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Original Article

Influence of dislocation density on the residual stresses induced while machining Al/SiC/RHA hybrid composites

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ABSTRACT

The present study aims at finding the residual stresses on aluminum hybrid composites during turning operation. The composites with varying percentage by weight reinforcement of 2, 4, 6 and 8 RHA and SiC in equal proportions were fabricated using two stage stir casting process. X-ray diffraction was used to study the residual stresses on the surface layer of the machined surface. It was observed that the residual stresses generated during casting were considerably larger when compared to the stresses generated during machining of composites. It was also noticed that the residual stresses were found to decrease with the increase in the reinforcement and increases with the increase in cutting speed. The related mechanisms are explained and presented in this work.

1. Introduction

Machining processes such as milling, turning, and grinding are important aspects of production. Safety and reliability are vital to assess the quality of the product. The residual stresses found in metals are mainly generated in the final steps of machining process and are also dependent upon the machining conditions. They have a significant effect on the performance of a part. Lower values of residual stresses are very much required for the present day scenario as the mechanical behavior of any material is affected by the thermal residual stresses. The main reasons of residual stresses initiation in machining operations are mechanical and temperature impacts, which change the subsurface physical and mechanical properties. Their influence depends to a large extent on the machining conditions, mainly selected cutting parameters. However, the residual stresses generated after machining the composites was mainly due to the difference in thermal expansion coefficient (CTE) between the reinforcement and the matrix. The magnitude of thermal residual stresses developed is related to many variables, including the type of reinforcement, volume fraction, the diameter of the particulates and aspect ratio.

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As the composite technology gains its importance in the present day scenario, the study of machinability and residual stresses induced while machining the composites is of importance. Arsenault and Taya [1] had investigated the residual stresses induced in the composite and the results confirmed that the stresses induced are due to the mismatch of thermal expansion coefficients between the matrix and the reinforcement soon after the metal matrix composite cools down from high temperatures. From the works of Henrikson [2] the residual stresses induced were found to be more tensile in nature when machining the ductile materials. Liu and Barash [3] focused on various aspects of the machining process that effect the residual stresses produced. They found that the four variables, namely the length of the shear plane, tool flank wear, the shape of the cutting edge and the depth of cut to determine the pattern of the residual stresses on a machined surface. Bouafia et al. [4] observed experimentally the effect of particle spacing, particle volume fraction, particles interaction and particle shape on the level of residual stress. The results show that a low volume fraction of SiC resulted in a low amount of residual stress and in a strong level in particle. His work also confirmed that the level of internal stresses as well as the particle size was increased with an increase in the temperature. Jang [5] studied the surface residual stresses as a function of machining speed, feed rate, and depth of cut, tool geometry and coating for turning of AISI 304 stainless steel. They found that the surface of the work piece was in a state of plane stress with the principal axes directions close to the hoop and axial directions. Their results confirmed that tool sharpness has the largest effect on the residual stress. Hu and Weng [6] reported that thermal residual stresses generated after cooling and their influence on the subsequent deformation behavior depends significantly on the aspect ratio of the inclusions. His study is based upon secant moduli approximation and a new homogenized effective stress to characterize the plastic state of the matrix. He successfully studied the influence of the thermal residual stress on the deformation behavior of a composite with a new micro-mechanical method. Ganev et al. [7] studied the impact of cutting conditions on residual stresses in the case of plain milling. They observed that the effect of cutting is pronounced on the sub-surface values of residual stresses. They concluded that there was an impact on the cutting forces due to the difference in temperature fields in the cutting zone. Thermal residual stresses, which are developed due to the difference of the coefficients of thermal expansion between the matrix and the reinforcement during the fabrication process, was analytically investigated on the elastoplastic behavior of the composites by Liu and Sun [8]. Relationships between the thermal residual stress state and macroscopic mechanical properties of the composites are discussed effectively by Mei [9]. The residual stresses induced in composites when cooling down from the processing temperature were determined using a cylinder model and using a finite element computer program by Bobet and Lamon [10]. The influence of factors such as interphase thickness and uncertainty in interphase properties including young's modulus and coefficient of thermal expansion was analyzed. The study of machinable SiC/Gr/Al composites was done by Leng et al. [11]. Their study confirmed that the presence of graphite particulates acts as a solid lubricant, which promotes chip formation during cutting, resulting in an improved machinability.

Table 1 – Chemical composition of A356.2 Al alloy matrix (wt.%).

Si	Fe	Cu	Mn	Mg	Zn	Ni	Ti
6.5–7.5	0.15	0.03	0.10	0.4	0.07	0.05	0.1

In the present work Al/SiC/RHA hybrid composites were fabricated and the residual stresses were determined on the foundry composites and the samples which were machined under different machining conditions. The results were compared and analyzed. Rice husk ash (RHA) was considered as a reinforcement in the present work as RHA is one of the inexpensive and low density reinforcements available abundantly throughout the world. RHA contains above 90% of silica, which makes the possible use of it as a reinforcement of widespread applications. As RHA is an agricultural waste byproduct the utilization of RHA has an additional benefit for decreasing the pollution. Siva Prasad et al. [12,13] studied the mechanical behavior and tribological characteristics of Al/RHA composites and the results show improved mechanical and tribological properties compared with the base alloy.

2. Experimentation

In the present study, A356.2 aluminum alloy was considered as the matrix material, RHA and SiC particulates as reinforcement with an average size of 25 μm and 35 μm respectively. The chemical composition of A356.2 and RHA are presented in Tables 1 and 2 respectively. The detailed fabrication process of the composites was presented in earlier works [12]. The residual stress components for A356.2 alloy and its composites were measured using PANalytical X-Pert Pro MRD system. The different experimental conditions considered are presented in Table 3. The theoretical basis has been expanded to allow determination of the full stress tensor using XRD. It is a well known fact that the stresses cannot be found directly, and hence, the strain in a set of lattice planes and in a certain direction is observed as a shift of the 2θ angle of the diffraction peak. The peak shift is recorded as a function of the sample tilt angle ψ in the strained sample at Φ angle and then residual stresses are calculated using elasticity theory. The samples for foundry composites were cut using a hack-saw to measure the residual

Table 2 – Chemical composition of RHA.

Constituent	Silica	Graphite	Calcium oxide	Magnesium oxide	Potassium oxide	Ferric oxide
%	90.23	4.77	1.58	0.53	0.39	0.21

Table 3 – X-ray diffraction experimental conditions.

Target	Cobalt
Wave length (A_0)	1.78901
Filter	Iron
Current (mA)	40
Voltage (kV)	45
Goniometer tilt	ψ
Diffraction angle (deg)	≈99°
Number of Ψ angles	−45° to +45°
Number of Φ angles	0°, 45° and 90°

Table 4 – Cutting conditions.

Cutting tool	Cemented carbide (SNMG 120408)
Tool holder	CTANR 2525-M16
Cutting speed (m/min)	40, 60, 100, 140 (varying)
Feed (mm/rev)	0.2
Depth of cut (mm)	0.5
Lubrication	Dry

stresses in order to eliminate the stresses developed during machining. Fabricated hybrid composite cylindrical bars of dimensions Ø 35 mm × 350 mm are turned on medium duty lathe of spindle power 2 kW. All the working and cutting conditions are outlined in Table 4. Before the machining, the test specimens were annealed and then pre-machined with 1 mm cut to remove any possible surface irregularity and to ensure a similar surface condition for all the specimens. The JSM-6610LV scanning electron microscope was used to study the microstructure of the Al/SiC/RHA composites.

3. Results and discussion

The scanning electron micrograph of 6% reinforced hybrid composite was shown in Fig. 1. From the micrograph, uniform distribution of the reinforcements was observed in the matrix alloy. Fig. 2 shows the comparison of residual stresses (radial) between the foundry composites and machined composites at a cutting speed of 40 m/min. It was observed that the residual stresses induced in foundry composites are

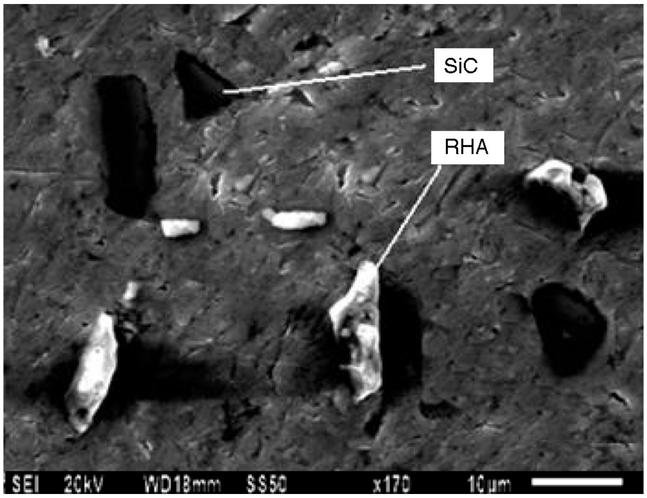

Fig. 1 – Scanning electron micrograph of 6% SiC/6%RHA hybrid composite.

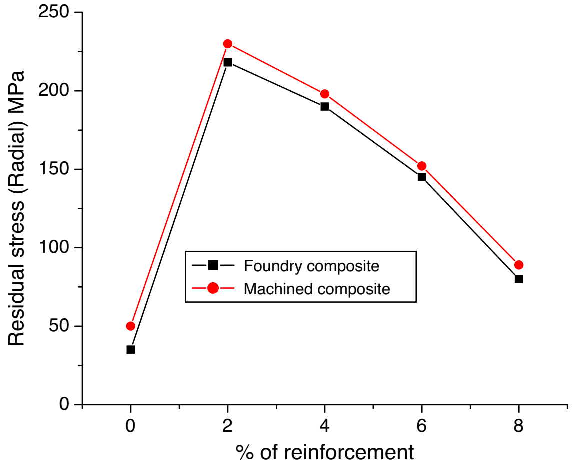

Fig. 2 – Comparison of residual stresses between foundry composites and machined composites.

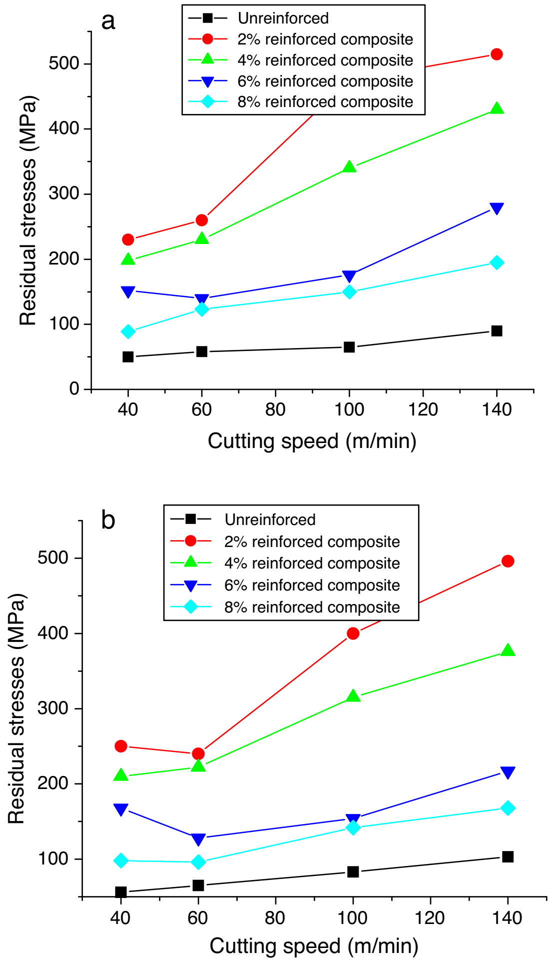

Fig. 3 – Variation of residual stresses with cutting speed: (a) radial and (b) circumferential.

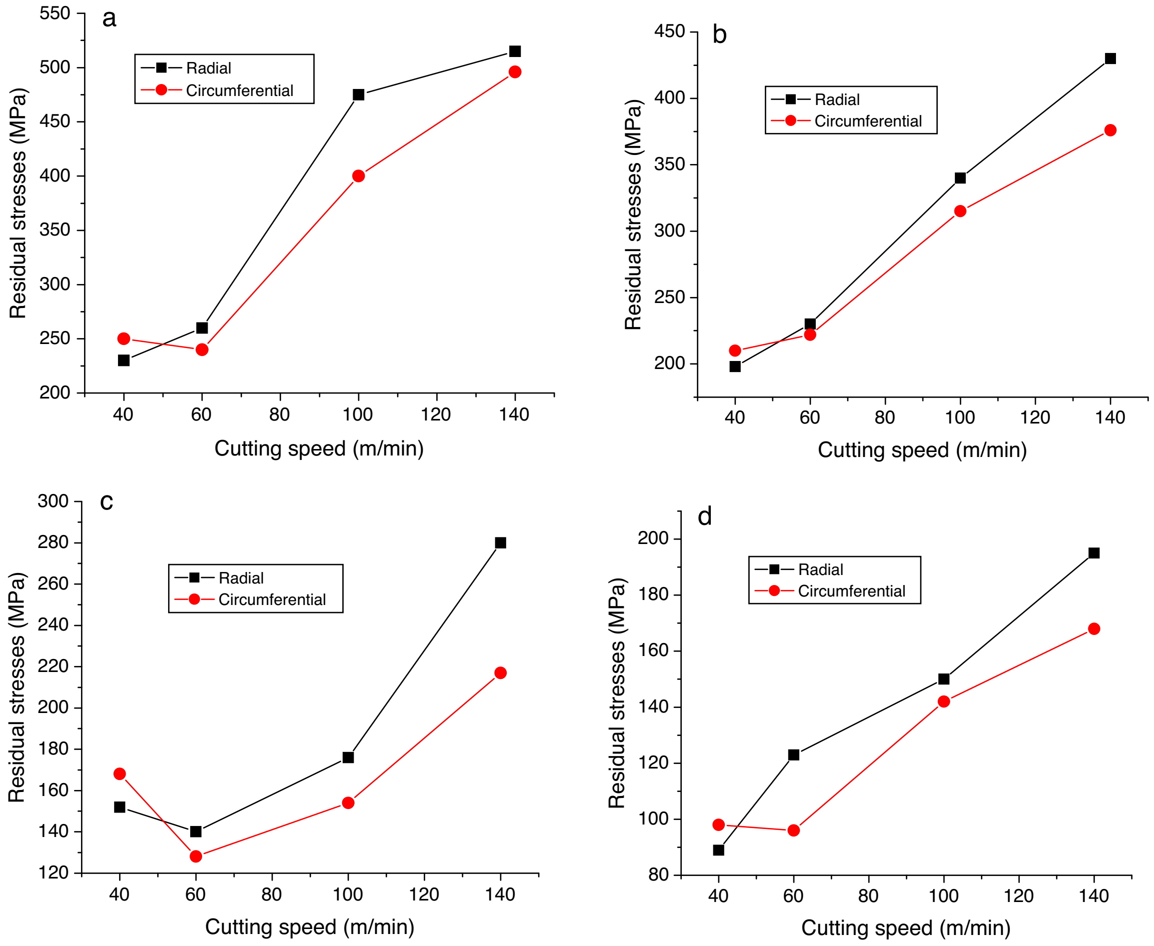

Fig. 4 – Comparison of radial and circumferential stresses: (a) 2%, (b) 4%, (c) 6%, and (d) 8%.

significant and a marginal difference in residual stresses was reported for machined composites. This can be explained as follows.

The residual stresses developed on the machined surface can be due to the (i) thermal residual stresses induced during fabrication of composites and (ii) residual stresses induced during machining of hybrid composites. The main contribution of the residual stresses was due to the thermal residual stresses, which arises due to the thermal mismatch between the CTE of the reinforcement and the matrix. During fabrication the aluminum matrix composites experience a temperature difference of about 630 °C and hence large residual stresses are induced.

The variation of radial and circumferential residual stress for unreinforced and hybrid composite is shown in Fig. 3a and b respectively. From Fig. 3a it was observed that the radial residual stresses decreases with the increase in the % of reinforcement. Also, it could be observed that the radial residual stresses increase with the cutting speed. All the residual stresses were found to be tensile in nature and this is in agreement with the earlier works reported by Henrikson [2]. An almost similar trend has been recorded for circumferential residual stress. The decrease in residual stresses with the increase in the % of reinforcement can be attributed to the following reasons.

3.1. *Dislocation density*

Lower dislocation densities in the Al matrix enable more plastic flow. Hence the decrease in residual stress for the composite can be attributed to the increase in the dislocation density due to the difference in coefficient of thermal expansion (CTE) of the reinforcement and matrix alloy. The CTE values of A356.2 alloy, RHA and SiC particulates are $21.4 \times 10^{-6}/°\mathrm{C}$, $10.1 \times 10^{-6}/°\mathrm{C}$ and $4.3 \times 10^{-6}/°\mathrm{C}$ respectively [12]. Due to this difference in CTE the dislocation density generated can be quite significant at the interface and can be predicted using the following equation:

$$\rho = \frac{B\varepsilon V_r}{bd(1 - V_r)} \tag{1}$$

The empirical relation for dislocation density can be modified for hybrid composites as

$$\rho = \frac{B\varepsilon(V_{\mathrm{RHA}} + V_{\mathrm{SiC}})}{bd(1 - (V_{\mathrm{RHA}} + V_{\mathrm{SiC}}))} \tag{2}$$

where B is a geometric constant, ε is the thermal mismatch strain, V_{RHA} and V_{SiC} is the volume fraction of the RHA and SiC particulates respectively, b is the Burgers vector, and d is the grain diameter of reinforcements. Based on Eq. (2) the

Table 5 – Variation of dislocation density with % of reinforcement.

S. no.	Weight (%) of reinforcement	Estimated dislocation density, ρ (m^{-2})
1	0.0	–
2	2.0	17.31×10^{11}
3	4.0	21.32×10^{11}
4	6.0	23.99×10^{11}
5	8.0	30.82×10^{11}

dislocation density was calculated with an assumption for the Burgers vector of 0.32 nm for Al [12] and are tabulated in Table 5. From Table 3 it was observed that the dislocation density increases with the increase in the % of reinforcement. As low dislocation density enables more plastic flow, it may be concluded that residual stress variation is inversely proportional to the dislocation density.

3.2. *Machining conditions*

The base material is subjected to high stresses by the cutting tool leading to non-homogenous plastic deformation. The increase in the cutting speed corresponds to an increase in strain rate and temperature. The kinetics of plastic flow of the aluminum matrix are highly dependent on the cutting conditions. Plastic deformation reduces the depth of the plastically deformed zone by restraining the plastic flow of the material. While machining hybrid composites the temperature at the tool and workpiece interface reaches 120 °C at maximum cutting speed due to the plastic deformation and friction between the tool flank face and the work piece. This results in softening of the matrix and upon removal of the cutting load residual stresses are induced on the machined surface. The residual stresses induced while machining was probably due to the dislocations formed because of the temperature gradient before and after the removal of cutting load. However, this contribution of residual stresses is much lower when compared to the residual stresses during fabrication. Fig. 4a–d shows the comparison of radial and circumferential stress for 2, 4, 6, and 8% hybrid composites. From the plots it was observed that circumferential stress is more than radial in all cases at a cutting speed of 40 m/min. However, as the % of reinforcement increases the radial stresses are observed to be dominant. Also, as the cutting speed increases the radial stresses tend to increase for almost all cases. As the author is more interested to study the effect of dislocation density on the residual stresses induced while machining, a detailed study should be performed to investigate this behavior and hence these variations are not studied in the present work.

4. Conclusions

X-ray diffraction was used to measure circumferential and radial stresses for both foundry and machined hybrid composite specimens. It was noticed that foundry composites have significant residual stresses induced due to the large difference in CTE between the reinforcement and the matrix. The residual stresses tend to decrease with the increase in the reinforcement. The reduction in residual stress values of the composite is due to the increase in the dislocation density with the % increase in reinforcement. It was concluded that samples with 8% reinforcement exhibited low residual values when compared to samples with 2, 4 and 6% reinforcement. This may be attributed due to the plastic deformation, which gets reduced with the increase in the dislocation density. Cutting conditions play a marginal role in influencing the residual stresses.

Conflicts of interest

The authors declare no conflicts of interest.

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