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Milling-induced damage characteristics of 70wt% Si/Al alloy

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Abstract

High-mass fraction silicon-aluminium (Si/Al) alloy (mass fraction of Si is larger than 30wt%), renowned for its excellent thermal conductivity and soldering performance, finds extensive application in the encapsulation shells of electronic components. However, the main challenges in machining Si/Al alloys stem from their high hardness, brittleness, and heterogeneity, resulting in poor surface quality and significant tool wear. In this work, milling-induced damages of 70wt% Si/Al were analyzed. K9 glass was selected as a reference group to reveal the damage characteristics caused by the heterogeneous of Si/Al alloy. In addition, the cutting force and machined surface roughness were investigated. The results show that brittleness and plasticity coexist in Si/Al alloy. The brittleness of silicon particles leads to the formation of pits and cracks on the machined surface, while the high ductility of aluminium contributes to the occurrence of burr defects. With the increase of feed rate, machined surface roughness of Si/Al alloy initially decreases and then increases. This study provides a technical guidance for the efficient machining of heterogeneous brittle materials.

Keywords: 70 wt% Si/Al alloy, heterogeneous brittle material, milling-induced damage, cutting force, surface roughness

1. Introduction

There is an ever increasing demand for electronic packaging materials exhibiting high thermal conductivity, low expansion coefficient, and excellent soldering characteristics [1]. 70wt% Si/Al alloy is well-suited to meet the exacting packaging requirements. However, the widespread application of 70wt% Si/Al alloy faces considerable impediments due to severe damage incurred during machining, primarily attributed to the substantial presence of high-hardness and brittleness silicon particles within the material. The microstructure of 70wt% Si/Al is shown in Fig. 1.

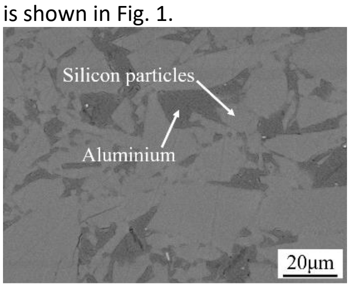

Figure 1. Microstructure of 70wt% Si/Al alloy

70wt% Si/Al alloy is a perfect example of a heterogeneous brittle material prone to diverse forms of machining damage under the ultrahigh stress-strain conditions inherent during milling processes. Niu et al. [2] involved Hopkinson bar tests, demonstrating the material deformation process under one-dimensional stress conditions and establishing a constitutive equation, thereby laying a theoretical foundation for the cutting of Si/Al alloy. In addition, Zhao et al. [3] explored the influence of cutting edge on the machining damage of the 70wt% Si/Al alloy, furnishing valuable technical guidance for tool selection.

While research on hard particle-reinforced aluminium-based materials has garnered significant attention, there remains a notable lack of comprehensive investigations into the intricate damage mechanisms specific to the high-mass fraction Si/Al material. This study adopts a comparative approach, utilizing a homogeneous brittle material—glass as a reference group, to analyze the influence of feed rates on the cutting forces and surface roughness of 70wt% Si/Al alloy. In addition, the milling-induced damages arising from the inherent heterogeneity of the 70wt% Si/Al alloy material was investigated.

2. Experimental configuration

In this work, 70wt% Si/Al alloy samples of dimensions 40 mm × 30 mm × 10 mm were selected as workpieces. K9 glass with the same size were set as the reference group. The milling tool with cutting-edge radii of 15 µm were homemade double-flute polycrystalline diamond (PCD) flat-end mills. The detailed parameters of the tool are listed in Table 1.

Table 1. Detail parameters of the milling tool

Diameter *d* (mm)	Radial rake angle γ (°)	Radial clearance angle α (°)	Helix angle *h* (°)
6	3	10	0

The schematic of the experimental setup is shown in Figure . Dry milling experiments were carried out on a three-axis high-precision machining centre (MMP 2522, Kern, Germany), and all the experiments were down-milling. In addition, according to previous cutting tests, the feed rate plays an important role in affecting the quality of the machined surface in milling of 70wt% Si/Al. The detailed cutting parameters are listed in Table 2.

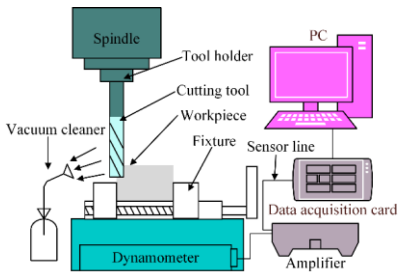

Figure 2. Schematic diagram of experimental setup

In addition, a dynamometer (9119AA1, Kistler, Switzerland) was utilized to measure the cutting force signal, recorded using cDAQ system of Nation Instruments. The machined surface roughness was measured by a three-dimensional profilometer (S neox, Sensofar, Spain). The morphologies of machined surface were observed by an optical microscope (Discovery. V20, Zeiss, Germany).

Table 2. Detailed cutting parameters

Cutting speed *v* (m/min)	Radial depth of cut a_e (mm)	Axial depth of cut a_p (mm)	Feed per tooth *fz* (mm)
150	1	1.5	0.001, 0.003, 0.01, 0.02, 0.04, 0.08

3. Results and discussion

3.1. Cutting force

During the cutting of K9 glass and 70wt% Si/Al alloy, the average cutting force exhibited different variations. As shown in Fig. 3, the changes in cutting forces with varying feed rates are depicted. Due to the large amount of Si particles in the workpiece, the cutting-edge is subject to high-intensity impacts during milling, resulting in significant fluctuations of cutting force. In milling of 70wt% Si/Al alloy, the cutting force initially decreased and then increased. Specifically, within the feed rate range of 0.001 – 0.003 mm/z, the cutting force decreased. This phenomenon was attributed to the feed rate being smaller than the cutting-edge radius, causing the aluminium in the Si/Al alloy to undergo ploughing with the cutting-edge. With an increase in feed rate, the ploughing effect diminished, leading to a gradual reduction in cutting force. The minimum cutting force of 47.6 N was reached at a feed per tooth of 0.003 mm. Beyond a feed per tooth of 0.003 mm, the cutting force increased with the feed rate. The ploughing effect became insignificant. Since there was no ductile material in K9 glass, no ploughing phenomenon occurred during its machining [4]. In addition, when milling K9 glass, abrupt fluctuations in cutting force occurred due to the brittle fracture of the material. In the case of Si/Al alloy, the minimum cutting force fluctuations appeared in the feed per tooth of 0.02 mm. Significant abrupt fluctuations in cutting force were observed when the feed per tooth exceeded 0.02 mm, as the high ductility of aluminium reduced the occurrence of brittle fracture in the material.

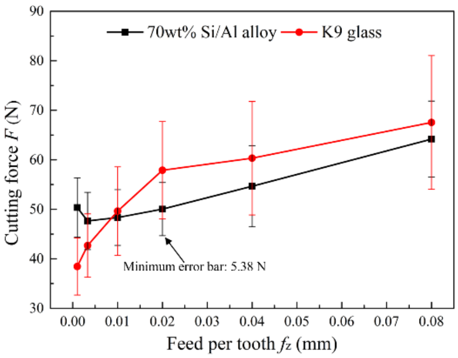

Figure 3. Variations of cutting force with feed rates

3.2. Milling-induced damage characteristics

As depicted in Fig. 4, the three-dimensional topography of the machined surfaces of K9 glass and 70wt% Si/Al alloy are illustrated. In comparison with K9 glass, the machining damages in Si/Al alloy also included pits and crack defects typical of brittle materials. The two kinds of damage were generated by the breakage of the high hardness silicon particles. In addition, owing to the heterogeneity of Si/Al alloy, the machined surface of 70wt% Si/Al alloy exhibited various forms of damages distinct from those observed in homogeneous brittle materials, such as burrs and scratches. Also, the variations of surface roughness with different feed rates are exhibited in Fig. 5. With an increase in feed rate, the machined surface roughness of 70wt% Si/Al alloy initially decreased and then increased, reaching its minimum (1.5 μm) at a feed rate of 0.02 mm/z. At feed rates below 0.02 mm/z, severe burrs cause larger surface roughness. Above 0.02 mm/z, increased pits and cracks lead to more roughness. In contrast, the machined surface roughness of K9 glass consistently increased with the feed rate, and catastrophic edge breakage started appearing in K9 glass beyond a feed per tooth of 0.01 mm.

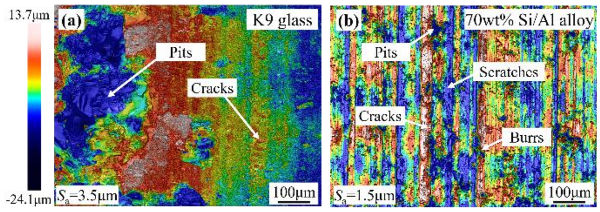

Figure 4. Machined surface topographies of K9 glass (a) and 70wt% Si/Al alloy (b)

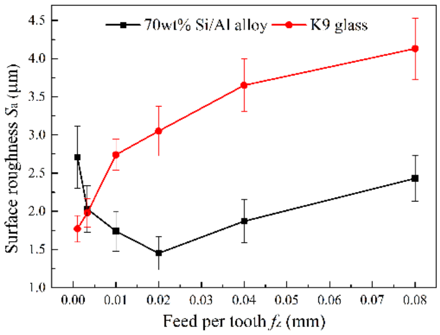

Figure 5. Variations of machined surface roughness with feed rates

4. Conclusions

Milling experiments were conducted to analyze the damage characteristics of 70wt% Si/Al alloy. The 70wt% Si/Al alloy material exhibits the characteristics of both brittle and ductile materials. The milling-induced damage includes pits and cracks caused by the breakage of hard silicon particles. There are also damages such as burrs and scratches generated by the excessive deformation of ductile aluminium.

Feed rates play an important role on machining damages in milling of 70wt% Si/Al alloy. The minimum surface roughness (S_a = 1.5 μm) achieved at a feed per tooth of 0.02 mm. When the feed rate below it, the plastic characteristics of the material dominate. Ploughing occurs during cutting, resulting in the high cutting force (51 N) and generation of many burrs and scratches. When the feed per tooth is larger than 0.02 mm, the brittle characteristics become dominant. The ploughing phenomenon diminished, but brittle fracture during machining increased, which leads to abrupt fluctuations in cutting force and deteriorated machining quality.

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