Original Article

Hardness, tensile and impact behaviour of hot forged aluminium matrix composites

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Tensile and impact testing and hardness measurements were carried out on hot forged aluminium matrix composites to understand the influence of alloying element and forming process on their mechanical properties. Pure aluminium preforms together with its composites such as Al4TiC, Al4Fe2C, Al4Mo2C and Al4WC were prepared using a suitable die-set assembly on a 1 MN capacity hydraulic press. Sintering operation was carried out in an electric muffle furnace at the temperature of 1200 °C for a holding period of 1 h. Immediately after the sintering process the cylindrical preforms were hot deformed in to a square cross-section bar of size 24 mm × 24 mm × 60 mm for preparing of tensile test and impact test specimens as per the respective ASTM standards. Standard tensile and impact test specimens were machined from the forged square rods. Standard ASTM procedure was followed to conduct the aforementioned mechanical testing. Further, microstructural studies on the hot forged square cross-section bar and hardness measurements were obtained and analysed.

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1. Introduction

Two most generally used manufacturing route for metal matrix composites are casting techniques and powder metallurgy (P/M) techniques [1]. The automotive and off-highway vehicle applications take over the ferrous P/M structural parts market. Particularly, low alloy steels are a familiar structural material for systems such as power plants, aircraft and naval industries or bearing material [2]. These alloys show excellent mechanical properties, low distortion and excellent weldability. They can be fabricated in various shapes such as bars, wires, sheets, forged parts, casts and powder metallurgy products. The presence of pores after the pressing and sintering process of metal powders is a limiting factor in the production of powder metallurgy (P/M) parts. Indeed, the mechanical properties such as tensile, hardness and impact strength are significantly influenced by this inherent porosity. Sintered
P/M preforms are particularly prone to fracture during forging because high amounts of pores in the preform act as stress risers. This is true for many P/M engineering components such as cam shaft pulleys, gears, sprockets, connecting rods, nozzles, pump parts, etc. [3,4]. These components during service are subjected to impact loads, tensile loads, torsional loads and compressive loads and the study of the mechanical behaviour under these loads is of great importance. Little research is conducted in the past on the mechanical behaviour of P/M aluminium metal matrix composite. In particular reinforcements such as iron carbide, molybdenum carbide and tungsten carbide provided the motivation to conduct this research.

Dannininger et al. [5] have presented the relationship between apparent density, Vickers hardness and tensile strength in P/M iron and steels sintered at standard temperatures. It has been reported [6–8] that the tensile, impact and fatigue properties of sintered steels are greatly influenced by sintering temperature, sintering time and compacting pressure. Dudrova and Kabatova [9] have presented that a fracture surface depicts the evidence of loading history, the defects caused by friction, alloy compositions or processing technology as well as microstructure characteristics and the necessary changes in the processing technology of the structural parts can be made from these analyses. Further, it has been reported [10,11] that the micromechanisms of fracture are strongly influenced by the matrix characteristics, the deformation rate and the presence of a notch in the test specimen. Toughness and hardness properties of high density sintered steel (Fe–4.0Ni–1.5Cu–0.5Mo–0.5C) have been studied by Moon [12]. It has been reported that both strength and toughness are also affected by the local strengths, ductilities and work-hardening characteristics of the necks, which in turn are functions of their local composition and microstructure. Trivedi et al. [13] and Rahimiana et al. [14] have evaluated the effect of composition and particle size, sintering temperature and sintering time on iron and aluminium alloys, respectively. It has been reported that as the particle size of alumina is reduced, the density is increased followed by a fall in density. In addition, at low particle size, the hardness and yield strength and compressive strength and elongation to fracture were higher, as compared to coarse particles size of alumina. A study by Srivatsan et al. [15] indicated that increasing the SiC in the aluminium metal matrix composite results in the high fatigue strength. Further, 15 wt.% SiC showed the highest fatigue strength. They also showed that the non-uniform distribution of the reinforcing particulate caused the crack propagation at low levels of applied stress. Another method of improving mechanical properties of sinter-hardened steel is post sinter tempering treatments to achieve specific structural performance goals [16,17].

Thus the present investigation is aimed to investigate the influence of high strength carbide particles addition on the mechanical properties of sintered powder metallurgy composite aluminium preforms during hot forging. Most powder metallurgy components produced after the primary process and even after the secondary operations are likely to achieve 85–92% theoretical density. Therefore, the strength of the powder metallurgy component such as tensile strength, impact strength, yield strength, etc. will be in the range of 65–85% theoretical maximum. Hence, a challenge for researchers in this field is to achieve higher relative density by applying innovative compaction and secondary deformation process and to increase the strength of the material by designing frontier materials by carefully selecting process parameters.

2. Experimental

2.1. Materials and characterization

Aluminium powder of diameter less than 150μm and carbide powders of diameter less than 50μm were used in the present investigation. The characteristics (apparent density, flow rate and particle size distribution) of aluminium powder, Al4TiC, Al4Fe3C, Al4Mo2C and Al4WC blends are shown in Tables 1 and 2.

2.2. Blending, compaction and sintering

The powders were mixed using standard procedure by weight percentage to prepare Al4TiC, Al4Fe3C, Al4Mo2C and Al4WC blends using PM400A ball mill at 200rpm for 2.5 h. Four compacts with initial relative density of 0.90 ± 0.01 of each composition were prepared using a hydraulic press where the pressure was determined first by plotting the compressibility curve of each composition. After the initial density verification, each compact was coated with alumina mixed in acetone. This paste was applied to avoid oxidation during the sintering process. Two coats were applied with 12 h drying period each time. After drying, the compacts were sintered in an electrical muffle furnace for a period of 60 min at 594 °C. Prior to this the compacts were dried at 220 °C in the same furnace for 30 min.
2.3. Mechanical properties

Immediately after the 594 °C sintering process, the aforementioned cylindrical compacts were deformed into a square cross-section bar of size 24 mm × 24 mm × 60 mm and the respective densities were measured. The anvil and hammer process was employed to hot deform the cylindrical specimens into square cross section bars. The heated specimen was placed on the anvil and a maximum of two shots were applied before re-heating at 594 °C for 15 min. After re-heating for 15 min, the cylindrical specimen was rotated by 90° and the same hammer deformation process was applied. Two specimens from each composition were directly taken for the cooling process after the final hammering and these were called sinter-forged furnace cooling (SFFC) and sinter-forged water cooling (SFWC). Similarly, the remaining two specimens were re-heated after the final hammering for 30 min at 594 °C and then were taken for similar cooling process called homogenous sinter-forged furnace cooling (HFC) and homogenous sinter-forged water cooling (HWC). Standard tensile (ASTM-E8) and impact (ASTM-E23) test specimens were machined as per the specifications given in the ASTM standards and are shown in Figs. 1 and 2. A Vickers hardness tester was used to conduct the hardness measurements on the forged test specimens. A standard tensile test was carried out where the strain rate was maintained at 0.1 mm/s. The force was read from the dial after 0.1 mm elongation in length. A stress strain graph was plotted to obtain the respective parameters such as ultimate tensile stress and breaking strength. The charpy impact test was carried out to obtain impact results.

2.4. Microstructure

Microstructural studies on the hot forged square cross-section bar were conducted using PMG Olympus microscope fitted with JCV KY-F55BE CCD camera interfaced with a computer for image capture and analysis. The samples were surface ground with 1200 grit emery paper and polished with 9 μm diamond paste, then with 3 μm diamond paste and finally with colloidal silica solution. The samples were washed with distilled water and pure ethanol and dried with warm flowing air. These samples were then etched with Keller’s reagent. They were then washed with distilled water followed by ethanol and dried with warm flowing air before microstructure viewing.

3. Results and discussion

Mechanical properties like tensile stress, impact strength and hardness play an important role in the selection of materials
in critical applications such as structures and machine components. A well-known problem in PM processed parts is that porosity cannot be fully eliminated. However, the design of materials with addition of carbides and other allowing elements subjected after sintering to secondary operations, such as extrusion and forging, helps in the pore elimination. These techniques would give better mechanical properties to the final processed part.

Fig. 3 gives the microstructural view of pure aluminium preforms. The grains are more globular, well defined and have
less amount of porosity at the intergranular regions compared to carbide reinforced aluminium metal matrix composites. Fig. 4 shows the microstructural views of carbide reinforced aluminium metal matrix composites. Generally, it is seen in these figures that the reinforcing particles are visible and fairly well distributed. Though some agglomeration of Fe₃C particulates could be seen in Al-4Fe₃C composite, the scattering mostly seemed to be fairly uniform throughout the aluminium matrix. The particle distribution and agglomeration observed in the microstructural view is invariant to the cooling techniques employed in this research work. Further, large open pores are not visible and these indicate that the processing technique employed to prepare the tensile and impact specimen is reliable. However, micro-void formations are observed along the reinforcing particles/matrix interface. This may act as stress risers and weakest points in the carbide reinforced aluminium composites causing crack initiation during the tensile and impact tests. It is noted in Fig. 4 that the grains are larger and elongated when subjected to the reheat process after the deformation process before final cooling. Generally, the morphology of grains changed as more elongated grains are observed when samples were subjected to the reheat process.

Table 3 provides the various mechanical properties like tensile, impact and hardness. Same has been analysed and presented in Figs. 5–9. It was noted that none of the composites exposed localized necking like in a fully dense material. Instead, they showed shearing type of fracture evident from the characteristic tensile stress–strain curves shown in Figs. 5 and 6. Four specimens of pure aluminium and each composite were prepared in this work. Heat treatments are employed to increase the mechanical properties of materials. Required values of hardness and strength can be acquired in the materials by proper heat treatments. Four cooling techniques involved in this work are sinter-forged furnace cooling (SFFC), sinter-forged water cooling (SFWC), homogeneous sinter-forged furnace cooling (HFC) and homogeneous sinter-forged water cooling (HWC). Two sets of specimens were directly taken for the cooling process after the forging operation called SFFC and SFWC. Another two sets of specimens were re-heated at the sintering temperature for 30 min after the forging operation before subjected to the cooling process called HFC and HWC.

It can be noted that the ultimate tensile strength (Fig. 7) is higher in the case when the preforms were water-cooled directly (SFWC) after the hot forging process in comparison to furnace cooling. This is true for the pure aluminium preforms as well as for all the composites. Water cooling the forged specimens led to improvement in ultimate tensile strength by about 14% in pure aluminium and by about 12% in the carbide reinforced aluminium composites. The same is not true when the specimens were re-heated to the sintering temperature.
after the forging process before the final cooling process, HFC and HWC. It can be noted that the ultimate tensile strength for homogenous cooling is higher in the case when the preforms were furnace-cooled when compared to water-cooled technique. Overall, there was hardly any improvement in ultimate tensile strength noted between direct sinter-forged cooling and homogeneous sinter-forged cooling techniques. It is noted that the ultimate tensile strength was highest for TiC and WC reinforced aluminium composites when compared to other composites and pure aluminium preforms (Table 3). An improvement of 15% in ultimate tensile strength was noted when pure aluminium was reinforced with TiC and WC carbide particulates. The tensile properties of pure aluminium are in par with Mo2C reinforced aluminium composites.

Fe3C reinforced aluminium composites produced the lowest tensile strength irrespective of final cooling method. Agglomeration of the Fe3C particles as seen in Fig. 4 is more dangerous than that of the other microstructures in Fig. 4. It shows the bonding property at reinforcement/matrix interfaces is poorer. As a consequence, the ultimate tensile strength is the lowest for Fe3C reinforced aluminium composite. Further, due to this reason Fe3C aluminium composites produced poor hardness and impact strength as seen in Figs. 8 and 9, respectively. This is true for both sinter-forged cooling and homogenous sinter-forged cooling techniques.

Pure aluminium showed poor hardness values irrespective of the four cooling techniques, SFFC, SFWC, HFC and HWC. On the other hand, WC reinforced aluminium composite showed the highest hardness values. However, the difference was not so large. The hardness values for TiC and Mo2C were almost the same irrespective of the final cooling technique. Further, small improvement is also observed in the hardness properties of pure aluminium and carbide reinforced aluminium composites for directly water-cooled specimens. The same is not true when the specimens were re-heated to sintering temperature after the forging process before the final cooling process, HFC and HWC. It can be noted that the hardness values of homogenous cooling are slightly higher in the case when the preforms were furnace-cooled as compared to water-cooled technique. Overall, there were hardly any improvements in the hardness values noted between direct sinter-forged cooling and homogenous sinter-forged cooling method.

It is seen (Fig. 9) that the pure aluminium preforms produced better impact strength in comparison to carbide reinforced aluminium composites. This is true for all cooling techniques. Amongst composites, generally it is seen that the impact strength of Mo2C reinforced aluminium composite were larger. In contrast, the lowest impact strength was obtained by the WC reinforced aluminium composites. This is true for all cooling techniques. Further, it is noted that the furnace cooling produced better impact strength to the water cooling technique for directly cooled specimens. This may be the result of low cooling rates provided by furnace cooling techniques causing a lower dislocation density. The density of WC powders (15.8 g/cc) is much higher compared to other

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**Table 3 – Tensile properties, hardness and impact strength of pure aluminium and carbide reinforced aluminium metal matrix composites.**

<table>
<thead>
<tr>
<th>Composite</th>
<th>Cooling technique</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Hardness (HV)</th>
<th>Impact strength (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>SFFC</td>
<td>52.40</td>
<td>26.90</td>
<td>392</td>
</tr>
<tr>
<td></td>
<td>SFWC</td>
<td>60.70</td>
<td>25.55</td>
<td>367</td>
</tr>
<tr>
<td></td>
<td>HFC</td>
<td>47.8</td>
<td>30.46</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>HWC</td>
<td>52.5</td>
<td>28.46</td>
<td>392</td>
</tr>
<tr>
<td></td>
<td>SFWC</td>
<td>65.00</td>
<td>28.32</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>HFC</td>
<td>71.80</td>
<td>30.22</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td>HWC</td>
<td>83.55</td>
<td>35.40</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>SFWC</td>
<td>73.28</td>
<td>32.40</td>
<td>218</td>
</tr>
<tr>
<td>Al-4TiC</td>
<td>SFFC</td>
<td>49.40</td>
<td>23.27</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>SFWC</td>
<td>52.10</td>
<td>24.79</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>HFC</td>
<td>45.5</td>
<td>24.96</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>HWC</td>
<td>37.59</td>
<td>27.76</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>SFWC</td>
<td>55.00</td>
<td>27.86</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td>HFC</td>
<td>61.90</td>
<td>30.69</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td>HWC</td>
<td>58.69</td>
<td>29.18</td>
<td>285</td>
</tr>
<tr>
<td></td>
<td>SFWC</td>
<td>35.48</td>
<td>27.52</td>
<td>280</td>
</tr>
<tr>
<td>Al-4WC</td>
<td>SFFC</td>
<td>61.70</td>
<td>33.36</td>
<td>213</td>
</tr>
<tr>
<td></td>
<td>SFWC</td>
<td>71.00</td>
<td>35.28</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>HFC</td>
<td>80.6</td>
<td>34.01</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>HWC</td>
<td>75.4</td>
<td>31.20</td>
<td>212</td>
</tr>
</tbody>
</table>
carbide powders, hence, the amount of WC powder required to form WC reinforced composite is much lower. Further, aluminium particles are bigger in size (150µm) in comparison to carbide particles (50µm). This means that the powder stacking will be poor in WC reinforced composite compared to other composite producing larger/elongated pores and elongated grains. This is evident in Fig. 4. Hence, the Al/WC composite shows poor impact strength. This is also true for homogenous cooling techniques. Overall, there were hardly any improvements in the impact strength values noted between direct sinter-forged cooling and homogenous sinter-forged cooling techniques.

Further, it can be noted that the breaking strength is the same as the ultimate tensile strength for pure aluminium and its composites. Once the ultimate tensile strength was reached the specimen maintained this strength before finally breaking. This is evident from Figs. 5 and 6.

4. Conclusions

The mechanical behaviour of aluminium metal matrix composites reinforced with tungsten carbide, molybdenum carbide, titanium carbide and iron carbide was investigated in this research. The results show that:

- Pure aluminium preforms produced more equi-axed grains and less intergranular porosity in comparison to carbide reinforced aluminium metal matrix composites. The grains were larger and elongated when the samples were re-heated before final cooling. Micro-voids formations are also observed along the reinforcing particles/matrix interface.
- The hardness values and ultimate tensile strength are observed to follow some degree of similar trend. On the other hand, the impact strength totally follows the opposite trend.
- The hardness values and ultimate tensile strength of carbide reinforced aluminium metal matrix composites were found to be higher for water-cooled compared to furnace-cooled technique for direct sinter-forged cooling. On the other hand, homogenous sinter-forged cooling follows the opposite trend.
- Hardly any improvement in hardness values, impact strength and ultimate tensile strength were observed when the re-heat process was employed before final cooling.

Conflicts of interest

The authors declare that there is no conflict of interests regarding the publication of this article.

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