

# Mechanical Properties and Microstructure of Forged Al MMCs Compared with Extruded Materials

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## Abstract

*Driven by a range of environmental concern and social pressure backed by legislation, there is a move towards reducing weight in road vehicles. These requirements led to considerable changes in car design in the last decade and will lead to further innovations. The use of light materials, such as aluminium, magnesium and metal matrix composites (MMCs) can potentially help the automotive industry to meet some of the future requirements. In particular low-cost particulate reinforced aluminium MMCs offer some attractive mechanical properties, such as high specific stiffness, strength and good wear resistance, for lighter components design. The thermomechanical processing route to the final component shape could improve some properties of these materials such as fracture elongation and toughness, which are essential for safety car components. This paper will deal with the evaluation of mechanical properties and microstructure of a AA6061-Al<sub>2</sub>O<sub>3</sub> MMCs H-shaped forged part, which is a representative of the typical section of loading bearing components.*

## Riassunto

In questi ultimi anni è cresciuta notevolmente la pressione sociale ed anche legislativa verso veicoli più efficienti in termini di consumi, con ridotte emissioni dannose, minor rumorosità, migliori caratteristiche di comfort e guidabilità.

Tutte queste esigenze hanno indirizzato la progettazione dei nuovi veicoli verso un miglioramento dell'efficienza dei motori ed in particolare ad una riduzione del peso complessivo dell'autoveicolo.

L'impiego di leghe leggere quali leghe di alluminio, magnesio e compositi a matrice metallica (MMC) può aiutare l'industria automobilistica a soddisfare future richieste a carattere legislativo. In particolare MMC a basso costo, quali quelli costituiti da leghe di alluminio rinforzate con particelle ceramiche, offrono delle caratteristiche meccaniche interessanti (alta rigidità specifica, buona resistenza meccanica e ad usura) per la progettazione di componenti più leggeri. Il processo di trasformazione termomeccanica potrebbe migliorare alcune proprietà di tali materiali quali l'allungamento a rottura e la tenacità che sono essenziali per la realizzazioni di componenti automobilistici di sicurezza. Questo articolo analizza l'influenza del processo termomeccanico di forgiatura sia sulle proprietà meccaniche che sulla microstruttura della lega AA6061-Al<sub>2</sub>O<sub>3</sub> MMCs-H ottenuta per estrusione. L'esperimento di forgiatura studiato è una trasformazione da barra estrusa in un particolare con sezione ad H, tipicamente presente in componenti automobilistici strutturali.

## Introduction

Driven by a range of environmental concern and social pressure backed by legislation, there is a move towards reducing weight in road vehicles. These requirements led to considerable changes in car design in the last decade and will lead to further innovations. The use of light materials, such as aluminium, magnesium and metal matrix composites (MMCs) can potentially help the automotive industry to meet some of the future requirements. Low-cost particulate reinforced aluminium MMCs, in particular, offer attractive mechanical properties, such as high specific stiffness, strength and good wear resistance, for lighter components design. These materials are isotropic and they can be processed using most technologies developed for monolithic alloys. One of the main drawbacks of these materials is the low ductility and low toughness, which limits their applications for safety car components. Previous research [1] showed that the optimum thermomechanical processing could improve the ductility of the particulate reinforced aluminium MMCs. The aim of the present work is to identify changes in microstructure occurring through forging process and to evaluate the effects of forging process on mechanical properties of 6061-10%Al<sub>2</sub>O<sub>3</sub> MMC. The specific forge trial studied is one from an extruded bar to a H-section part, which is a representative of typical section of load bearing car components.

## Materials

In order to reduce the weight up to 35% of an existing steel suspension arm by replacing steel with aluminium MMCs without subsequent loss of strength, stiffness and ductility, the mechanical properties of the latter should meet the following requirements:

- elastic modulus not less than 80 GPa.
- yield strength not less than 300MPa.
- fracture elongation not less than 10%.

Among the available Al MMCs on the market, the 6061-10%Al<sub>2</sub>O<sub>3</sub> alloy appears to be the most promising material for such an application.

Thus, the material under investigation is a commercial Al 6061-Al<sub>2</sub>O<sub>3</sub> particulate composite supplied by Duralcan USA. The material designation is W6A.10A which nominally contain 10% by volume of 6µm Al<sub>2</sub>O<sub>3</sub> particulate. The as-received material is in the extruded condition, a bar of 80 mm in diameter. Based on the dimension of the as-extruded bar a H-section for the forged part has been designed (Fig. 1). Such a H-section can be considered as a typical cross section for a load bearing suspension arm.

Forging has been performed at Stampal S.p.A. Italy. The part temperature is 430°C, and the die temperature (lower/upper) is 257/346°C. The forged parts are heat treated to the T6 condition. The heat treatment parameters are as follows: solution treatment at 560°C for 1h, water (17°C) quenching and aging at 176°C for 10h. The as-extruded bar is also heat treated following the same procedure.

## Mechanical testing

The mechanical properties are determined by room temperature tensile testing. Tensile specimens are machined from the extruded bar and from the H-section forged part with the testing direction parallel to the previous extrusion direction. Fig. 1 shows the positions in the H-section, from which the tensile specimens are machined. Specimens have a reduced section length of 30 mm and a diameter of 8 mm with threaded ends. Tensile tests are carried out at a strain rate of 1.1x10<sup>-3</sup>s<sup>-1</sup>. At least 5 valid tests are performed for each material.

## Examination of microstructure

Firstly, the initial microstructure before tensile testing is investigated. The transverse section of the H-section forged part is examined. The symmetrical nature of the forging means that it is sufficient to prepare a half of the cross section. Macroetching is performed using hot sodium hydroxide. The macro- and microstructure over the cross section is examined by optical microscopy. Microstructure observation of the longitudinal section is also carried out in two regions: A and B as shown in Fig. 1. In order to do this, the threaded ends of the tensile specimen (after testing) are sectioned longitudinally for metallographic examination. A longitudinal section of the extruded material is also prepared following the same procedure. Secondly, the fracture surface of tensile specimens (both forged and extruded) is examined by SEM.

## Results and discussion

The E modulus, yield strength, ultimate (fracture) strength and fracture elongation determined by tensile testing are shown in Fig. 2. Comparing the forged material to the extruded one the E modulus and the fracture elongation are increased by 8% and 28% respectively. The strength of the material does not appear to be



affected by the forging process, but the standard deviation of the strength value is affected, being  $\pm 6-8$  MPa ( $\sim 2\%$ ) for the forged material and  $\pm 13-14$  MPa ( $\sim 4\%$ ) for the extruded material. The stiffness and the strength of the forged material have met the requirement, but the target of elongation value (10%) has not been reached.

A close study of the results of the individual tensile tests shows that the specimen (A1) which has the highest elongation is machined from A region (see Fig. 1), while the specimen (B1) with the lowest elongation is from B region. The mechanical properties of these two specific specimens are given in Table 1 and compared with the average value of the extruded material.

**TABLE 1 - Mechanical properties**

Specimen	E (GPa)	$\sigma_{\gamma}$ (MPa)	$\sigma_{\mu}$ (MPa)	c (%)
forged A1	83,6	323,6	352,9	8,7
forged B1	80,1	314,0	342,5	6,9
extruded av.	76,8	329,6	358,3	6,5

Fig. 3 shows the forged part and the macrostructure of a half cross section of the forged part. It is noticed that the grain structure in B region is coarser than that in A region.

An early investigation [2] has shown that microstructure inhomogeneities, such as particle-free areas and particle clusters are present in the as-extruded bars. Fig. 4 shows the microstructure, particularly the spatial distribution of  $Al_2O_3$  particles, of a cross-section of the forged sample. Low magnification is used allowing that the microstructure of a large area of about  $10 \text{ mm}^2$  is shown by a single micrograph. Particle-free area of  $100-300 \mu\text{m} \times$  a few mm is frequently found in B region, while A region has a more uniform microstructure.

The microstructure of the longitudinal section of the forged material is shown in Fig. 5. The material in A region (Fig. 5(a)) is free of particle-free areas and contains less particle clusters. The microstructure in B region (Fig. 5(b)) is similar to that in extruded material (Fig. 5(c)), containing particle-free bands ( $100-200 \mu\text{m}$  in width and millimetres in length) and particle clusters ( $30-200 \mu\text{m}$  in diameter). The fracture surface of forged material (specimen A1 from A region) and of extruded material are shown in Fig. 6. Both exhibit ductile fracture of the matrix and brittle fracture of the  $Al_2O_3$  particles (Fig. 6(a)). However, areas characteristic of brittle fracture are often seen in the fracture surface of extruded material (Fig. 6(b)). The size of such area is up to  $100 \mu\text{m}$  in diameter. In these areas even the matrix does not exhibit ductile fracture. It is believed that this type of local area of brittle fracture is related to the presence of particle clusters in the material.

Comparing the microstructure of the H-section forged part to that of the extruded bar, it is obvious that one of the important microstructural changes occurring through forging process is the change of  $Al_2O_3$  particle distribution. The magnitude of this change varies, being large in region A and small in region B. This microstructural changes correlate with the macroscale deformation of the material during the forging process. The finite element modelling of the same forging process (an Al MMC extruded bar been forged into a H-shape section) predicts [3] that the strain value in A region is around 1, the second highest in the cross section (the

highest value is found near the flash), and the strain value in B region is around 0.5, the lowest in the cross section. It appears that more homogenous microstructure (more uniform particle distribution and finer grains) is obtained in the region which is subjected to higher strain during forging.

The microstructure observation also correlates well with the mechanical properties of the material. First, forging process generally reduces the microstructure inhomogeneities present in the extruded material and leads to on average an increase in the E modulus and fracture elongation, as well as a decrease in the scattering of the strength value. Second, it has shown that the higher ductility is achieved in region A, where a more homogeneous microstructure is obtained through the forging process, while the lower ductility is found in region B where the material inherits microstructure inhomogeneities from extruded bar. It appears that the distribution of  $Al_2O_3$  particles has an important influence on the fracture behaviour and ductility of the material. This observation is in agreement with Lloyd [4], who has suggested that the damage occurring in particle clusters because the high triaxial stress in these local regions initiates final fracture. Ref [4] also suggested that the tensile elongation of particle MMCs is very sensitive to the heat treatment, decreasing with increasing strength of the matrix. To improve the ductility of the forged part, future work will be focused on optimizing the particle distribution through extrusion and forging processes and optimizing the heat treatment procedure after forging.

## Conclusion

The mechanical properties and the microstructure of a 6061-10%Al<sub>2</sub>O<sub>3</sub> H-section forged part has been investigated and compared to those of the extruded bar. The following has been found:

1 The changes in microstructure occurring through forging process correlate with the macroscale deformation of the material. In general forging process reduces the microstructure inhomogeneities such as particle clusters and particle-free bands, and refines the grain structure.

2 The increase of both the elastic modulus and the fracture elongation in the forged material can be related to the more homogeneous structure.

3 No particular influence of the forging process on the strength of the material has been observed, but the scatter in the  $\sigma_y$  and  $\sigma_u$  measured values is lower in the forged material, probably related to the more homogeneous structure.

4 The obtained results, compared with the target values are quite satisfactory in terms of elastic modulus and yield strength. The 10% elongation target has not been reached. An improvement in this direction could be obtained through particular heat treatments and optimization of the extrusion and forging process.

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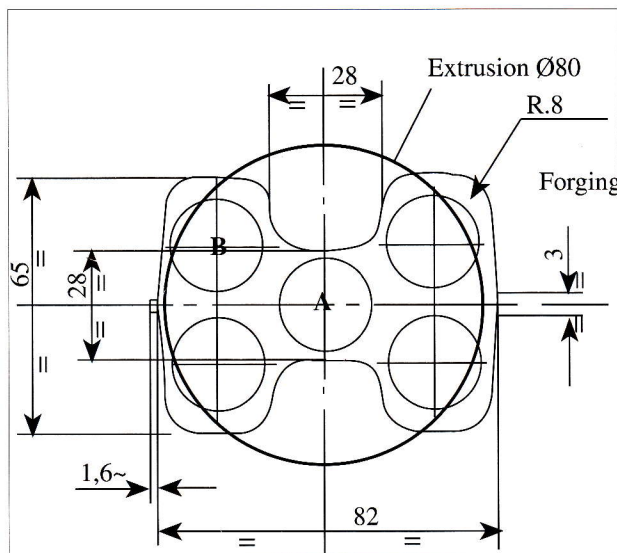


Fig. 1  
Design of the H-section

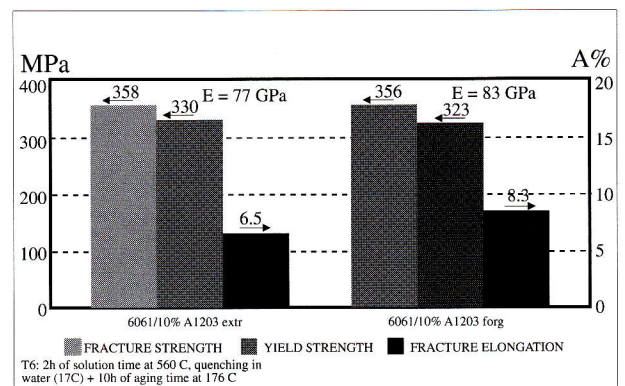


Fig. 2  
Mechanical properties determined  
by tensile testing for the forged and extruded  
6061-10%Al<sub>2</sub>O<sub>3</sub>



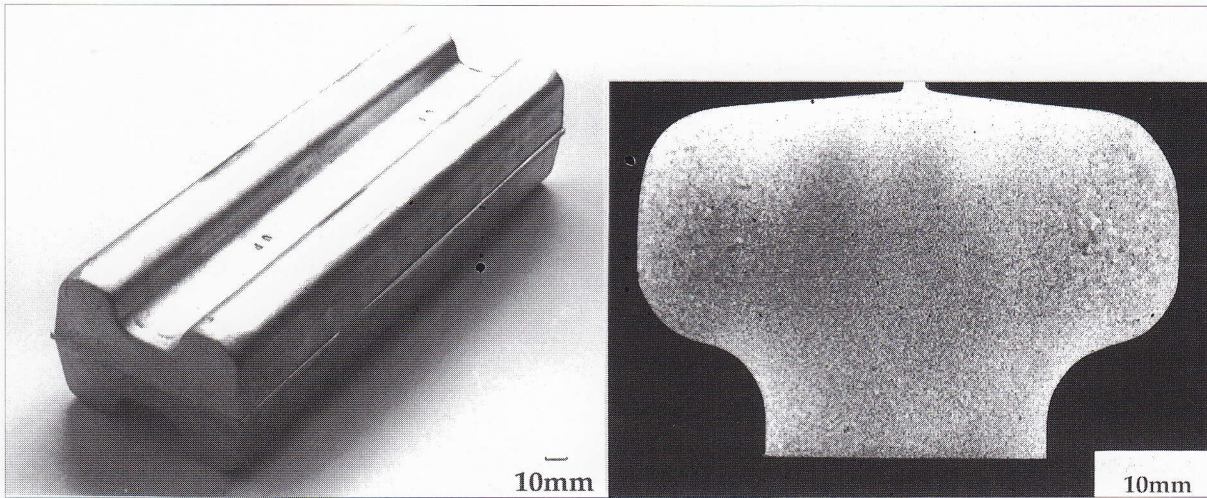


Fig. 3  
(a) H-section forged part.  
(b) Macrostructure of 6061-10%Al<sub>2</sub>O<sub>3</sub> H-section forged part (hot caustic etching).

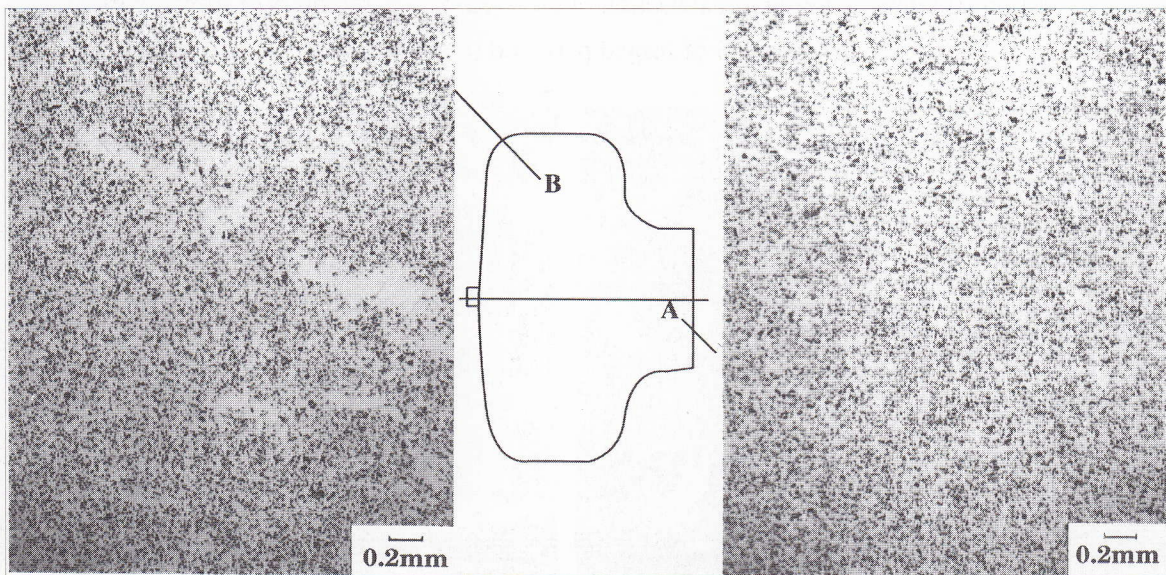


Fig. 4  
Microstructure of cross section of 6061-10%Al<sub>2</sub>O<sub>3</sub> forged part.



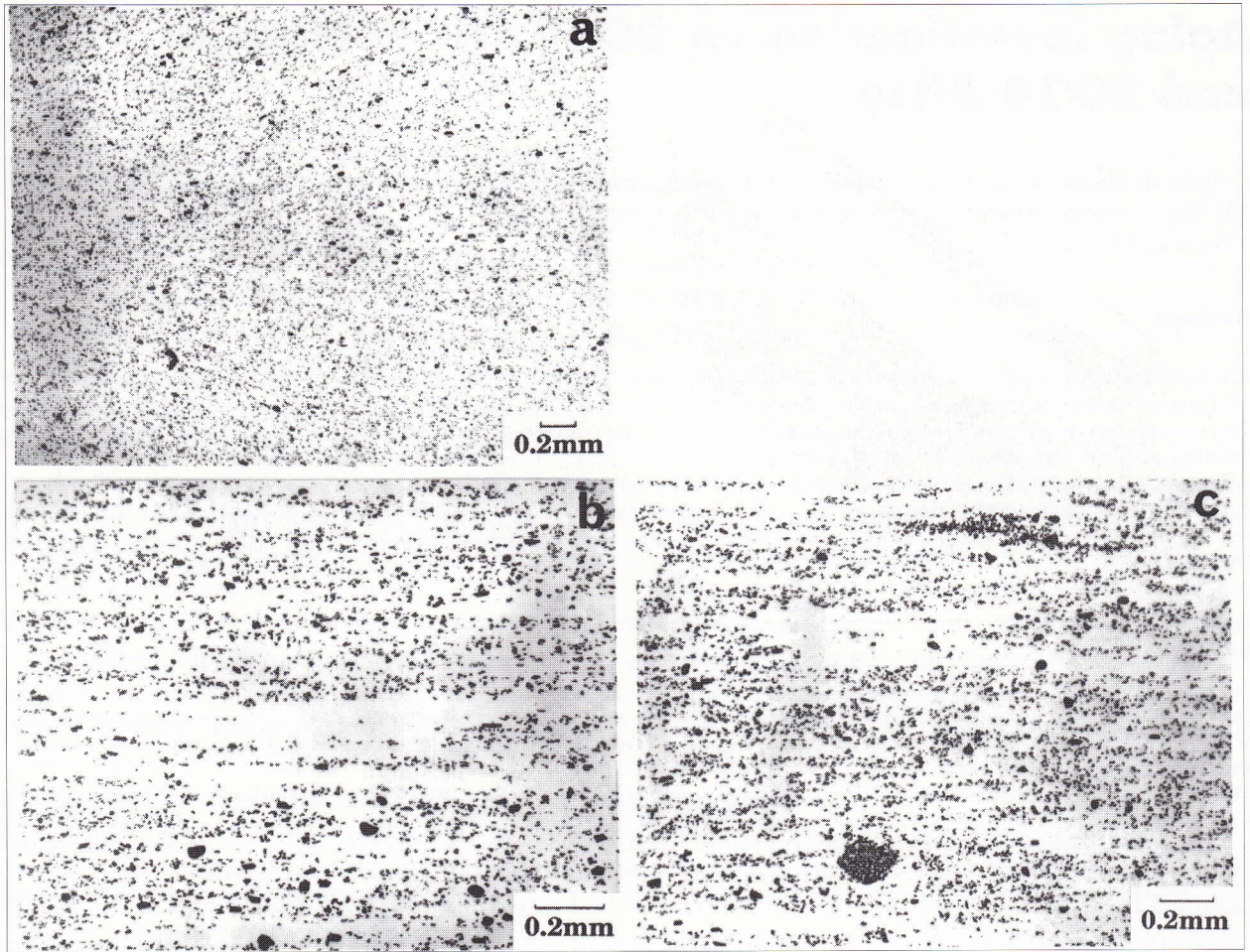


Fig. 5  
 Microstructure of longitudinal section of 6061- $\text{Al}_2\text{O}_3$  (a) region A of forged part,  
 (b) region B of forged part, and (c) extruded bar.

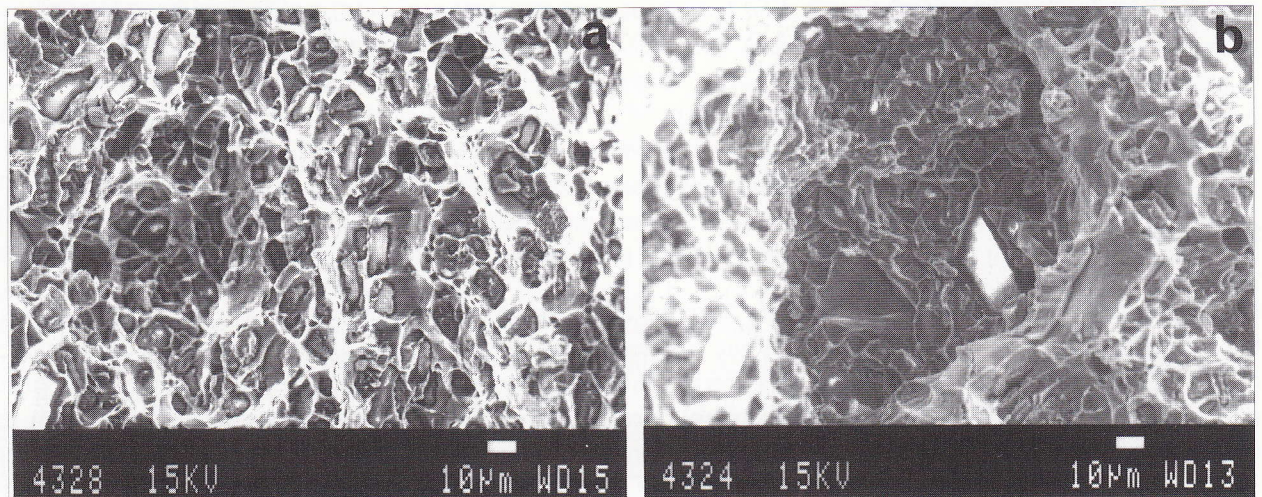


Fig. 6  
 Fracture surface of (a) forged (specimen A1 from A region), and (b) extruded 6061-10% $\text{Al}_2\text{O}_3$