Hot workability of aluminum particulate composites

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ABSTRACT. This paper analyzes hot torsion flow curves [1-5], microstructures [1,2,6-9], constitutive equations and extrusion finite element modeling (FEM) [10-13] of aluminum composites. Those results come mainly from previous studies of prof. H.McQueen et alii. Metal-matrix composites (MMC) of 6061, 7075, 2618 and A356 alloys with Al_2O_3 or SiC particles (15-30 μm) were produced by liquid metal mixing. Aluminum alloy matrices reinforced with particles of Al_2O_3 or SiC possess higher strength and stiffness as well as greater wear resistance and improved high temperature properties [14-17]. MMC produced by liquid metal mixing are secondarily fabricated by traditional mechanical forming (extrusion, forging or rolling) [18-21]. Materials were deformed over the temperature range 300 to 500°C and strain rates 0.1 to 4/5 s^{-1}. At 400°C (and lower T) the strength of composites is higher than that of the alloys. With exception of 6061 and 2618, there is almost no difference in strength at 450°C while at 500°C composites appear to be softer than the alloys. 2618 MMC exhibit lower ductility then A356 and 6061 MMC that exhibit similar ductility. 7075 alloy and MMC decline from good ductility at 400° to very low at higher T because of GB precipitation [1-5]. The softening of the alloys with increasing T (and with decreasing strain rate) is due to improved DRV. The softening of composites depends on more complicated changes in microstructure: DRX occurs to a limited extent along with dynamic recovery. Furthermore, the composites retain heterogeneous substructures in both quenched and air cooled torsion specimens since no static recrystallization occurred after torsion [1,2,6-9]. Constitutive analysis was developed according to Garofalo hyperbolic stress equation and showed that the MMC increase in strength and in activation energy Q_{HW} as alloying element and particles contents rise. The extrusion was modeled using the finite element software DEFORM^{tm}. This program uses a flow formulation approach and an updated Lagrangian procedure; it possesses an automatic remeshing scheme to allow the modeling of large or localized deformations. Extrusion was modeled for a billet with diameter 178 mm and height 305 mm, an extrusion ratio R = 31 and ram speed VR = 2.6 or 5 mm/s in similarity to previous modeling [10-13]. The constitutive laws determined by the torsion tests have been used in the model to calculate flow stresses. Models were developed for the initial billet temperatures TB from 300 to 500°C. From modeling temperature T, strain ε, strain rate $\dot{\varepsilon}$ and stress σ distribution together with T_{Max} and P_{Max} were determined. The results were validated by comparing to actual extrusions. The grid distortions and distributions of ε and $\dot{\varepsilon}$ are independent of material properties. As TB increases (from 300°C to 500°C) the composite extrusion pressure decreases towards that of the bulk alloys. This applies: from 300 °C to 400°C for A356 and 7075 above which the composite pressure is equal or lower than that of alloys and from 300°C to 500°C for 6061 and 2618. The maximum load increases in order of matrix alloy 6061, A356, 7075 and 2618. The temperature increases in the same order. Because of incipient melting in 2618 is near to 500°C, TB must be limited for this alloy. Since constitutive analysis for a new alloy, on its adoption for a previous extrusion production, is often available, correlation of maximum extrusion pressure P_{Max} with activation energies Q_{HW} was made [22].

SOMMARIO. Questo lavoro analizza sia le curve di flusso derivanti da prove di trazione a caldo [1-5] che la microstruttura [1,2,6-9] e le simulazioni del processo di estrusione (FEM) [10-13] di compositi in lega di alluminio. I risultati in analisi derivano principalmente da studi del Prof. H. McQueen. I compositi studiati (a matrice in lega 6061, 7075, 2618 e A356), di seguito indicati con la sigla MMC (Metal-Matrix-Composites), sono stati ottenuti via liquid metal mixing con particelle di rinforzo in Al_2O_3 o SiC (15-30 μm). In genere i compositi prodotti via liquid metal mixing esibiscono proprietà meccaniche superiori alle rispettive leghe bulk sia a temperatura ambiente che elevata. Sono inoltre caratterizzati da una migliore resistenza all'usura [14-17]. Tali compositi vengono lavorati secondo i tradizionali processi di estrusione, fucinatura o laminazione [18-21]. MMC e leghe bulk in analisi sono stati sottoposti a prove di torsione a caldo a temperature T comprese tra 300 e 500°C e velocità di deformazione $\dot{\varepsilon}$ tra 0,1 e 4/5 s^{-1}. La resistenza di tutti compositi è risultata superiore a quella delle rispettive leghe a T inferiore ai 400°C, mentre a T più elevata solo i compositi delle leghe 6061 e 2618 hanno continuato ad esibire migliori performance delle leghe bulk. La duttilità dei compositi in lega 2618 è risultata essere sempre inferiore a quella dei compositi in lega A356 e 6061. Per la lega 7075 e i suoi MMC si è osservata una forte riduzione della duttilità a T superiore ai 400°C imputabile alla precipitazione di composti grossolani a bordo grano [1-5] mentre per gli altri compositi la duttilità aumenta notevolmente a partire da 400°C. La relazione tra duttilità e T di deformazione è fondamentale nel controllo delle difettosità dell'estruso. Si è dimostrato che il comportamento a caldo delle leghe bulk è controllato dal solo recupero dinamico (DRV), quello dei compositi sia da recupero dinamico che da ricristallizzazione dinamica (DRX). Inoltre, nei compositi non si è osservata ricristallizzazione statica dopo torsione [1,2,6-9]. L' analisi alle equazioni costitutive è stata sviluppata secondo l'equazione di Garofalo (1) e ha dimostrato che, nei compositi, l'energia di attivazione (Q_{HW}) cresce all'aumentare del contenuto di particelle. Le simulazioni del processo di estrusione sono state sviluppate, utilizzando il software agli elementi finiti DEFORM^{tm}, per una billetta con diametro di 178mm e altezza 305mm imponendo un rapporto di estrusione R = 31 e velocità dello spintore VR = 2.6 o 5 mm/s in analogia alle modellizzazioni precedenti [10-13]. Sono state utilizzate temperature della billette (TB) comprese tra 300-500°C. I risultati sono stati validati per confronto con estrusioni reali. Le distribuzioni delle deformazioni (ε) e delle velocità di deformazione ($\dot{\varepsilon}$) sono risultate indipendenti da tipo di materiale considerato. All' aumentare della TB (da 300 a 500°C), la pressione di estrusione dei compositi si riduce approssimandosi a quella delle leghe bulk. Questo è risultato valere fino a 400°C per i compositi delle leghe A356 e 7075 e fino a 500°C per i compositi delle leghe 6061 e 2618. Il carico massimo e la massima T (T_{Max}) di estrusione crescono entrambi nell'ordine seguente: 6061, A356, 7075 e 2618. All'aumentare di TB, l'incremento di T_{Max} è simile al variare di materiale e VR. I valori di T_{max} confrontati con la minima T dell'intervallo di fusione dei diversi materiali consentono la scelta della massima TB.

KEYWORDS. Al matrix composites; Hot torsion; Microstructures; Constitutive analysis; Workability.

INTRODUCTION

Particulate aluminum matrix composites are significant improvements over the matrix alloys in modulus, strength, hardness and fatigue and wear resistance (but reduced ductility). Metal-matrix composites (MMC) produced by liquid metal mixing are secondarily fabricated by traditional mechanical forming (extrusion, forging or rolling) [18-21]. Hot shaping is expected to reduce cracking and degradation through particle cracking or debonding [1, 9, 19-21]. The hot torsion mechanical behaviors of the composites (10-20% Al_2O_3 or SiC) and alloys have been reported for 6061 [2, 22, 23], A356 [23, 3-5] 7075 [24] and 2618 [8]; the first two were with SiC and the last three with Al_2O_3. The hot workability was studied in the ranges of 300 to 500°C and strain rates 0.1 to 4/5 s-1 to determine ductilities and flow stresses. The microstructures were examined to understand the hot working mechanism and partly define product properties [1, 2 6-9]. Modeling by DEFORM^{tm} (based on the constitutive equation) [10-13] was performed to determine T, strain ε , strain rate $\dot{\varepsilon}$ and stress σ distribution in the billet during extrusion and to give information on how extrusion parameter affect the extreme values of load and of temperature, strain and stress in distribution.

HOT FLOW CURVES ANALYSIS: STRENGTH AND DUCTILITY

The composition of alloys and MMC is given in Tab. 1.
The flow curves of composites follows general patterns (Fig.1).
At 200°C, the flow curves are rounded peaks, the strength being much higher and ductility lower than the alloys.
At 300°C the flow curves are low broad peaks (higher than the alloy) and lower ductility than the alloy.
At 400°C the flow curves are very broad plateau with ductility fairly similar to the alloy.

Material	Chemical compositions (wt. %)				
	Mg	Cu	Fe	Si	Other
6061 6061/10%Al_2O_3 6061/15%SiCp 6061/20%Al_2O_3	0.97	0.28	0.58	0.71	0.04Mn
A356 A356/15%SiCp	0.35	0.2	0.2	7.0	0.1Mn
7075 7075/10%Al_2O_3 7075/15%Al_2O_3	2.86	1.46	0.2Cr	0.03	5.83Zn
2618 2618/10%Al_2O_3 2618/20%Al_2O_3	1.6	2.3	1.1	0.18	1.0Ni

Table 1: composition of materials.

The trend to low, long flat curves continue at 500°C with strain to failure over 2 except for 7075 materials.
The ductilities of the MMC, although much lower that the alloys below 300°C increased intensively between 400°C and 500°C. The relatively high composite ductility near 500°C and 1 s^{-1} indicates a good potential for avoiding surface cracking at the die corner.
The limited ductility of MMC generally resulted from linking up of voids nucleated at large reinforcing phases; cracking dominates at low T, decohesion at high T. 2618 MMC exhibit lower ductility than A356 and 6061 MMC that were similar. The 7075 alloy and composites declined from good ductilities (ε_f ~1.5 at 400°C) at very low at 540°C as result of formation of GB precipitates. The T and $\dot{\varepsilon}$ dependence of the ductilities are significant in estimating surface defect formation in extrusion from the knowledge of the maximum values of T, ε and $\dot{\varepsilon}$.
The hot flow curves exhibit lower σ as T rises and as $\dot{\varepsilon}$ decreases .
At the low T (400°C or lower) the strength of composites is higher than the alloys.
In composites the particles are well dispersed and caused strengthening through the additional dislocations generated in the alloy matrix when deformed.
In plot σ_p V_s T, σ_p drops very rapidly at low T but more gradually near 500°C (Fig.2).
With exception of 6061 and 2618, there is almost no difference in strength at 450°C, while at 500°C composites appear to be softer than the alloys. The cause of strength cross over is not clear. In 7075 bulk alloy at T higher than 400°C, the low stress could be related to the progressive cracking due to coarse grain boundary precipitates. In 7075 MMC the low stress could be related to an increased degree of conversion of high density tangles into high misorientation cells as an initiation of dynamic recrystallization that never produced new grains.

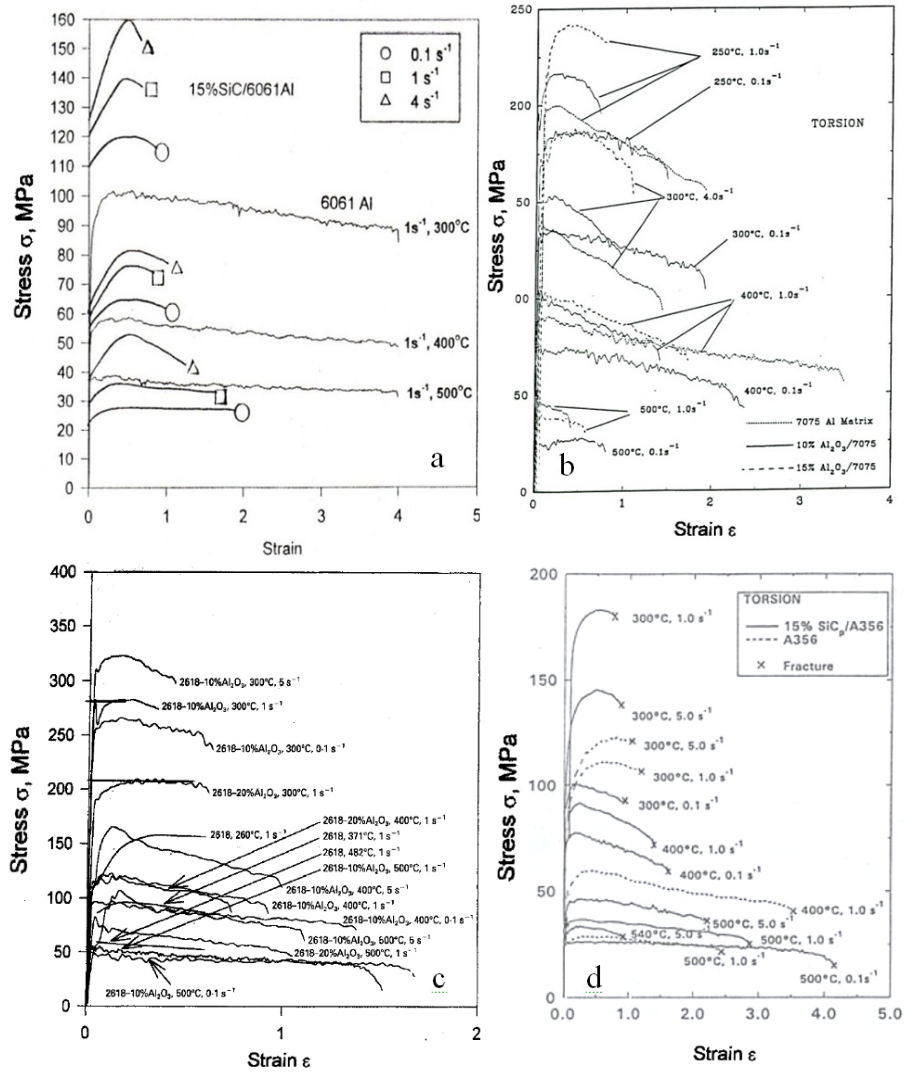

Figure 1: Hot torsion flow curves for (a) 6061 alloy and 15%SiC composites, (b) 7075 alloy with 0, 10 and 15% Al_2O_3 (c) 2618-10%Al_2O_3 at $\dot{\varepsilon}$=0.1, 1, 5s^{-1} and 2618-20%Al_2O_3 and 2618 alloy at $\dot{\varepsilon}$=1 s^{-1}, (d) A356 and A356-15% SiC.

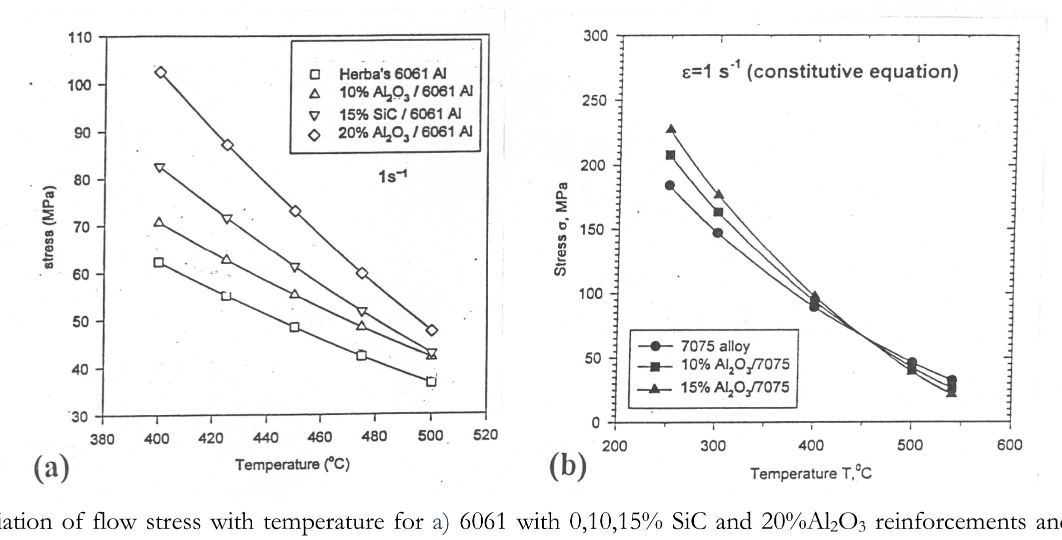

Figure 2: Variation of flow stress with temperature for a) 6061 with 0,10,15% SiC and 20%Al_2O_3 reinforcements and b) 7075 with 0,10,15% Al_2O_3, crossover of values exhibited at T lower than 500°C.

MICROSTRUCTURE EVOLUTION DURING HOT DEFORMATION

Generally dynamic recovery (DRV) is the sole restoration mechanism in Al alloys developing a subgrains structure inside elongated grains. Ductility is usually high because DRV softens grains and slows crack formation. Solutes, in the form of atmospheres hinder dislocation glide reducing DRV and ductility and raising the flow stress. Fine dispersoids pin dislocations and reduce DRV. Precipitation hardening alloys may present varied behaviors as a result of changes in precipitate morphology. In the alloys the softening with rising T or falling strain rate is related entirely to improved recovery as observed in the increase in spacing of subgrains walls and of the dislocations in both the walls and the subgrains (Fig.3).

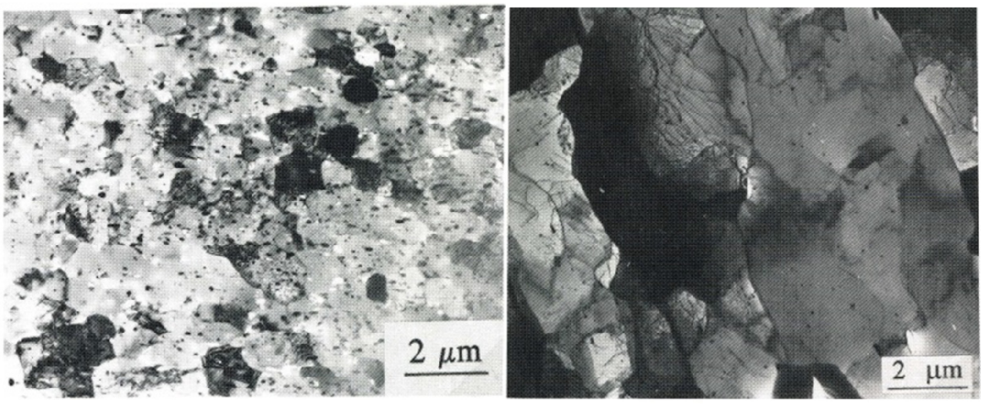

Figure 3: Subgrains observed in torsion specimens strained to $\varepsilon_F > 2$ in TEM become enlarged as T rises or $\dot{\varepsilon}$ declines (a) 7075, 300°C, 0.5 s^{-1}, (b) 7075, 400°C, 0.5 s^{-1}

The presence of particles reduces recovery and rise strength.

The softening of composites depends on more complicated changes in microstructure which is more heterogeneous than the alloys as a result of turbulent and intense plastic flow surrounding the rigid particles. About a third of the matrix volume exhibit subgrains but these are considerably less recovered and smaller than in the bulk alloys for the same conditions (Fig.4). The remaining two thirds exhibit highly misoriented cells which could be precursor to dynamic recrystallization nuclei and provide softening compared to the dense microstructure (Fig.5). Static recrystallization was not observed after torsion test in composites both quenched or air cooled because of pinning by reinforcing particles so that MMC have high strength in comparison with those of alloys.

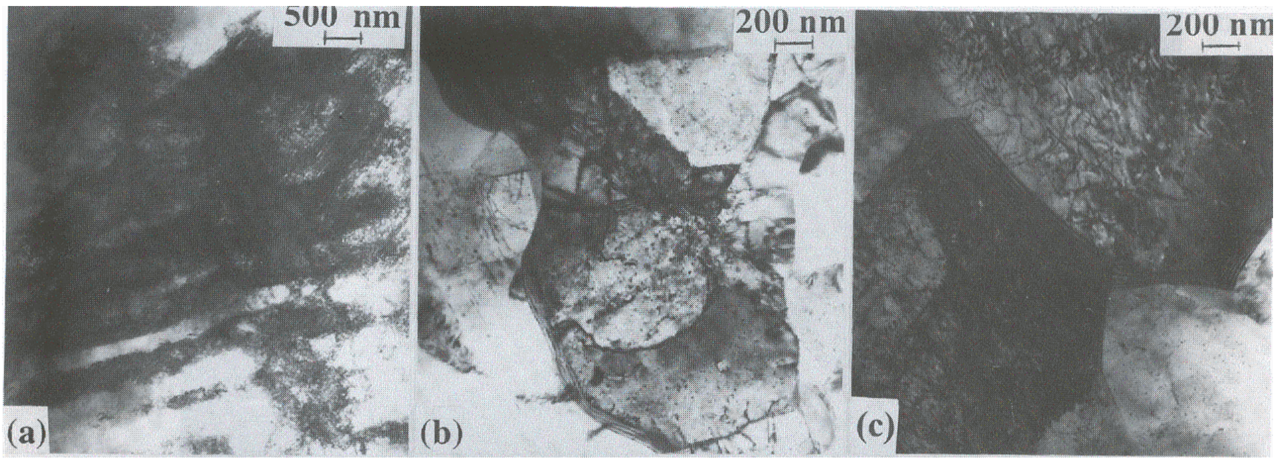

Figure 4: Subgrains observed (TEM) in torsion specimens 2618-20%Al_2O_3 at 200°C (a), 300°C (b), 400°C (c) 1s^{-1}.

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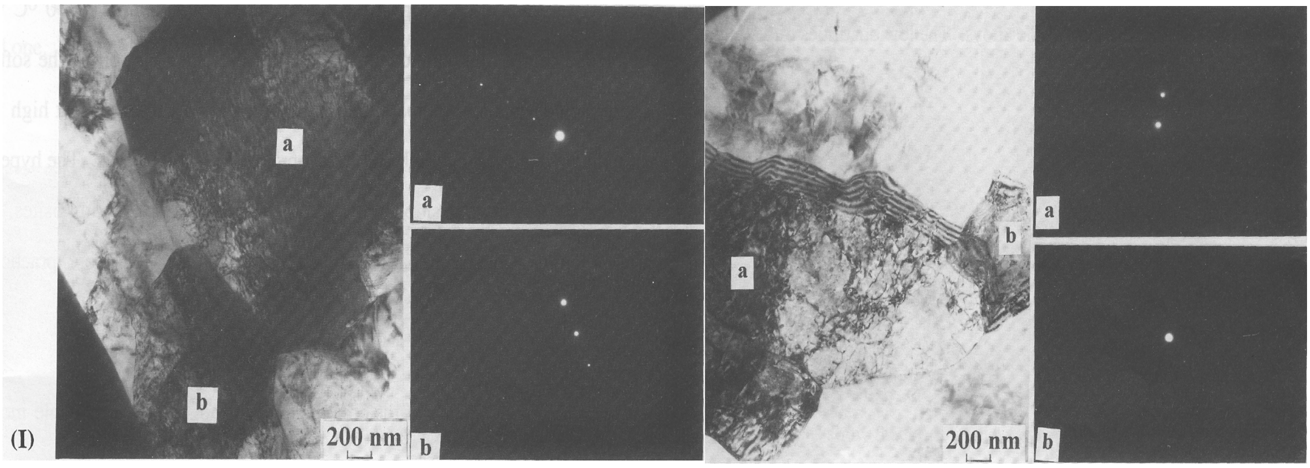

Figure 4: TEM observation s show highly misoriented dyamic recrystallized grains (a) 2618 20% Al_2O_3 and (b) 6061 20% Al_2O_3, 400°C, 1 s^{-1}.

CONSTITUTIVE EQUATIONS AND FEM ANALYSIS

For the alloys and composites, constitutive analysis was carried out using Garofalo hyperbolic stress equation:

$$A (\sinh \alpha \sigma_p)^n = \dot{\varepsilon} \exp (Q_{HW}/RT) = Z \quad (1)$$

where A, α (= 0.052 MPa^{-1} common to many Al alloys), n and Q_{HW} are constants (R = 8.31 kJ/mol); Z is the Zener-Hollomon parameter that includes the two control variables.

The activation energy Q_{HW} it is a measurement of how much σ_p rises, as T declines and how alloying influence the strength. The constitutive analysis showed that (Tab. 2) the composites increase in strength and in activation energy Q_{HW} as alloying element and particle contents rise.

Constitutive analysis were employed in a finite element analysis (DEFORM^{tm} software) of rod-like extrusions from a 178 mm billet with ratio R = 31, ram speed VR = 2.6 or 5 mm/s and billet Temperature TB from 300 to 500°C . Modeling was performed to determine T, ε, $\dot{\varepsilon}$ and σ distribution together with T_{max} and P_{max}. The results were validated by comparing to actual extrusions. The grid distortions and distributions of ε and $\dot{\varepsilon}$ resulted independent of material properties; both ε and $\dot{\varepsilon}$ depend however on R, whereas only $\dot{\varepsilon}$ depends on VR. Die corner was found to be the area with the largest localized deformation. P_{Max}, mean σ_M and T_{Max} were strongly dependent on material properties as well as on R, VR and TB.

At the critical end of upsetting (when flow start trough die aperture) the mean stress σ_M and ε achieve their maximum values near the die corner. At this step pressure reaches a maximum value. As extrusion proceeds and the billet shortens, pressure decreases (as a result of deformation heating and reduction of friction) to reach a steady state in the load stroke curves. As the process develops, σ_M and ε decrease to some extent. T and $\dot{\varepsilon}$ continue to increase to their maximum at the beginning of steady stage.

Varying extrusion parameter (TB, VR and R) FEM gives information on how they affect the process and the extreme values of load and temperature, strain and stress in distribution. As TB increases (from 300°C to 500°C) the composite extrusion pressure decreases towards that of the bulk alloys. This applies: from 300°C to 500°C for 6061 and 2618; from 300 °C to 400°C for A356 and 7075 above which the composite pressure is equal or lower than that of alloys (Fig.5a).

The T_{Max} increase is much higher for 6061 and 2618 composites than for alloys whereas for A356 and 7075 composites, T_{Max} is slightly higher than bulk alloys at 350-400°C and lower at 450°C-500°C (Fig.5b). The maximum T indicates weather the incipient melting point has been reached; melted films at segregated particles are opened up by stress leading to surface cracking. Because of incipient melting in 2618 near to 500°C, TB must be limited whereas 6061 materials gave T_{Max} below the minimum melting point (Fig.5b).

Material	d (400°C-1s^{-1}) µm	Q_{HW} kJ/mol	n	logA
6061	3.4	205	3.5	12.1
6061/10%Al_2O_3	2.0	180	2.8	10.4
6061/15%SiCp	1.3	233	2.6	14.1
6061/20%Al_2O_3	1.0	246	2.0	15.1
A356	1.9	161	2.9	8.2
A356/15%SiCp		263	3.2	15.1
7075	1.8	237	2.5	14.2
7075/10%Al_2O_3		274	2.4	17.0
7075/15%Al_2O_3		290	2.2	18.3
2618		149	1.9	8.3
2618/10%Al_2O_3		238	1.1	15.0
2618/20%Al_2O_3		132	1.1	7.3

Table 2: Constitutive constants and subgrains diameter for MMCs and bulk alloys.

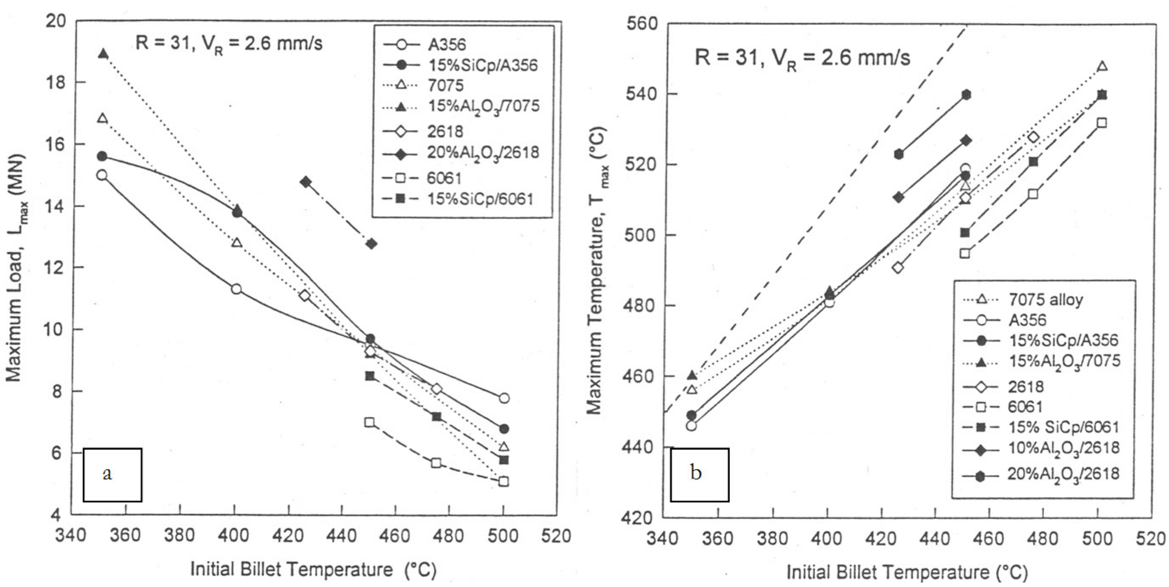

Figure 5: The dependence for extrusion at R = 31 and VR = 2.6 mm/s on the billet insert temperature TB of: (a) maximum load for the 6061 and 2618 materials rises with increased reinforcement content; whereas for A356 and 7075, this is true only below about 425°C; and b) maximum temperature rise is generally less for lower reinforcements but there is a crossover for 7075 at about 425°C.

The P_{Max} (Fig. 6) increases in order of matrix alloy 6061, A356, 7075 and 2618. 6061 composites have lower pressure than those of equivalent composites. For 7075 composites the loads and T_{Max} are exceeded only by those of 2618. The extrusion modeling of alloys and MMC showed some interesting relationships between the control variables (TB, VR, R) and the dependent parameters (Load max, Tmax). The load-stroke curves (Fig. 7) had the traditional shape and agreed with extrusion trials. The load drops with rising TB and falling VR and stress reinforcements in agreement with the strength of materials. With rising TB, the maximum load decreases almost linearly with increasing steepness as the composite strength rises (Fig.8b). T_{Max} increases with increasing TB with similar slopes with rising materials strength and VR (Fig.8a).

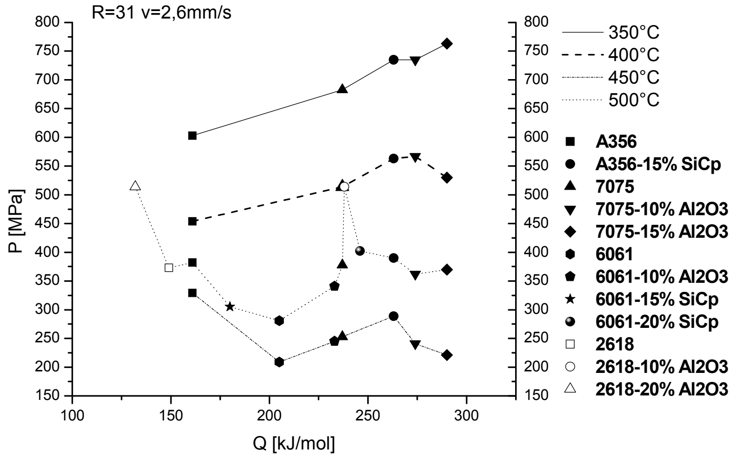

Figure 6: The maximum extrusion pressure P_{Max}, calculated by DEFORM^{tm} plotted against Q_{HW} for all composites and alloys extruded at R=31 and VR=2.6mm/s.

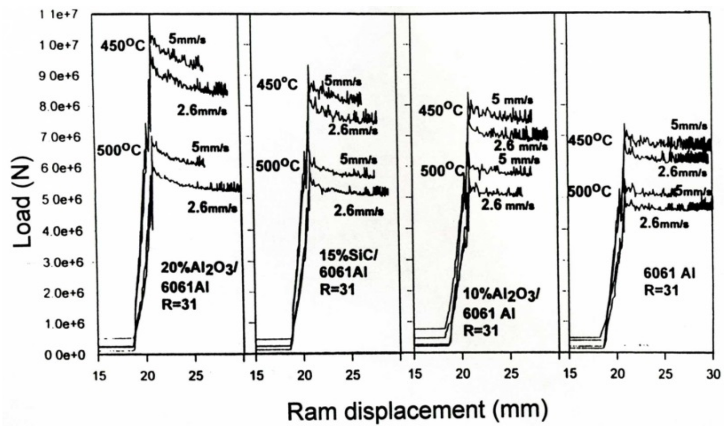

Figure 7: Load-stroke for extrusions of 178 mm diameter billet at 450 or 500°C, VR = 2.6 or 5 mm/s and RE = 31: a) $20\%Al_2O_3/6061$; b) 15%SiC/6061, c) 10% $Al_2O_3/6061$, and d) 6061 alloy. The load drops with rising TB and falling VR and stress reinforcements in agreement with σ_p.

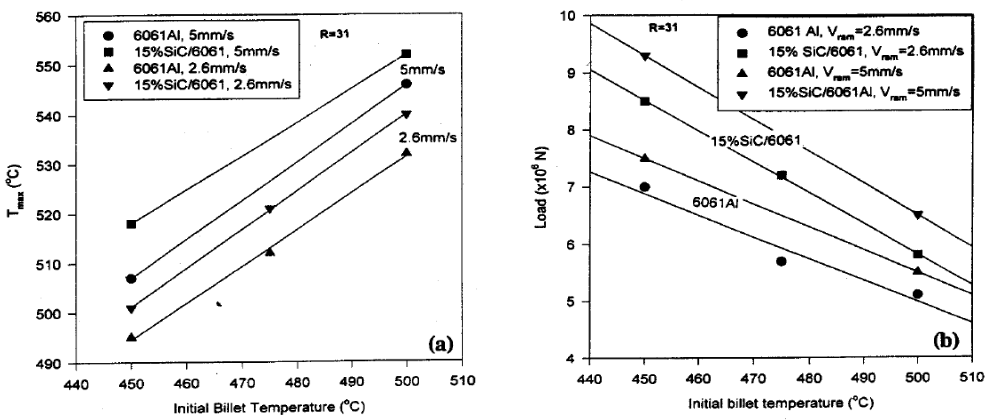

Figure 8: Modeled influence of TB during extrusion of 6061 and 6061-15%SiC at R=31 on T_{Max} (a) and Load Max (b) for VR= 2.6 or 5mm/s and R=31.

CONCLUSIONS

The main conclusions are summarized in the following:
a) At low T of torsion test (400°C or lower), the strength of composites is higher than the alloys.
With exception of 6061 and 2618, there is almost no difference in strength at 450°C while at 500°C composites appear to be softer than the alloys. P_{Max} has the same trend.
b)2618 MMC exhibit lower ductility than A356 and 6061 MMC that exhibit similar ductility. 7075 alloys and MMC decline from good ductility at 400° to very low at higher T because of GB precipitation.
c)The softening of the alloys with increasing T (and with decreasing strain rate) is due to improved DRV. The softening of composites depends on more complicated changes in microstructure: DRX occurs to a limited extent along with dynamic recovery. MMC can retain substructures with rapid cooling since no recrystallization occurs after torsion.
d)With rising TB, the maximum load decreases almost linearly with increasing steepness as the composite strength rises. T_{Max} increases with increasing TB, with similar slopes with rising materials strength and VR.
e)The values of T_{Max} is important in avoiding defects: since T_{Max} exceeded incipient melting point of 2618 materials, TB must be limited. 6061 materials gave T_{Max} much below the minimum melting point.

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