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Shaping metal–matrix composites by thixotropic machining

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Industrial summary

Thixotropic machining was demonstrated for the shaping of an aluminium–matrix particulate composite. The process involved deforming the remelted composite in a thixotropic state and releasing the applied stress while the composite was still in that state. However, the process-induced cracking was particularly severe when the cutting tool tended to adhere to the thixotropic composite.

Keywords: Metal–matrix composites; Thixotropic; Machining; Shaping; Cutting; Remelting

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1. Introduction

Due to their high modulus, high strength and low ductility, metal–matrix composites are difficult to machine or shape after fabrication. This difficulty increases with increasing volume fraction of the reinforcement. Techniques employed for machining metal–matrix composites [1,2] include cutting by diamond tools [3–5], carbide tools [4–7] and lasers [8,9]. These techniques are expensive due to either equipment cost or time cost. In this work, we have developed a new method, called thixotropic machining, for shaping metal–matrix composites.

Thixotropy refers to the behaviour of a solid–liquid slurry which acts as a solid when no stress is applied, but flows like a liquid when pressure is applied. The thixotropic behaviour of a liquid metal based slurry has been exploited for stir casting (called thixocasting or compocasting) metal–matrix composites. In this casting method, the thixotropic slurry is formed after rigorous stirring and the thixotropic behaviour is useful for avoiding the sinking or floating of the reinforcement particles, whiskers or fibres in the slurry. However, the thixotropic behaviour of slurries formed by melting metal–matrix composites has not been previously demonstrated. The thixotropic behaviour of melted metal–matrix composites is valuable for the shaping or machining of these composites, as the thixotropic behaviour allows the machining to be achieved by applying pressure to the slurry and immediately releasing the pressure while the composite's matrix is still molten. This thixotropic machining method differs from the previously reported plastic processing method [10], which does not make use of the thixotropic behaviour of the melted metal–matrix composite, as the plastic processing method involves applying pressure to the slurry and maintaining the pressure until the solidification of the slurry is complete. The very short time of pressure application in thixotropic machining greatly increases the efficiency of the shaping process. Both thixotropic machining and plastic processing require much lower pressures than conventional solid-state machining.

The elastic processing method [10] had been demonstrated only for reinforcements in the form of whiskers or fibers. At the same volume fraction solid in the slurry, a slurry with a fibrous reinforcement is expected to be more viscous than one with a particulate reinforcement, so the attainment of thixotropy is expected to be easier with the former. In this work, we have demonstrated thixotropy in the case of a particulate reinforcement.

2. Experimental

The metal–matrix composite used for demonstrating the feasibility of thixotropic machining was an aluminium–matrix aluminium nitride particle composite fabricated by the pressure infiltration of pure liquid

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aluminium into an evacuated preform consisting of AlN particles and about 0.1 wt.% of a phosphate binder. The AlN volume fraction in the preform or the composite was 59%. Details of the fabrication method are given in a previous publication [11].

Thixotropic machining was carried out using a steel ram fitted at one end with a cutting tool having a V-shaped (90° within the V shape) tip. The sample to be shaped was placed underneath the V-shaped tip and was supported by a piece of ceramic. Pressure to the ram was provided by a hydraulic press (Carver). A sample, its ceramic support and the V-shaped tool were located in the bore of a tube furnace with an inside diameter of 2 inches. A thermocouple was placed next to the ram and was allowed to almost touch the sample surface. The furnace was purged with nitrogen gas at a flow rate of 20 $\mathrm{cm^3\,min^{-1}}$. Three types of V-shaped cutting tools were used, namely ceramic (Macor or Macro Machinable Glass Ceramic, Corning Glass Works), molybdenum and graphite colloid coated molybdenum. These materials were chosen because of the need for the tool to be sufficiently stiff at the machining temperature of 660–665 °C. (The melting temperature of aluminium is 660 °C.) The graphite coating served to reduce the adhesion between the tool and the thixotropic sample, as this adhesion degraded the shaping effectiveness. Nitrogen purging was necessary only when the tool was graphite-coated molybdenum, as the graphite oxidises in air when heated, but it was conducted in all cases anyway.

The actual process involved heating up the furnace to 660–665 °C at a rate of 600 °C $\mathrm{h^{-1}}$ and then maintaining the temperature for 5 min, while the tip of the cutting tool (a straight edge) was in contact with the top surface of the sample. A force of less than 100 lb was applied to the ram for less than 30 s, after which the tool was immediately moved away so that it did not touch the sample any more. The resulting strain rate was estimated to be 70 µm in 30 s. After this, the furnace was allowed to cool to 300 °C, and then the sample was removed from the furnace.

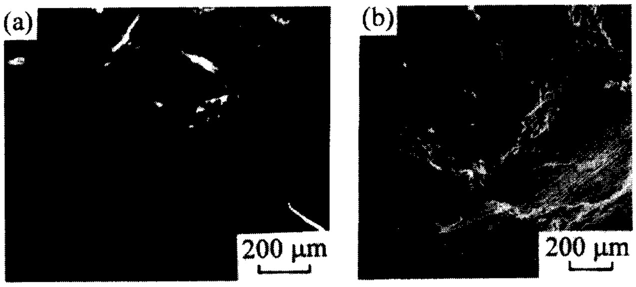

Fig. 1. SEM photographs of a V-shaped groove produced by thixotropic machining using a Macor cutting tool: (a) lower magnification view in the direction of the groove; (b) higher magnification view at an oblique angle.

Fig. 2. SEM photograph of a V-shaped groove produced by thixotropic machining using a molybdenum tool.

Fig. 1 shows SEM photographs at two magnifications of the V-shaped groove left on the sample surface after thixotropic shaping with the V-shaped Macor tool. The lower magnification view (Fig. 1(a)) in the direction of the bottom edge of the V-shaped groove shows that the 90° angle of the V-shape is faithfully produced in the sample, but the bottom part of the V-shaped groove was slightly undulating due to squeezing the thixotropic material away from the tip of the groove. The higher magnification view (Fig. 1(b)) at an oblique angle shows the surface of the groove and the presence of cracks emanating from the tip of the groove. These cracks were generated during thixotropic machining due to the stress/strain concentration at the tip of the tool. Furthermore, due to the low matrix strength in the thixotropic state, pre-existing cracks may open up, thus resulting in additional cracks away from the tip of the groove. After the machining, the Macor tool was found to be damaged at its tip due to the low tensile strength of Macor and the slight adhesion between the Macor tool and the sample in the thixotropic state. Macor debris (bright spots in Fig.

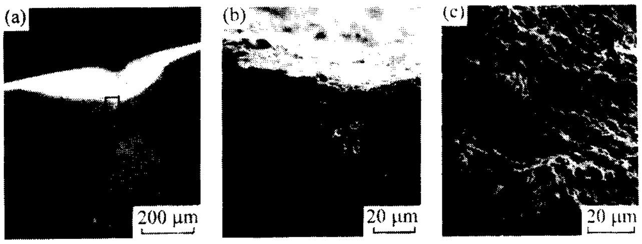

Fig. 3. SEM photographs of a V-shaped groove produced by thixotropic machining using a graphite-coated molybdenum tool. The groove viewed at an oblique angle (a) at lower magnification and (b) the boxed region in (a) at higher magnification. (c) The smoothness of the cut surface.

1(b)) remained in the groove. This problem means that other materials should be used for the tool.

Fig. 2 shows the groove produced by using a molybdenum tool (without graphite coating). The V shape was produced in the sample, but due to severe sticking between the tool and the sample, the sample was torn upon removal of the tool.

Fig. 3 shows the groove produced by using a graphite-coated molybdenum tool. With the graphite coating, the adhesion problem vanished. Nevertheless, some cracks were still observed to emanate from the groove (Fig. 3(b), which is a high magnification view of the region indicated by the box in Fig. 3(a)). The degree of smoothness of the cut surface is shown in Fig. 3(c).

3. Conclusions

The feasibility of thixotropic machining of metal–matrix composites was demonstrated. Shaping using this technique is possible at a stress and in times which are small compared to those required for solid-state machining. However, thixotropic machining suffers from crack generation, which is particularly severe when the cutting tool tends to adhere to the sample in the thixotropic state. Thus, the choice of tool material is critical. Further development of this technique is warranted.

Although thixotropic machining was demonstrated for a particulate composite, it is expected to be easier for a whisker composite due to the lower tendency for cracking in the presence of whiskers.

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