Research Article

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Study on hot deformation behavior and workability of stir-cast Al6063-6wt.% steel_p based composites

<https://doi.org/10.1515/jmbm-2021-0012>

Received Jan 19, 2021; accepted Aug 15, 2021

Abstract: Investigation on the hot deformability and workability of stir cast 6 wt.% steel particles reinforced aluminium 6063 matrix composites was undertaken in this study. Flow stress – strain curves generated from hot compression tests performed at strain rates of 0.01, 0.1, 1, and 10 s^{-1} , and temperatures between $200\text{--}400^\circ\text{C}$, were used to study the flow behavior of the composite, while processing map developed from analyses of the deformation data, was used to establish the deformation mechanisms and processing safe zones for effective workability. Flow stress oscillations were observed to be prevalent at lower deformation temperatures and strain rates; largely due to the settling of reinforcement particles at grain boundary vicinities, rather than a homogeneous distribution. Also, the flow behaviour was largely strain rate insensitive. The dominant flow mechanism based on the flow stress patterns, processing map and microstructural validation was established to be dynamic recovery. Safe regions for processing based on Murty's and Gegel's criteria established the safe processing zones to be $\sim 270\text{--}400^\circ\text{C}$ at $0.01\text{--}1.0\text{ s}^{-1}$ and $380\text{--}400^\circ\text{C}$ at 10 s^{-1} . Deformation processing was unsafe at $200\text{--}260^\circ\text{C}$ at $0.01\text{--}1.0\text{ s}^{-1}$ and between $200\text{--}380^\circ\text{C}$ at $1.0\text{--}10\text{ s}^{-1}$.

Keywords: Al 6063/steel_p composite, hot deformation, dynamic strain ageing, processing map, deformation mechanism, workability

1 Introduction

The development of aluminium based composites reinforced with metallic materials is a fairly new research sub-area in the composite community. Its pursuit is founded on the limited formability and toughness normally characteristic of traditional ceramic reinforced AMCs [1, 2]. The use of hot working processes to enhance the formability of ceramic reinforced aluminium matrix composites (AMCs) has partially been helpful, but the inherent brittle nature of the ceramic reinforcement still poses some problems [3, 4, 5]. During hot forming, the deformability of the soft aluminium matrix and that of the hard-ceramic reinforcement are often incompatible resulting in inhomogeneous plastic strains particularly within the vicinity of the matrix-reinforcement interface. This often results in composite damage and restricted safe processing zones, which practically makes hot deformation processing of ceramic reinforced AMCs quite difficult [6, 7].

The use of metallic reinforcement in AMCs has been opined to have the capacity to address the potential limitations noted in ceramic reinforced AMCs. Several studies have advanced the scientific thoughts serving as the basis for its consideration [8, 9]. Fundamentally, there is inherent good ductility and toughness in metals when compared to ceramics, better wettability between metals than metal-ceramics, and close thermal properties compared to

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metal-ceramic system, are some of the factors which have favoured metallic reinforced AMCs over ceramic reinforced AMCs [10, 11, 12]. It is also factored on the use of a refractory metal reinforcement and one with very low solubility in the matrix, which helps ensure minimal dissolution in the lattice structure or formation of undesirable intermetallics [13, 14]. Some of the metallic reinforcements which have been used in AMCs are Ni, Mo, Ti, Cu and Fe, but most of the studies have been focused on room temperature evaluation of material properties [15, 16, 17]. It is noted that even for monolithic alloys, higher deformability and intricate shaping are often achieved with the adoption of warm/hot forming processes [18]. Thus, hot deformation processing will be highly essential for use in intricate shaping of metallic reinforced AMCs. However, this research pathway, has only been remotely studied in the composite community.

The present study leverage on these identified gaps to investigate the hot deformation behavior and workability of Al6063 alloy reinforced with steel particles using processing maps. Deformation processing maps combine parameters of power dissipation efficiencies and instability parameters which help to establish safe processing zones based on appropriate selection of deformation temperatures, strain rates and strains to avoid instabilities and damage to the composite [19]. Some studies have reported that AMCs reinforced with steel particles show improved interface bonding, mechanical and fracture properties compared to AMCs reinforced with the use of SiC or Al₂O₃ [1, 20]. But little is known about its hot deformation characteristics, which knowledge is essential to understand its amenability to high plastic forming and shaping for components and parts development.

It is expected that the research outcomes from the study will provide as a first step, the necessary insights for understanding the hot deformation characteristics of this new class of AMCs.

2 Materials and method

2.1 Casting

Aluminum (6063) (Al-0.4Si-0.47Mg-0.01Mn-0.19Fe), matrix composite reinforced with 6wt. % steel particles (average particle size of 50 μm) was the composite investigated in this study. The 6 wt. % Fe composition was selected based on results from our previous studies [2, 21]. The composite was produced following procedures reported in Alaneme *et al.* [22]. Charge calculation was used to determine the amounts of the Al 6063 alloy and steel particles needed

for the composite production. The Al alloy was melted in a crucible furnace, after which it was cooled gradually to semi-solid state ($\sim 600^\circ\text{C}$). Then, the steel particles (which were preheated to avoid inducing undesirable temperature gradients in the melt) were added and manually stirred to attain a uniform particles/melt mix. The mixture was superheated to $750^\circ\text{C} \pm 20^\circ\text{C}$, and subjected a mechanical stirring at 400 rpm for 10 minutes. The melt was afterwards cast using a metal mould, then machined to sample dimensions of 10 mm diameter and 15 mm length.

2.2 Compression testing

The compression tests were performed on the samples at constant temperatures, using a Gleeble 3500 thermomechanical simulator at strain rates of 0.01, 0.1, 1.0 and 10.0 s^{-1} and temperatures 200, 250, 300, 350 and 400°C . Preceding the hot-compression testing, the wrapping method was used to attach chromelalumel thermocouple to the center of the composite samples [23]. Then, the samples were compressed to a constant global strain of 50%, after which the deformed samples were compressed air-cooled promptly to preserve the ensuing microstructures. The test generated stress-strain data, were analysed and then used in developing a processing map [24]. The processing maps were used to establish the most advantageous regions for working the composites. This region was determined using power dissipation efficiency following Eq. (1) and (2). Also, unsafe regions of deformation were indicated on the map. The unsafe region of the processing map represents combination of parameters that are capable of inducing defects in the deformed AMCs. These regions were determined using Gegel [25] and Murty's [26] instability criteria expressed in Eq. (3) and (4), respectively:

$$m = \frac{\partial J}{\partial G} = \frac{\dot{\epsilon} \partial \sigma}{\sigma \partial \sigma} = \frac{\partial(\ln \sigma)}{\partial(\ln \dot{\epsilon})} \quad (1)$$

$$\eta = \frac{J}{J_{\max}} = \frac{2m}{m+1} \quad (2)$$

$$\xi(\dot{\epsilon}) = m < 0 \quad (3)$$

$$\xi(\dot{\epsilon}) = \frac{2m}{\eta} - 1 < 0 \quad (4)$$

Where m is strain rate sensitivity, G is power generated by temperature rise, J is power dissipated through microstructural evolution, η is power dissipation efficiency, and $\xi(\dot{\epsilon})$ is the instability criterion [27, 28].

Figure 1: True stress-true strain curves of Al6063/6 wt.% steel_p composite under different compression conditions: (a) 0.01 s^{-1} ; (b) 0.1 s^{-1} ; (c) 1 s^{-1} ; (d) 10 s^{-1}

2.3 Microscopy

A Zeiss Sigma[®] FEG-SEM (field emission gun) in backscattered electron (BSE) mode and EDX analysis was utilised for structural characterization of the composite. Before microscopy, the samples were prepared to standard metallographic surface finish, and etched with Weck's reagent for $\sim 18 \text{ s}$.

3 Results and discussions

3.1 Flow behavior

Figure 1 show the compressive flow stress-strain profile of the Al6063/6wt%steel_p composites deformed at different temperatures and strain rates. The plots show a general decrease in flow stress with increase in deformation temperature, while anomalous flow stress oscillations and negative strain rate sensitivity predominantly characterized the flow stress- strain rate relations. The prevalence of negative strain rate sensitivity is supported by the peak stress – temperature plot presented in Figure 2.

Figure 2: Effect of testing temperature (200–400°C) and strain rate (0.01–10 s⁻¹) on the peak stress Al6063/6 wt.% steel_p composites.

The decrease in the flow stress with increase in temperature is accounted for by the dominance of dynamic softening over work hardening with increasing temperature. Higher temperature avail dislocations greater thermal activation energy for climb and cross slip mechanism which then complements gliding of dislocations [29, 30]. Thus, dislocations are better activated to overcome barriers to their motion. This is coupled with greater tendency for the redistribution and annihilation of dislocations at higher temperatures [31]. Thus, the capacity for dislocation density increase is greatly reduced by the equally activated dislocation annihilation process which reflects in the lower flow stress observed at higher temperatures at all deformation strain rates in the composite [29].

The negative strain rate sensitivity observed in the composite particularly at strain rate of 0.01, 0.1 and 1 s⁻¹ has been observed in a few Al based alloy systems [32, 33]. In Al 5xxx and Al 6xxx – T6 alloys, this phenomenon has been associated with negative strain rate sensitivity and linked to Portevin le Chatelier (PLC) effect (dynamic strain ageing) arising from solute atoms/particles interaction with dislocations [34]. In the case of the Al6063/6wt.% steel_p composite studied, the negative strain rate sensitivity was accompanied with anomalous flow stress oscillations, which are not manifest in the characteristic fashion noted for PLC effect. Figures 3 and 4, suggest that the stress oscillations are on account of the segregation of the steel particles majorly along the grain boundaries. Thus, the inhomogeneous distribution of the steel particles in the Al matrix, results in the stress oscillations. At the grain interiors (Figure 3), the force required to move dislocations are lower because there are little or no steel particles present – hence, there

Figure 3: Point scan SEM-EDS analysis of grain centre of Al 6063/6 wt.% steel_p composite.

are less barriers to the motion of the dislocations. This invariably translates to lower flow stresses along the grain interiors during the deformation process. However, within the vicinity of the boundaries, the steel concentration is higher (Figure 4), hence the shear stresses to facilitate the motion of the dislocations is expected to increase in magnitude on account of the pinning and restraining effects of the particles on the dislocations [2]. This is complemented with the extra work the dislocations will need to navigate through the boundaries, on account of the back stress exerted by the boundaries on the dislocations, and the extra energy required to change slip plane orientations on moving across boundaries to adjoining grains [35, 36]. Thus, the stress oscillations should not be confused with the dynamic strain ageing seen in some Al 5xxx and 6xxx series [33, 34, 37]. The EDS observations points to the need to improve the steel particles dispersion in the Al matrix during processing, using our stir casting methodology. This will form part of further investigations to be undertaken by our group.

3.2 Microstructure evolution

Representative micrographs of the as-cast and hot compression tested Al6063/steel_p composite are presented in Figures 5 and 6. It is observed from Figure 5 that the as-cast microstructure contains grains that are well defined with steel particles (white phase) aligned along the grain boundary vicinity. There are also no little signs of casting defects observed in the microstructure. From Figures 6(a) and (b), it is observed that the grains are oriented (aligned) at an

Figure 4: Point scan SEM-EDS analysis of boundary area of Al 6063/6 wt.% steel_p composite.

axis in response to the deformation force, and the development of defects in the microstructure was more likely at 200°C (the lowest deformation temperature utilized in the study) and higher strain rate of 10 s⁻¹ than at strain rate of 0.01 s⁻¹. There also appears to be boundary thickening due to the coalescence of more reinforcement particles at 10 s⁻¹ compared to what is observed at 0.01 s⁻¹ strain rate (Figure 6a and b). This observation is not anomalous because 200°C is or within the lower warm working range for aluminum and thus formability will be more constrained compared to higher temperatures on account of the lower thermal activation for dislocation redistribution or annihilation processes [38]. Also, higher strain rates at such low temperature will result in more resistance to flow due to the rapid pace of dislocation pileup over redistribution and annihilation processes (processes resulting in softening), thus increasing the tendency for cracking and fracture of the material [39]. Deformation at 300°C and 10 s⁻¹ (Figure 6c) also shows similar microstructural features as that observed at 200°C and 10 s⁻¹, where grain alignment in response to the deformation, and the congregation of the reinforcements (steel particles), along the boundary vicinity is observed. However, macroscopic defects or cracking in the composite is not observed, which may be due to the relatively higher thermal activation energy achieved at 300°C compared to 200°C. Higher thermal activation energy favours more dislocation redistribution and annihilation and thus improves the plastic deformability of the composite [39, 40]. At 400°C, the dense packing of the reinforcements along the boundaries is not observed when the microstructures at 0.01 s⁻¹ (Figure 6d) deformation strain rate and that at 10 s⁻¹ (Figure 6e) are compared. It is ob-

served that the microstructures show less distorted grain structures with features more synonymous with substantial subgrain reorientation and migration (substantial dynamic recovery) but without well-defined recrystallized grains. This is an indication that dislocation redistribution and annihilation is more intense at the deformation temperature of 400/1.0 s⁻¹. The temperature of 400°C is within the hot working range of Al and thus within/near the recrystallization temperature of Al where dynamic softening are more thermally activated than the temperatures of 300°C and 200°C.

Figure 5: SEM-BSE image of As-cast Al 6063/6 wt.% steel_p composite.

3.3 Processing maps

3.3.1 Processing maps analysis

The processing map of the Al 6063/steel_p composite at strain of 0.5 are presented in Figure 7. It is noted that the domain with peak dissipation efficiency were between 30 and 40%, which suggests that dynamic recovery (DRV) was the prevalent softening mechanism in this region. Prasad and Ravichandran [28] had reported that the power dissipation for the occurrence of dynamic recrystallization (DRX) in high stacking fault metal such as Al may be as high as 50%. The peak power dissipation efficiency obtained in this study at this strain is lower than 50%, hence indicating that DRX is unlikely to be the dominant softening mechanism but favors DRV. Table 1 presents the summary of the different safe and unsafe regions indicated on the processing maps at successive strain. It is seen that DRV provided the softening mechanism when the composite samples were

Figure 6: As-deformed microstructures of the Al6063/6 wt.% steel_p composite subjected to deformation at: (a) 200°C and 0.01 s⁻¹; (b) 200°C and 10 s⁻¹; (c) 300°C and 10 s⁻¹; (d) 300°C and 0.01 s⁻¹; (e) 400°C and 10 s⁻¹.

deformed at regions with the highest power dissipation efficiency.

The regions which are identified as unfavourable conditions for deforming the composite samples are listed and are noted to have power dissipation efficiency that are less than 25%. The dominance of DRV as the major softening mechanism is supported by previous studies [25, 26] where it was reported that most Al based alloys and composites exhibit DRV due to their high stacking fault energies. Although the occurrence of DRX in Al based composites has also been observed by previous researchers, the typical strain rates for the occurrence of DRX were reported to be less than 0.01 s⁻¹. On the map (Figure 7), the contour lines with numbers indicate the power dissipation efficiencies, while the light yellowish regions are indicative of instability regions. From the Figure, it is observed that the instability regions overlap with or fall within the regions having negative power dissipation efficiencies – noted as regions of flow instability. This indicates that there is reasonable agreement between the Gegel's and Murty's instability criteria. There were also regions where both criteria did not give coinciding unsafe processing zones. Such occurrence is not uncommon with the use of both criteria, as Ma *et al.*

[41] reported that Murty's criteria is most reliable in predicting flow instability at low strain rates and high deformation temperatures. The temperatures and strain rates which are safe and unsafe for processing the composite are summarized in Table 1. Deformation processing at temperatures within the range 200–260°C at 0.01–1.0 s⁻¹ and 200–380°C at 1.0–10 s⁻¹, were reported unsafe for deformation processing of the composite. This is consistent with the observations in Figure 6b for instance, where it was noted that the samples deformed at 200°C and 10 s⁻¹ had signs of microvoids on them – confirming the undesirability to undertake deformation under such processing condition. From Table 1 also, the safe domains for processing of the composite were observed to be ~270–400°C at 0.01–1.0 s⁻¹ and a narrow temperature range of 380–400°C at 10 s⁻¹. Figures 6d and 6e which are the microstructures of the composites deformed at 400°C, and 1 s⁻¹ and 10 s⁻¹ strain rates respectively, fall within the safe processing domains predicted by the processing maps. It is observed that there is absence of defects in both microstructures, and that signatures of well-defined DRX are absent, hence supporting the claim that DRV was the dominant softening mechanism exhibited by the composites. Thus, the microstructures vali-

Table 1: Instability and stability regions for 6063Al/6 wt.% steel_p composite.

Strain	Highest power dissipation efficiency	Deformation mechanism as indicated by power dissipation efficiency	Temperature (°C) instability region	Strain rate (s ⁻¹) Instability region	Temperature (°C) stability region	Strain rate (s ⁻¹) Stability region
0.5	33	DRV	200-280 200-380	0.01-1.0 1.0-10	270-400 380-400	0.01-1.0 10

date the reliability of the processing maps for determination of safe and unsafe zones for deformation processing of the Al 6063/steel_p based composite.

Figure 7: Processing maps of Al 6063/6 wt.% steel_p composite at strain of 0.5.

4 Conclusion

The flow behavior, deformation mechanisms and workability of Al 6063/6 wt.% steel_p based composite hot compression tested at temperatures of 200, 250, 300, 350 and 400°C, and strain rates of 0.01–10 s⁻¹ was reported in this study. From the results, it was observed that:

- flow stress oscillations generally characterized the flow behavior; and the flow stress showed dependence on deformation temperature but exhibited considerable negative strain rate sensitivity;
- safe processing zones to be ~270–400°C at 0.01–1.0 s⁻¹ and narrow temperature range of 380–400°C at 10 s⁻¹ while deformation processing was unsafe at

200–260°C at 0.01–1.0 s⁻¹ and between 200–380°C at 1.0–10 s⁻¹;

- based on the flow stress patterns, absence of microstructural reconstitution, and the power dissipation efficiency values, the dominant softening mechanism was established to be dynamic recovery.

Funding information: The authors wish to acknowledge the Materials Design and Structural Integrity Research Group, Federal University of Technology, Akure for facilitating the production of the composites used in this study, and the African Academy of Sciences Grant No [ARPDF 18-03] for providing the financial support to carry out axisymmetric compression testing and microstructural analyses at University of the Witwatersrand South Africa.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

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