\textsubscript{2} by FSP. Due to the dispersed phases improved ultimate tensile strength was observed for the hybrid composite. Furthermore, decreased coefficient of friction and better wear resistance were demonstrated for the hybrid composite. Machining composites arise critical issues unlike machining pure metals and alloys. Due to the presence of different phases with diversified properties, composites may exhibit abnormal behaviour during machining. This kind of machining behaviour depends on the type of composite and the fraction of the composite dispersed in the matrix. In our earlier work, due to the addition of graphene into Al5083 alloy, lower cutting forces were recorded which was claimed to the solid lubricant effect imparted into the composite due to the addition of graphene [6]. Understanding the machining behaviour of composite is crucial as most of the times, machining is a compulsory process to develop structures made of composites.

Among the available aluminium alloys, Al5083 contains magnesium as the main constituting alloying element. The applications of Al5083 can be found in manufacturing marine structures and components [7]. On the other hand, carbon nanotubes (CNTs) as dispersing phase have been widely used in developing MMCs due to their potential to promote better properties [8]. Fly ash is a waste product results from the coal burning in the thermal power plant which contains SiO\textsubscript{2} and Fe\textsubscript{2}O\textsubscript{3} phases. Hence, in the present work, Al5083 alloy has been chosen as matrix material and combination of fly/CNTs reinforcements were used to produce composites by FSP route. Microhardness measurements were carried out for the composite and also subjected to machining by conducting drilling experiments to assess the machining behaviour of the composite.

2. Materials and methods

AL5083 aluminum alloy sheets of size 100 X 100 X 5 mm (Venku metals, Hyderabad, India) were used as base material. CNTs (single walled) were procured from nano Wings, Khammam, India. Fly ash was collected from Dr Narla Tata Rao Thermal Power station, Vijayawada, India. In order to develop hybrid composites, equal amounts of CNTs and fly ash (50% and 50%) were filled in the grooves machined on the surface of the workpieces. The grooves were produced on the surface of the workpiece of width 1 mm and depth 2 mm. The workpieces were then fixed on a specially fabricated attachment on the vertical milling machine work table. The milling machine is an automated type which can be given auto feed and speed. Then the FSP tool was fixed in the spindle of the milling machine. In the present study, the spindle of the milling machine does not have the vertical axis tilting facility and hence, the tool tilt angle was assumed to be 0 degrees. The geometrical dimensions of FSP tool are mentioned in our earlier work. Based on the preliminary experiments, processing was completed at 1400 rpm and 25 mm/min processing parameters. Before starting the process, the grooves were closed by using an FSP tool without having a pin to eliminate the escape of the filled reinforcing phases from the grooves. Then, FSP process was carried to develop the surface MMCs. Fig 1 shows the schematic illustration of composites development by FSP.

After processing, specimens were cut across the processed zone and also from the base materials to investigate the microstructure and micorhardness. For microstructural observations, the samples were polished as per the standard metallographic procedure and chemically etched the polished surfaces with Keller’s reagent. Then the optical microscope images (Leica, Germany) were obtained. Vickers indentation method (Omni Tech, India) was adopted to assess the hardness of the samples. Machining experiments were done by drilling holes in base alloy and the composite to study the machinability. The workpieces were fixed on the load cell (Kestler, Germany) which was fixed on the work table of
the drilling machine. Drilling of holes was done by using a 6 mm dia thrust drill bit at two different rotational speeds and two feed rates. No lubricant was applied during the machining experiments. While drilling the composites, holes were produced in the middle of the stir zone. Measurement of cutting forces was started when the tool tip touched the workpiece surface and continued for a few seconds.

![Fig 1 Schematic illustration of developing surface composites by FSP.](image)

3. Results and discussion

From the macroscopic observations, defect free stir zone was observed after FSP. Fig 2 shows the microstructure of Al5083 alloy and produced composite. The base alloy has a typical microstructure that contains solid solution grains and intermetallics at the grain boundaries. The microstructure of composite has combination of gray and white regions which suggest the presence of reinforcements (CNTs and fly ash). During FSP, the material that is stirred within the nugget zone contains mixing of reinforcement and base material and results in a band like structure as shown in Fig 2 (b). This is similar to earlier reports where appearance of bands in the composites produced by FSP is a common finding. In the present work, CNTs and fly ash reinforcement has been incorporated within the matrix and the combination of dark and bright regions were appeared in the stir zone.

![Fig 2 Microstructural observations: a) Al5083 and b) composite](image)

The microhardness measurements obtained for the samples are presented in Fig 3. From the average hardness values, increased hardness can be noticed for the composite and the increment is significant.
compared with Al5083. The distribution of the hardness within the composite was also observed as higher within the stir zone due to the presence of reinforcement and also due to the smaller grains which is usually found in FSPed materials.

Fig 3 Microhardness data: a) average hardness values and b) hardness distribution of the samples.

Fig 4 Cutting force profiles of the composites recorded during the drilling experiments: a) 120 rpm with 42 mm/min feed, b) 120 rpm with 15 mm/min feed, c) 300 rpm with 42 mm/min feed and d) 300 rpm with 15 mm/min feed.

The machining studies from the drilling experiments revealed that at the increased rotational speeds decreased cutting forces were observed. This can be understood by considering the generation of higher heat due to the increased RPM during drilling in the machining zone. Compared with the base alloy [9], the mean cutting forces were observed as slightly increased for the composites. This can be ascertained to the role of incorporated reinforcements into Al5083. The variations within the cutting forces were also observed as higher in the composites. During the machining of composites, presence of different phases leads to different level of resistance against the drill bit. Therefore, the cutting
forces are observed with more variations. The preliminary studies from the Al5083 composite with CNTs and fly ash demonstrates higher hardness. Furthermore, higher cutting forces with more variations are important observations which help to assess the machining behaviour of the composite.

4. Conclusions

In the present work, hybrid composites of Al5083 dispersed with CNTs/fly ash were fabricated through FSP. Defect free stir zone was observed in the FSPed composite. Increased hardness due to the grain refinement and incorporated CNT and fly ash was measured for the composites compared with the base alloy. Machining studies by conducting drilling experiments demonstrated the role of added reinforcement to increase the cutting forces during drilling the composites. Variations within the measured cutting forces were also observed as higher in the composites due to the presence of different phases. The preliminary observations suggest that by incorporating CNTs and fly ash, Al5083 based structures can be fabricated with ease of machining with improved mechanical properties.

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