Hot Forming Related Properties of Al-based Particulate Composites

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Abstract

The hot tensile deformation behaviour of the 6061/Al_2O_3, 2618/Al_2O_3 and 2618/SiC particulate reinforced composites was investigated over a range of temperatures and strain rates. A unreinforced 6061 monolithic alloy was also considered for comparison purposes. The composite materials exhibited a similar hot working behaviour with anticipated onset of matrix restoration mechanisms as a function of temperature with respect to the unreinforced alloy. Microstructural analyses on broken specimens allowed to observe reinforcement damage and matrix evolution during hot deformation.

Riassunto

Nel presente lavoro sono state studiate le caratteristiche di deformabilità a caldo dei compositi 6061/Al2O3, 2618/Al2O3 e 2618/SiC in un intervallo di temperature e velocità di deformazione di interesse per la valutazione della loro lavorabilità a caldo. Oltre ai compositi è stata compresa tra i materiali per le indagini una lega di alluminio 6061 non rinforzata, studiata a scopo di confronto. Tutti i compositi considerati hanno fatto riscontrare un comportamento simile alla deformazione plastica a caldo e un anticipo dei dell'attivazione dei meccanismi di ripristino dinamico in funzione della temperatura rispetto alla lega non rinforzata. Ulteriori analisi microstrutturali sui campioni deformati alle alte temperature hanno consentito di valutare le modalità di evoluzione della microstruttura e di danneggiamento e cedimento nei materiali.

Introduction

Discontinuously reinforced metal matrix composites (MMC's), especially aluminium based particulate reinforced composites, have emerged as a new class of advanced materials having attractive combination of mechanical properties (enhanced stiffness, isotropic behaviour), physical properties (low coefficient of thermal expansion, low density) and wear resistance.

Their isotropic properties make them amenable to most conventional metalworking processes such as rolling, extrusion, forging [1]. Owing to limited plasticity at room temperature, particulate reinforced MMC's are more suited to processing at elevated temperature. In such condition the enhanced matrix plasticity prevents localisation of stresses around particles to build up, thus reducing the extent of particle damage by cracking or interface decohesion.

Despite the similarities to unreinforced monolithic alloys, standard processing parameters of the matrix cannot be directly adopted for the corresponding particulate reinforced composite and hence, the forming temperatures and strain rates have to be optimised for each specific composite system. Research in this field is indeed very active as demonstrated by the number of papers recently published on hot deformation behaviour [2-5], efficiency and instability maps [6-11], microstructure and microstructural damage [12-17] during elevated temperature plastic strain of Al-based MMC's.

The present investigation is aimed at focussing on hot deformation under tensile conditions of three particulate reinforced composites and a monolithic unreinforced alloy. Analysis of data obtained at four different testing temperatures and three strain rates allowed to state general trends for high temperature mechanical behaviour of composites and to comment on variations existing amongst materials differing in their reinforcement type or matrix composition.

MATERIALS AND EXPERIMENTAL PROCEDURES

Four different materials were considered to investigate hot formability of MMC's. A 6061/20%Al_2O_3 particulate reinforced composite and the corresponding monolithic unreinforced 6061 alloy were selected to evaluate the effect reinforcement addition on high temperature behaviour of the matrix alloy. Further testing on a 2618/20%Al_2O_3 and a 2618/20%SiC particulate reinforced composite allowed to assess the effect of reinforcement type. Both materials were manufactured by the producer through a proprietary molten metal mixing process and supplied as extruded bars having a diameter of 80 mm.

After material heat treatment to T6 temper, cylindrical tensile specimens with a gauge length of 30 mm and a diameter of 6 mm were machined. Tensile tests were carried at 350, 400, 450 and 500°C at strain rates of $1 \cdot 10^{-3}$, $1 \cdot 10^{-2}$, $1 \cdot 10^{-1}$ s^{-1}. A soaking time of 30 minutes at testing temperature was maintained before pulling to fracture the specimens. From recorded data, true stress vs. true plastic strain plots were obtained and analysed to draw information on evolution of strength, flow stress, ductility and strain rate sensitivity of the different materials.

In addition, microstructural analyses were performed by SEM and optical microscopy on longitudinally sectioned fractured specimens.

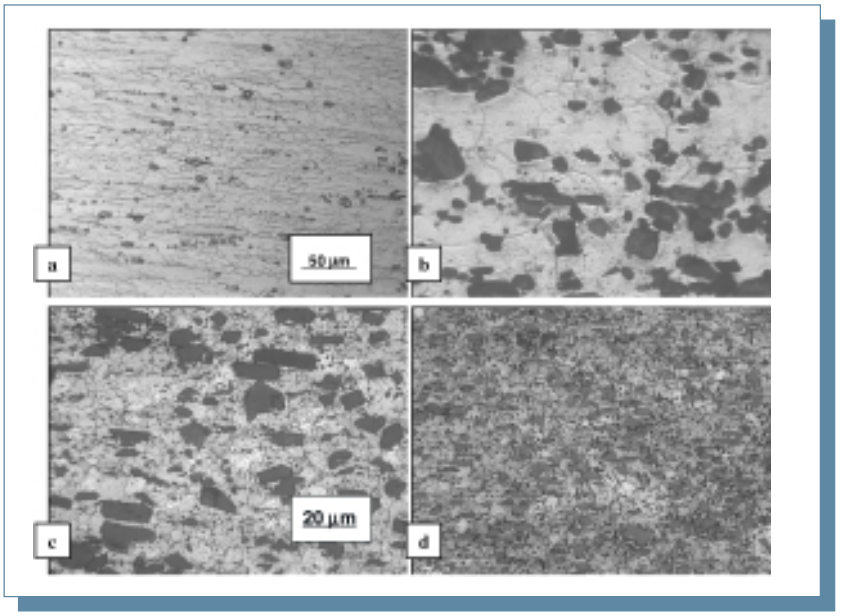

Fig.1: Representative optical micrographs of the materials investigated. (a) 6061 monolithic alloy, (b) 6061/20%Al_2O_3 composite, (c) 2618/20%Al_2O_3 composite, (d) 2618/20%SiC composite

RESULTS AND DISCUSSION

Figure 1 summarises the materials microstructure after T6 heat treatment. In the unreinforced 6061 alloy, a fine structure of both equiaxed and elongated grains was observed. On the contrary, in the corresponding 6061/20%Al_2O_3 composite, the structure was made up of larger fully equiaxed grains. A much finer matrix grain structure was noticed in the 2618-alloy based composites. In these materials a fairly copious precipitation of phases rich in Fe-Ni-Cu-Si (as detected by EDS microanalyses) was noticed in the matrix.

The micrographs in figure 1 also demonstrate that the reinforcement size was larger for the Al_2O_3- than for the SiC-reinforced composites. The average particle size was estimated to be 21 µm in the former case and 11 µm in the latter.

The high-temperature stress-strain curves of the 6061 alloy and of the 6061/20%Al_2O_3 composite are depicted in figure 2 to discuss on the general behaviour of the materials under tensile strain condition. The curves refer to tests performed at decreasing temperatures, from the top to bottom: 350-400-450-500°C. In literature, data on hot forming behaviour are usually generated under compression or torsion testing in order to better simulate common hot working condition and retard material instability. Elongations greater than 50% are readily achieved also in MMC's and an almost constant flow stress regime is generally reached after a peak stress [8,12,14,15]. On the contrary, in tensile testing, necking soon occurs and composite damage is reported to develop more easily by ceramic particle cracking [16,18-20]. However, it must be considered that stress conditions having a tensile component during metalworking are often produced in shaping complex geometries. Therefore, apart from the fundamental research interest, in-

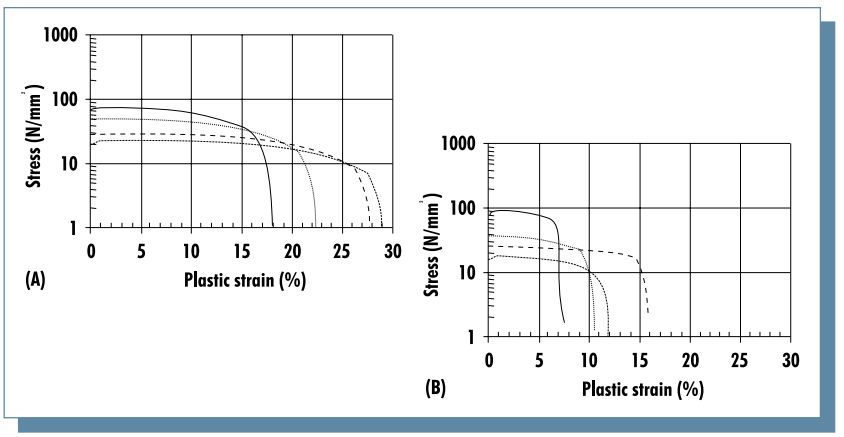

Fig.2: True stress vs. true plastic strain curves of the 6061 alloy (a) and of the 6061/20%Al_2O_3 composite (b) at a strain rate of $1 \cdot 10^{-2} s^{-1}$

vestigations on high temperature tensile behaviour of MMC's are of great practical importance.

Data on tensile strength of the materials investigated are better visualised in figure 3, where the profiles of UTS are given as a function of test temperature and strain rate. In the examined temperature range, the unreinforced alloy showed a continuous and decreasing trend of UTS with increasing temperature. In the composites, at temperatures exceeding 400°C, a substantial plateau of the UTS values was noticed for the slowest strain rate investigated. Such trend was supposed to be related to the anticipated activation of restoration mechanisms in the composite matrices during hot deformation. In literature, depending on composite and testing conditions investigated and authors interpretation, either dynamic recrystallisation (DRX) or dynamic recovery were proposed as active mechanisms. It is also well established that reinforcement addition decreases the critical strain for DRX due to increased dislocation generation during hot deformation, thus anticipating the onset of dynamic restoration regime with respect to the unreinforced monolithic alloy [14].

As expected, a increase in strain rate produced a shift toward higher stress values of the curves and reduced possibility of structure restoration. The above mentioned plateau at temperatures higher than 400°C became less evident at the strain rate of $1 \cdot 10^{-2}$ s^{-1} and completely absent at the highest strain rate level.

Finally, it is worth emphasising that, apart from slight differences probably related to experimental data scatter, the two 2618 alloy based composites had a substantially identical tensile behaviour thus confirming that, at high temperatures, the reinforcement strengthening effects are of little significance and even lower importance can be addressed to small differences in reinforcement distribution and size.

In figure 4, data on tensile ductility of the 2618/20%SiC and 2618/20%Al_2O_3 composites are given as a function of temperature and strain rate. The comparison is proposed to discuss on the effects of reinforcement type and size. It can be observed that the composite with finer particles (SiC) experienced a clear improvement in tensile ductility with increased testing temperatures. On the contrary, in the Al_2O_3 reinforced material, the ductility remained at low levels even at the highest temperature investigated.

Interpretation of the above data were supported by microstructural observations carried out on longitudinally sectioned broken specimens. Figure 5 shows typical micrographs taken close to fracture surface of the 2618/SiC and the 2618/Al_2O_3 composites. Limited damage associated to ceramic particles is visible in figure 5a, referring to an as polished sample observed by SEM. Ductile voids originated either by decohesion of particle-matrix interfaces or by fracture of the coarser and more elongated particles. No predominant failure mechanism as a function of material or testing conditions was identified from micrographs and analyses of the fracture surfaces. Figure 5b is an optical micrograph of an etched samples showing that the deformed structure featured well recrystallised fine equiaxed grains. Again, this behaviour was observed in all of the composites investigated at the testing temperature of 500°C. Further work is currently in progress to elucidate the grain structure modification at lower deformation temperatures.

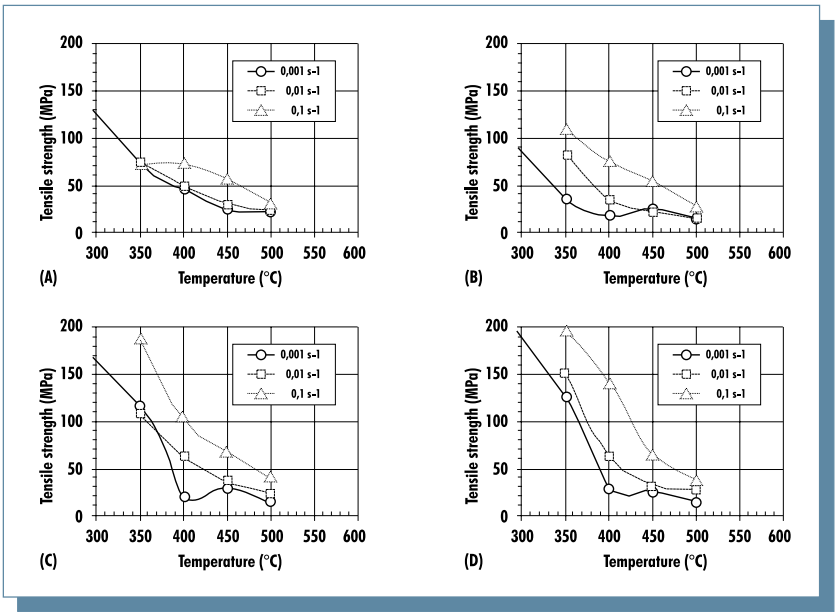

Fig.3: Evolution of ultimate tensile strength as a function of temperature and strain rate for the materials investigated. (a) 6061 monolithic alloy, (b) 6061/20%Al_2O_3 composite, (c) 2618/20%Al_2O_3 composite, (d) 2618/20%SiC composite

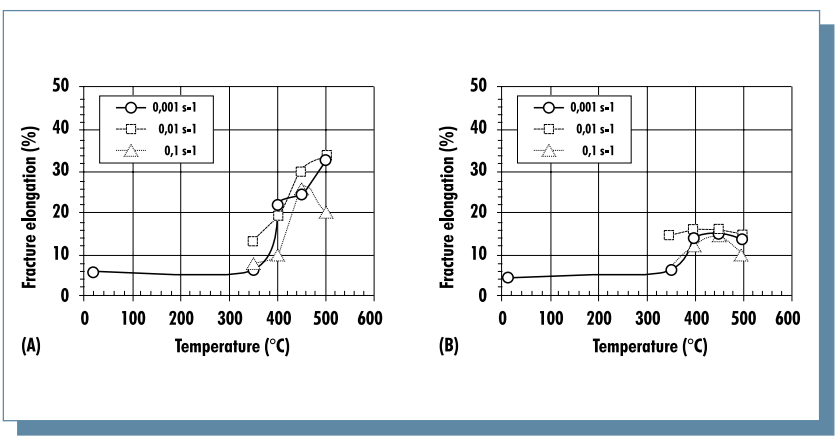

Fig.4: Evolution of tensile ductility as a function of temperature and of strain rate for the (a) 2618/20%SiC and (b) 2618/20%Al_2O_3 composites

CONCLUSIONS

The hot tensile deformation behaviour of the 6061/Al_2O_3, 2618/Al_2O_3 and 2618/SiC particulate reinforced composites and of the unreinforced 6061 monolithic alloy was investigated over a range of temperatures and strain rates.

The data allowed to state differences with the unreinforced alloy and similarities amongst the hot deformation behaviour of the three composites. In the composites, the action of dynamic restoration mechanisms inducing an abrupt decrease of the flow stress was observed, at the lowest strain rate, at temperatures exceeding 400°C whereas the monolithic alloy featured a significantly higher strength at this testing temperature.

The high temperature strength of the composites was ruled by matrix properties, the 6061 alloy matrix being softer than the 2618 one, as expected. The two 2618-based composites showed a substantially identical behaviour as a function of temperature and strain rate. The only difference was observed in tensile ductility whereby the composite reinforced with the coarser Al_2O_3 particles revealed to be more brittle than the 2618/SiC material, especially at the highest testing temperatures.

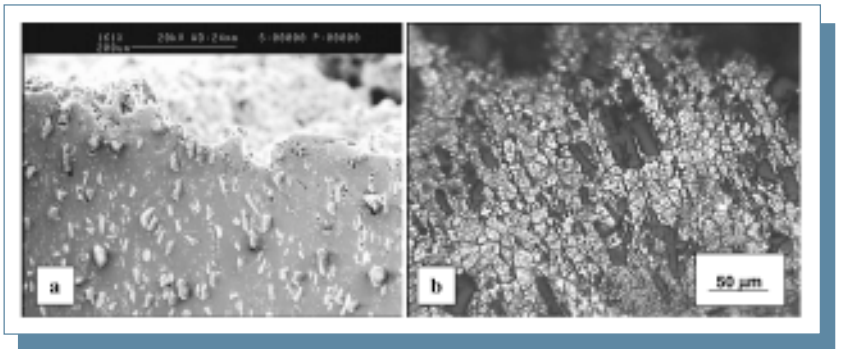

Fig. 5: Micrographs of sectioned specimens of the 2618/SiC composite strained at 350°C, $1 \cdot 10^{-3} s^{-1}$ (a) and of the 2618/Al_2O_3 composite strained at 500°C, $1 \cdot 10^{-3} s^{-1}$ (b)

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