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Research article

Influence of process parameters on the workability characteristics of sintered Al and Al–Cu composites during cold deformation

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Abstract: An experimental investigation on the process parameters affecting the workability characteristics of sintered aluminium (Al) and aluminium–copper (Al–Cu) composites during cold forging has been carried out. Cylindrical billets of Al, Al–3%Cu and Al–6%Cu with height to diameter ratio (aspect ratio) of 0.45 and 0.9 were cold deformed under three different frictional conditions (nil/no lubricant, graphite lubricant and zinc stearate lubricant). As such, some important process parameters influencing the workability of these composites such as the initial preform geometry and different volume percent of Cu addition to the Al composite preforms on the relative density, R and physical parameters such as stresses affecting the workability stress index, β have been investigated. Also, the effects of the different frictional conditions on the same are presented. It was established that the nil/no lubricant condition and preforms of the lower aspect ratio yielded improved densification, higher values of stresses and better workability. Furthermore, Al–Cu composites were developed to yield better combined properties such as improved densification and workability than monolithic Al. However, the addition of Cu reduced the axial strain to fracture. As such, a decrease in the densification and the workability characteristics was noted with an increase in the volume percent of Cu.

Keywords: workability; composites; cold forging; height to diameter ratio; relative density

1. Introduction

The powder metallurgy (PM) manufacturing method is a metal processing technique that produces parts from metallic powders which are usually processed from scrap metals. PM manufactures parts by blending elemental powders, compacting these blends in a die and then sintering in a furnace [1]. The sintering process transforms the compacted mechanical bonds between the metallic powders into metallurgical bonds by a solid state transformation process [2]. The PM method is better utilized to develop dissimilar materials from different elements yielding enhanced combination of properties with close tolerance [3]. This makes the PM method ideal in the manufacture of composites. Furthermore, PM method ensures a sustainable process route, minimizes wastage, possesses many technical benefits and is economical when compared to other conventional techniques [4,5]. The flexibility of this technique allows the manufacture of almost every material that can be processed into powder form. PM components produced from Al are currently in demand due to its excellent light-weight to strength properties although majority of production were preoccupied by steels and copper based alloys [6]. However, the main drawback of PM method is that it contains considerable amount of pores even after the sintering process. These pores act as stress risers causing components to fracture and deform more easily. Friction at die contact surface also tends to cause the same which limits its use and this has been comprehensively studied by Güner et al. [7]. Therefore, secondary deformation operations are employed to eliminate these voids which consequently improve the material properties and augments densification. Some of these operations include powder forging, extrusion, rolling, etc. Nevertheless, accomplishing 100% densification is still practically not possible. Despite these inadequacies, the PM technique is still extensively studied and used as its advantages outweighs the drawbacks, but mainly as it allows for recycling of materials which limits the environmental impact. Also, this technique produces parts to net or near-net shaped and this eliminates the need for secondary machining. This subsequently reduces the risk of water pollution arising from cutting fluids and oil involved in other conventional production methods that requires secondary material removal operations. As such, the study of forming characteristics of PM components is fundamental in the bid to produce parts free from defects with optimum densification. Thus, the prediction of failure is critical especially in the initial phases of deformation for prompt alterations in process parameters to prevent fracture. Thereby, Abdel-Rahman and El-Sheikh [8] highlight the significance of the process parameters controlling the metal flow in upsetting that affects the workability. These include the shape, dimensions, stress, strain, temperature, friction and density. Workability is the capacity of a material to withstand the induced internal stresses of forming without being damaged. The most common mode of failure in bulk forming process is ductile fracture [9]. Workability is a complex phenomenon that depends on the process and the material parameters. Thus, the workability of PM components is critical in the design of a forming operation to produce defect free parts.

The workability behavior of Al–Fe composite under the triaxial stress state was conducted by Narayanasamy et al. [9] where the effect of the bulging had been taken into account by a new true strain. A drastic change in the workability characteristics of the preforms were observed after analyzing the curves. This was attributed to the different content of iron, particle sizes and aspect ratios. An important study was conducted by Abdel-Rahman and El-Sheikh [8] where the influence of the relative density on the forming limit of PM preforms in deformation was reported. The workability factor was investigated which described the influences of the mean and the effective stress. The latter is a function of the relative compact density which has been discussed using two theories for PM characterization in upsetting and fracture. Moreover, a study was conducted by Ravichandran et al. [10] on the synthesis and forming characteristics of cold deformed Al–TiO_2 PM composites under plane stress state conditions. The addition of TiO_2 to the Al increased the strength coefficient and decreased the strain hardening index. Additionally, a decrease in the densification and deformation characteristics was noted upon addition of more volume percent of TiO_2. Furthermore, Wolla et al. [11] conducted a study on the workability of PM Al–Cu composites. This study investigated the forming limit diagrams for PM Al–Cu preforms for different initial relative densities and Cu contents. It was established from this study that densification increased with an increase in the Cu content in the composite under similar working conditions. Also, the friction factor between tool and work piece interfaces demonstrated increasing pattern for all the cases with decrease in the initial relative density and increase in the Cu content of the composite. Another study was conducted on the hot workability and densification behavior of sintered PM Al–B_4C preforms during upsetting by Seetharam et al. [12]. This study reports that the workability increased with an increase in the axial strain and relative density irrespective of the deformation temperature and B_4C content in the Al composite. Narayan and Rajeshkannan have presented a good set of work on the workability characteristics of PM preforms [5,13–16]. An experimental investigation was carried out to evaluate the effects of various carbide contents (Al–4%TiC, Al–4%WC, Al–4%Fe_3C and Al–4%Mo_2C) and different aspect ratios (0.4 and 0.6) on the relative density (R), stress ratio parameters, $(\sigma_\theta / \sigma_{eff}), (\sigma_m / \sigma_{eff}), (\sigma_z / \sigma_{eff})$ and workability [13]. It was reported that the TiC compacts established better densification and workability characteristics; however, it limits the height strain to fracture. Moreover, a study on the workability of sintered Al composites during hot deformation using strain hardening parameters was carried out by Narayan and Rajeshkannan [14]. The hot workability of Al composites (Al–4TiC, Al–4WC, Al–4Fe_3C and Al–4Mo_2C) were carried out and it was reported that the TiC containing compacts achieved highest densification followed by Fe_3C, then Mo_2C and lowest for WC. Furthermore, the lower aspect ratio composites achieved better densification rate. Also, the lower aspect ratio TiC containing compacts attained better workability. The densification and forming limit of Al4TiC, Al4WC, Al4Fe_3C and Al4Mo_2C were examined and it was established that Al4TiC achieved better densification than others tested. Also, better final height and diameter strain at fracture were attained by Al4Mo_2C and Al4WC composites [15]. Another analysis on the forming limit of molybdenum (Mo) reinforced carbon (C) steels was carried out by Rajeshkannan and Narayan [16] where Fe–0.8%C, Fe–0.8%C–1%Mo, Fe–0.8%C–1.5%Mo and Fe–0.8%C–2.0%Mo were cold forged to determine the workability behavior. Mo reinforced carbon steel demonstrated better densification which increased with increase in volume percent of Mo. Also, the graphite lubricated preforms attained better densification than the nil lubricant condition. As such, the graphite lubricated Mo reinforced carbon steel exhibited better workability.

Although a considerable amount of work has been reported on the workability of PM materials, no attempts are seen evaluating the effects of composition, lubrication and aspect ratio on the densification and workability characteristics of Al, Al–3%Cu and Al–6%Cu with aspect ratio of 0.45 and 0.9 and initial density of 86%. Thus, this work investigates the effects of the initial preform geometry and different weight percent of reinforcement addition to the Al composite preforms on the relative density, R and physical parameters such as stresses affecting the workability stress index, β are investigated. Also, the influence of the different lubrication and the aspect ratio on the densification and workability behavior of the aforesaid composites have been studied.

2. Materials and method

2.1. Specimen preparation

Atomized Al powder of less than or equal to 150 µm size (diameter) and Cu reinforcement of less than or equal to 50 µm in size (diameter) were used to prepare Al, Al–3%Cu and Al–6%Cu composites. The basic characteristics of the elemental powders used in this study are given in Tables 1 and 2.

Table 1. Characterization of aluminium powder and its blends.

Property	Apparent Density (g/cc)	Flow rate, (s/50 g) by Hall Flow Meter	Density (g/cc) at pressure of 130 ± 10 MPa
Al	1.091	87.306	2.356
Al-3%Cu blend	1.162	85.684	2.307
Al-6%Cu blend	1.228	83.875	2.280

Table 2. Sieve analysis of aluminium powder.

Sieve size (µm)	200	+150	+100	+75	+45	−45
Retention in sieve (Weight%)	0.5	15.2	58.2	9.9	6.8	9.4

Al and the reinforcement powders were accurately weighed and blended in a planetary ball milling machine, model Retsch PM400MA for a period of 2 hours at a speed of 200 rpm. To avoid oxidation, these powders were kept in airtight containers. These blends were then compacted on a 100 tonne capacity hydraulic press yielding green compacts of height-to-diameter ratio of 0.45 and 0.9. The compressibility analysis was carried out for each material so as to obtain an initial theoretical density of 86%. An indigenously developed ceramic coating was applied on the free surface of the compacts to avoid oxidation. This was dried for a period of 12 hours at normal atmospheric conditions. Ceramic re-coating was done in the direction 90° to that of the earlier coating and dried again for 12 hours. The ceramic-coated compacts were sintered in an electric muffle furnace at a temperature of 220 ℃ for 30 minutes and then at the temperature of 594 ℃ for 60 minutes.

2.2. Cold upsetting

The sintered and furnace cooled preforms were cleaned and initial dimensions of the cylindrical billets were measured and noted for initial density calculations. The cold upsetting was carried out between a flat die-set assembly. Each compact was compressively deformed in incremental step loading of 2 tonne using a 100 tonne hydraulic press under different frictional conditions (nil/no lubricant, graphite lubricant and zinc stearate lubricant) until a visible crack appeared at the free surface. Dimensional measurements of the deformed height (h_f) and deformed diameters (top surface contact diameter, D_{c1}, bottom surface contact diameter, D_{c2} and bulged diameter, D_b) were carried out after each interval of loading. The density of the forged specimen was determined using

Archimedes principle. As such, parameters such as axial strain, percent relative density, axial stress and workability stress index were calculated using these experimental results.

2.3. Microstructure analysis

The microstructure analysis of the fully deformed Al composite preforms was carried out to analyze the bonding between the matrix and the reinforcements. As such, the deformed samples were cut into half and hot mounted using a mounting press. These sectioned samples were then polished using grit sandpapers (#240, 400, 600, 800 and 1200) by changing the direction of grinding perpendicularly to that of the initial angle. The specimen was rinsed and dried and then cloth finished using Al_2O_3 and constant supply of water. These were then cleaned using water, then with ethanol and then dried with warm air. Keller's reagent was used to etch the polished surface using surgical cotton after which it was cleaned with distilled water, then using ethanol and then a blower for drying. An optical microscope was used for microscopic examinations of these samples.

3. Results and discussion

Cold deformation operations are employed to eliminate pores present in PM components. This enables the materials to fill up the pores, which subsequently reduces the bulk volume. As a result of cold deformation, the part densification and strength improves considerably. Some of the key performance indicators during cold deformation are material composition, preform geometry, preform and die contact surface frictional condition and other forming parameters such as stress and strain rate [8,17]. As such, Figure 1 is drawn between the relative density, R and axial strain, ε_Z to determine the effects of Cu addition to Al on the densification behavior of PM compacts. Further, Figure 2 shows the microstructural evaluation of Al, Al–3%Cu and Al–6%Cu and Figures 3 and 4 give the effects of lubrication and aspect ratio respectively on the densification behavior of PM compacts. The curves are generally seen to follow a similar characteristic pattern in Figures 1, 3 and 4. Higher rate of densification with respect to axial strain are noted in the initial phases of deformation until axial strain of about 0.1. A steady state of densification is noted after this. The pore closing rate was higher in the initial stages of deformation that promoted densification substantially with little increase in axial strain. However, the pore closure rate decreased as deformation progressed causing a steady state of densification until strain hardening. Moreover, the highest levels of densification are noted with pure Al composites followed by Al–3%Cu with the lowest achieved by Al–6%Cu. Al experienced greater levels of induced strain and was deformed more resulting in better densification. This is because Cu addition inhibited deformation limiting the height strain to fracture. The particle size of Cu is three times smaller than Al and increasing the Cu content in the Al matrix alloy increases the number of pores. However, it reduces the size of the pores as the initial density is same for all the composites. Hence, for the Al–6%Cu composites, the number of pores present will be higher compared to Al or Al–3%Cu but the size of the pores will be much smaller as demonstrated in the microstructures in Figure 2. Similar behavior is noted in studies carried out by Ravichandran et al. [10] and Sivasankaran et al. [18] where increasing weight percent of reinforcements decreased the densification.

Figure 2 exhibits the optical micrographs of cold forged Al, Al–3%Cu and Al–6%Cu composite samples after deformation. These micrographs reveal the presence of the matrix (Al) and the reinforcements (Cu) in each sintered composite. Also demonstrated in these microstructures are the pores or defects and the grain boundaries. Figure 2a displays the microstructure of sintered pure Al whereby larger pore sizes are noted. However, better formation of grain boundaries (GB) are noted in pure Al than others. Figure 2b,c demonstrates the microstructures of Al–3%Cu and Al–6%Cu respectively. A larger number of smaller sized pores than pure Al are noted in these composites as explained in the early part of the discussion on the densification mechanisms in Figure 1. In other words, the pore size becomes smaller as the content of the reinforcements increases in good agreement with findings of Sivasankaran et al. and Kumar et al. [18,19]. Nevertheless, the volume percent of pores still remains the same as all these composites have the same initial relative density of 86%.

Lubrication is an important parameter in the forming process as it is seen to improve the flow of metal pertaining to crack formation. The relationship in Figure 3 determines the effects of lubrication on the densification behavior. The characteristics nature of the curves generally follows a similar pattern. However, the nil lubricated compacts exhibit the highest levels of densification in terms of the final attained density followed by graphite and zinc stearate lubricant conditions. This behavior can be attributed to the lateral deformation phenomenon. The nil lubricated compacts resisted the most to lateral deformation reducing the effects of barreling. Bulging or the barreling effect is a major cause of fracture at the free surface of the preform. This resistance permitted a larger compressive forming load enabling better material properties. Moreover, it is also noted that the effect of lubrication is clearly evident over the effect of composition as nil lubricated Al–3%Cu achieved better densification than graphite lubricated pure Al. However, the effect of lubrication is negligible at the beginning of deformation as most values overlap but significant differences are noted in the final stages of upsetting. Another important observation is that lubrication increases the height strain to fracture. This was more evident with zinc stearate lubricant than graphite. Graphite and ZS lubrication are few of the most widely used solid lubricants in the forming of materials. Lubricants are employed to improve the flow characteristics improving the quality of the component and also the tool life apart from enhancing secondary deformation which are essential in the PM technique.

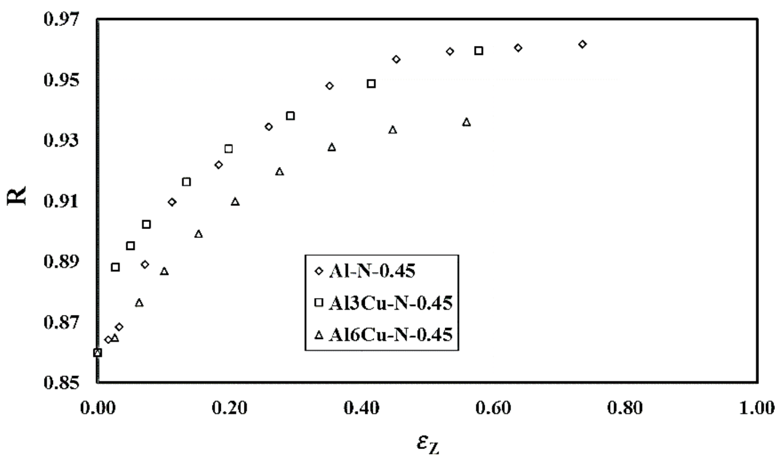
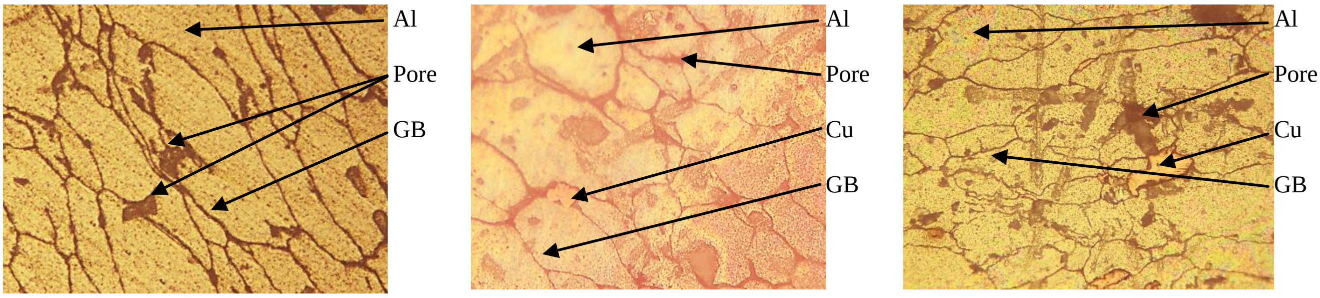


Figure 1. Influence of Cu content on the relative density, *R* against axial strain, ε_Z of Al composites under nil/no lubricant condition during cold upsetting.



(a) Al (b) Al–3%Cu (c) Al–6%Cu

Figure 2. Optical micrographs of sintered cold deformed aluminium composites.

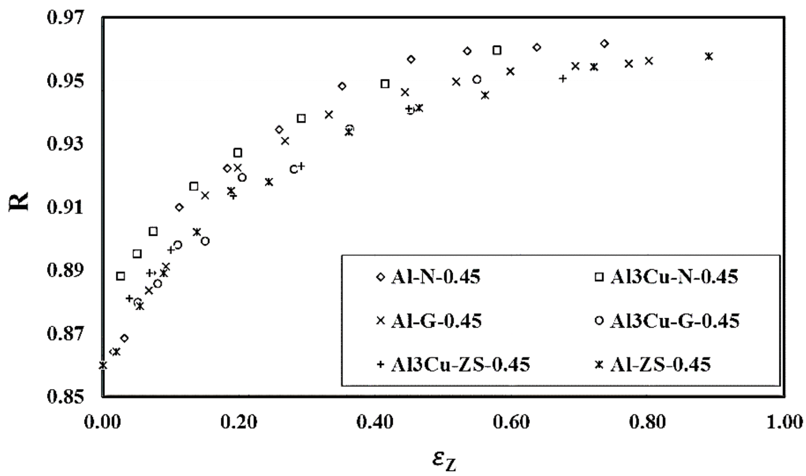


Figure 3. Influence of lubrication on the relative density, R against axial strain, ε_Z of Al composites during cold upsetting.

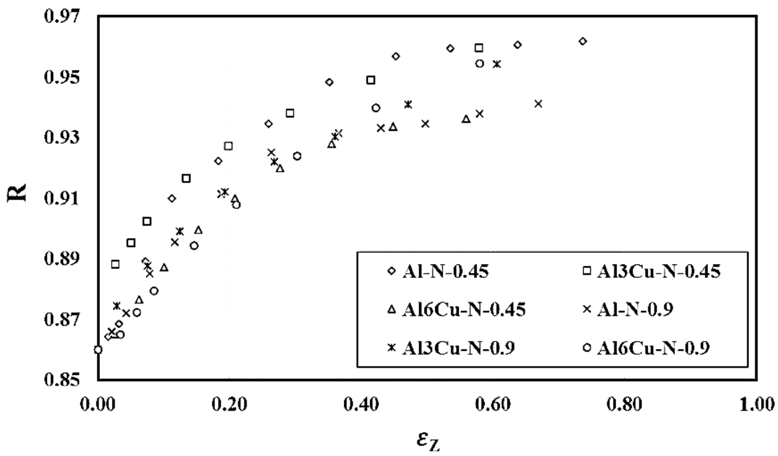


Figure 4. Influence of aspect ratio on the relative density, R against axial strain, ε_Z of Al composites during cold upsetting.

The effects of aspect ratio are more evident at the end of deformation as seen in Figure 4. The lower aspect ratio generally exhibits higher densification with pure Al and Al–3%Cu. The preforms with the lower aspect have a lower pore bed height which closes pores more efficiently and subsequently improves the densification. Another vital observation made is that increasing the aspect ratio reduces the height strain. However, the effect of Cu addition on the extent of deformation is greater than the effect of increase in aspect ratio.

The stress parameters are critical in the design of forming operations because of complexity arising from pores present in PM materials which are a major cause of failure. Therefore, Figures 5–7 are drawn between the axial stress, σ_z and axial strain, ε_Z to determine the effects of Cu addition to Al, lubrication and aspect ratio respectively on the stress behavior of Al PM compacts. The axial stress acts longitudinally and is compressive in nature. The axial stress increases as deformation progressed until fracture. However, greater increase in axial stress is noted at the beginning of the deformation with respect to axial strain in agreement with a study carried out by Raj et al. [20]. This can be attributed to matrix work hardening due to materials internal resistance to deformation. This is followed by geometric work hardening in the intermediate stage with negligible increase in matrix work hardening before fracture in the final stages of deformation. Furthermore, the characteristic nature of curves follows a similar pattern. However, careful observations reveal little effect of composition in the initial stages of deformation as most values correspond as seen in Figure 5. Nevertheless, the highest stress levels are noted by Al–6%Cu followed by Al–3%Cu and then Al. This could be attributed to the existence of greater levels of pores existing between particles as discussed in the densification relationship established in Figure 1. On the other hand, pure Al preform experienced the lowest amount of axial stresses despite being deformed the greatest as Cu addition decreased the axial strain at fracture. Cu exhibits strong work hardening which is typical of single phase face centered cubic (FCC) structure. However, a possible increase in temperature due to the incremental step loading reduces the fatigue strength of cold worked Cu leading to reduced axial strain at fracture [21]. Thus, pure Al can be deformed more if it is free from defects.

The characteristics nature of the curves in Figure 6 generally follows a similar pattern. Nonetheless, it is seen that the nil lubricated preforms demonstrate greater levels of axial stress against axial strain. Increasing the frictional conditions at the contact surface of the preforms provides resistance to lateral deformation which allows for greater compressive deformation levels. Thus, the evident higher values of stresses noted with the nil lubricated preforms. The highest value of axial stress attained is for nil lubricated Al–6%Cu followed by Al–3%Cu and then pure Al. Furthermore, the effect of lubrication is more apparent with the Al–6%Cu composites as graphite and zinc stearate lubricated preforms demonstrated the lowest values of axial stress respectively. A possible reason could be the addition of Cu which reduced the height strain to fracture in Al–6%Cu; otherwise, lubrication is seen to facilitate height strain as is observed with the others.

Figure 7 demonstrates the effects of aspect ratio which are observed to be negligible in the beginning but significant in the final stages of deformation. For majority given axial strain, the lower aspect preforms experienced the higher values of axial stress whereby the highest was observed with the Al–6%Cu compacts. Thus, other compacts with the higher aspect ratio can be compressed more be it free from cracks.

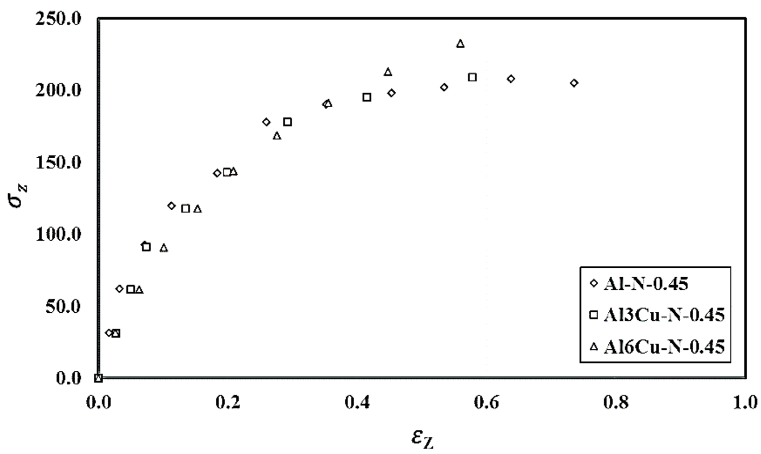


Figure 5. Influence of Cu content on the on the axial stress, σ_z against axial strain, ε_Z of Al composites under nil/no lubricant condition during cold upsetting.

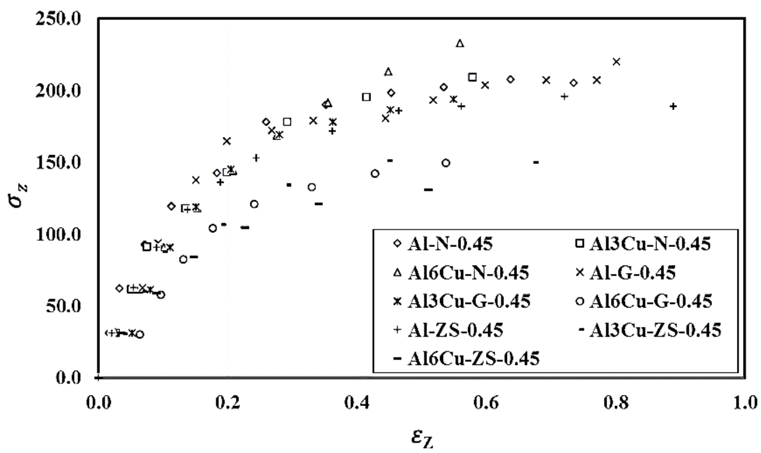


Figure 6. Influence of lubrication on the on the axial stress, σ_z against axial strain, ε_Z of Al composites during cold upsetting.

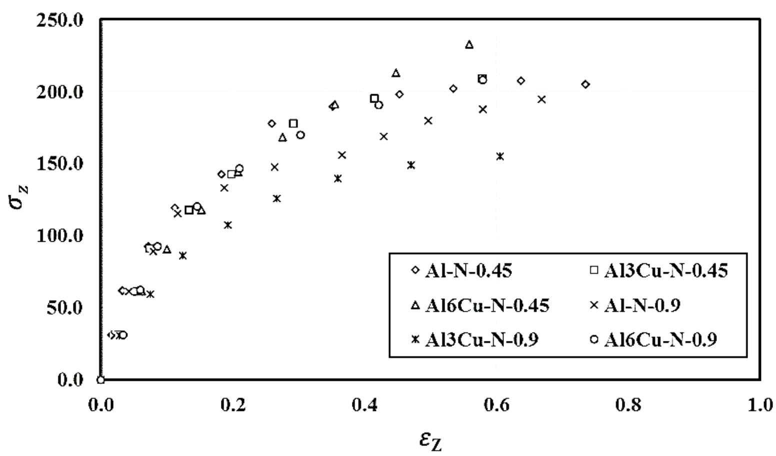


Figure 7. Influence of aspect ratio on the on the axial stress, σ_z against axial strain, ε_Z of Al composites during cold upsetting.

The design of forming operations of PM components is of utmost significance and the workability stress index, β is an important parameter which establishes a safe working zone so that parts free from defects are manufactured. In this regards, Figures 8–10 are drawn between the workability stress index, β and axial strain, ε_Z to determine the effects of Cu addition to Al, lubrication and aspect ratio respectively on the workability characteristics of Al PM compacts. The workability stress index, β increases as deformation progresses until strain hardened. The same has been established in the densification mechanism where the relative density increased with deformation as highlighted by Abdel-Rahman and El-Sheikh [8]. The formation of curves reveals two stages; the initial stage with greater levels of workability characteristics with little increase in strain and the latter with very little increase in workability with respect to greater levels of deformation. The compacts internally resisted deformation in the initial stage of deformation yielding greater workability and as such, greater levels of geometric work hardening occurred resulting in greater effective pore closure. The latter stage show matrix work hardening as majority pores had closed before fracture. Moreover, pure Al achieved best workability characteristics, but at greater levels of deformation than Al–3%Cu and Al–6%Cu as seen in Figure 8. The addition of Cu reinforcements reduced the height strain and the workability characteristics as a result. As discussed earlier, the difference in particle size of Cu and the pores resulted in a lower packing of inter-particles and pores the reason being for the lower workability characteristics with the addition of Cu as explained in Figure 1 and seen in the microstructures in Figure 2.

Figure 9 represents the effects of lubrication on the workability stress index. The effects of lubrication are more apparent in the final stages of deformation. However, this behavior is generally more obvious with the nil lubricated preforms where the highest workability was established by nil lubricated pure Al but at greater levels of induced strain. Employing lubricants such as graphite and zinc stearate addition are seen to enhance height strain but the addition of Cu overrides this effect and reduces it to fracture as is observed in the case of Al–6%Cu.

Figure 10 demonstrates the effects of the aspect ratio on the workability characteristics against axial strain, ε_Z of Al composites under the nil/no lubricant conditions during cold upsetting. The lower aspect ratio preforms attained better workability with Al and Al–3%Cu but not with Al–6%Cu. The pure Al compacts achieved good workability but at greater height strain as the addition of Cu reduced the height strain. However, an increase in aspect ratio may have slightly promoted height strain but the effect of Cu addition was more prominent.

It is noted that the addition of Cu to Al matrix up to a weight percentage of 6% had a detrimental effect on the densification and workability characteristics. A solution to this can be compositing Al–Cu with other reinforcements such as TiC to see the densification and workability characteristics. Future work by the authors will include compositing such hybrid materials.

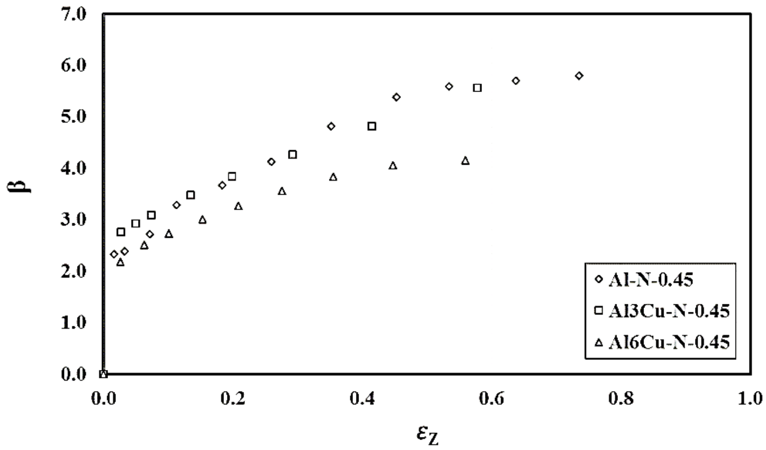


Figure 8. Influence of Cu content on the on the workability characteristics against axial strain, ε_Z of Al composites under nil/no lubricant condition during cold upsetting.

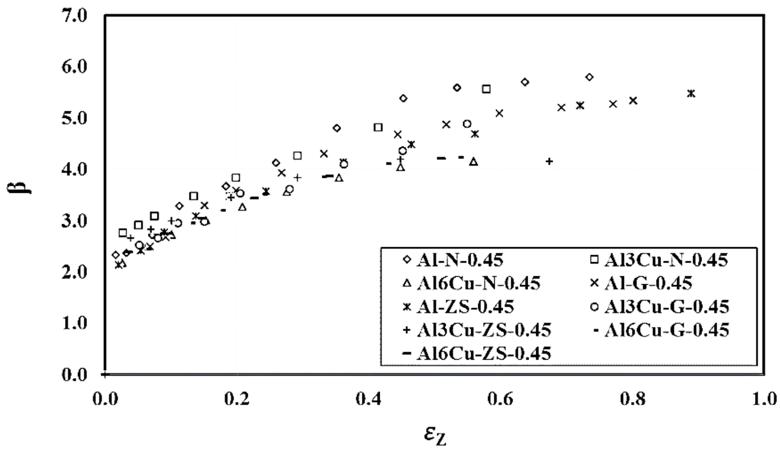


Figure 9. Influence of lubrication on the on the workability characteristics against axial strain, ε_Z of Al composites during cold upsetting.

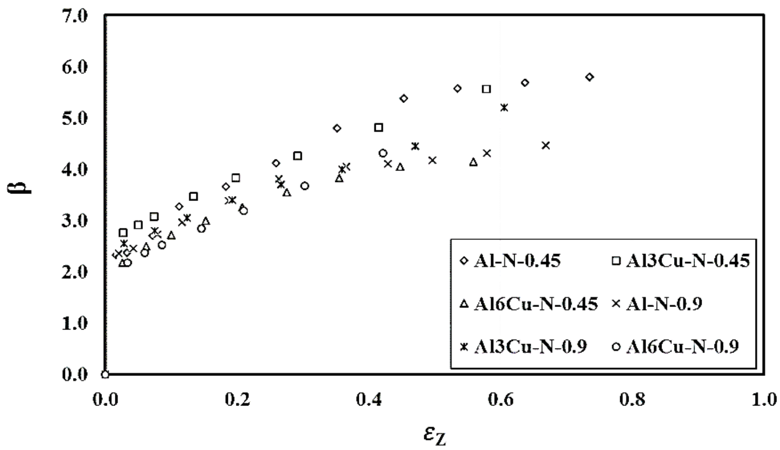


Figure 10. Influence of aspect ratio on the on the workability characteristics against axial strain, ε_Z of Al composites during cold upsetting.

4. Conclusion

Composites are developed to attain better combination of properties whereby the advantages of a particular material can complement with lacks in the other. As such, pure Al, Al–3%Cu and Al–6%Cu composites were successfully synthesized by the PM technique in the bid to improve the densification and the workability characteristics. As such, the densification and workability of these were studied by cold upsetting in plane stress conditions under the influence of lubricating conditions and aspect ratios. The following has been established for the aforesaid composites and respective conditions:

- The densification, values of axial stress and workability increases as deformation progresses.
- The nil lubricated and the lower aspect ratio preforms attained higher densification, axial stresses and workability characteristics.
- However, increasing Cu reinforcement addition to the Al matrix reduced the densification and the workability characteristics but increases stress levels. This is because Cu addition limits the height strain to fracture.
- As such, pure Al attained better densification and workability at greater levels of deformation.
- Furthermore, increasing the aspect ratio of preforms also reduces the axial strain but the influence of Cu addition is more significant.
- Thus, it can be said that higher contents of Cu reinforcements only (3 and 6%) should not be utilized in compositing the Al–Cu system. Moreover, lower contents of Cu addition (less than 3%) to Al can be tested in future for possible enhancements in densification and workability.

Conflict of interest

The authors declare no conflict of interest in regards to the publication of this article.

References

1. Manonukul A, Salee A (2013) Relationship between atmospheric dew point and sinterability of Al–Si based alloy. *J Mater Sci Technol* 29: 70–76.
2. Ghasali E, Pakseresht AH, Agheli M, et al. (2015) WC-Co particles reinforced aluminum matrix by conventional and microwave sintering. *Mater Res* 18: 1197–1202.
3. Meignanamoorthy M, Ravichandran M (2018) Synthesis of metal matrix composites via powder metallurgy route. *Mech Mech Eng* 22: 59–69.
4. Umasankar V, Xavior MA, Karthikeyan S (2014) Experimental evaluation of the influence of processing parameters on the mechanical properties of SiC particle reinforced AA6061 aluminium alloy matrix composite by powder processing. *J Alloy Compd* 582: 380–386.
5. Narayan S, Rajeshkannan A (2011) Workability studies in forming of sintered Fe-0.35C powder metallurgy preform during cold upsetting. *J Iron Steel Res Int* 18: 71–78.
6. Kumar A, Gupta M (2016) An insight into evolution of light weight high entropy alloys: a review. *Metals* 6: 199.
7. Güner F, Cora ÖN, Sofuoğlu H (2018) Effects of friction models on the compaction behavior of copper powder. *Tribol Int* 122: 125–132.

8. Abdel-Rahman M, El-Sheikh MN (1995) Workability in forging of powder metallurgy compacts. *J Mater Process Tech* 54: 97–102.
9. Ramesh T, Prabhakar M, Narayanasamy R (2010) Workability studies on Al-20% SiC powder metallurgy composite during cold upsetting. *Adv Prod Eng Manag* 5: 33–44.
10. Ravichandran M, Naveen SA, Anandakrishnan V (2015) Synthesis and forming characteristics of Al–TiO_2 powder metallurgy composites during cold upsetting under plane stress state conditions. *J Sandw Struct Mater* 17: 278–294.
11. Wolla DW, Davidson MJ, Khanra AK (2014) Studies on the formability of powder metallurgical aluminum–copper composite. *Mater Design* 59: 151–159.
12. Seetharam R, Subbu SK, Davidson MJ (2017) Hot workability and densification behavior of sintered powder metallurgy Al-B_4C preforms during upsetting. *J Manuf Process* 28: 309–318.
13. Narayan S, Rajeshkannan A (2016) Workability studies of sintered aluminium composites during hot deformation. *P I Mech Eng B-J Eng* 230: 494–504.
14. Narayan S, Rajeshkannan A (2017) Studies on formability of sintered aluminum composites during hot deformation using strain hardening parameters. *J Mater Res Technol* 6: 101–107.
15. Narayan S, Rajeshkannan A (2018) Densification behavior of sintered aluminum composites during hot deformation. *AIMS Mater Sci* 5: 902–915.
16. Rajeshkannan A, Narayan S (2018) Forming limit analysis of molybdenum reinforced carbon steels. *Key Eng Mater* 777: 306–310.
17. Narayanasamy R, Anandakrishnan V, Pandey KS (2008) Effect of geometric work-hardening and matrix work-hardening on workability and densification of aluminium–3.5% alumina composite during cold upsetting. *Mater Design* 29: 1582–1599.
18. Sivasankaran S, Sivaprasad K, Narayanasamy R, et al. (2010) An investigation on flowability and compressibility of AA 6061_{100-x}–x wt.% TiO_2 micro and nanocomposite powder prepared by blending and mechanical alloying. *Powder Technol* 201: 70–82.
19. Kumar DR, Loganathan C, Narayanasamy R (2011) Effect of glass in aluminum matrix on workability and strain hardening behavior of powder metallurgy composite. *Mater Design* 32: 2413–2422.
20. Raj APM, Selvakumar N, Narayanasamy R, et al. (2013) Experimental investigation on workability and strain hardening behavior of Fe–C–Mn sintered composites with different percentage of carbon and manganese content. *Mater Design* 49: 791–801.
21. Höppel HW, Mughrabi H, Vinogradov A (2009) Fatigue properties of bulk nanostructured materials, In: Zehetbauer MJ, Zhu YT, *Bulk Nanostructured Materials*, Weinheim, Germany: Wiley-VCH, 481–500.