Hot Deformation Behaviour of Al 6061Alloy / SiCp Composite

Abd El-Fattah M. Khourshid

Assoc. Prof. Production Eng. And Machine Design Dept., Faculty of Engineering, Menoufia University, EGYPT.

ABSTRACT

The hot deformation behaviour of 6061Al alloy/SiCp composite are investigated by means of compression tests under constant strain rates of 0.1, 1.0, and 5.0 s^{-1} and at temperatures ranging from 100 to 500 °C. The high reductions, varying from 10 to 60 % with intervals of 10% are set to investigate the hot workability of these materials. A specially designed furnace has been fabricated for this purpose. The flow stress data are analyzed in terms of strain rate and temperature sensitivities. The experimental results show that the flow stress decreases as the temperature increases. The strain rate affects the flow stress slightly. The forming limit diagram of 6061Al alloy/SiCp composite was determined. It was shown that the forming limits increases with increasing temperature and the variation in strain rate has a significant effect on hot workability.

KEYWORDS

Metal matrix composite (MMCs). Deformation. Structure. Strain rate. Mechanical properties. and Hot workability.

Nomenclature

$\dot{\varepsilon}$	Strain rate, s^{-1}
ε_f	fracture strain,
Q	apparent activation energy for deformation, kJ mol^{-1}
R	universal gas constant, 8.314 , kJ mol^{-1}

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T temperature, K
A constant, S^{-1}
α constant, MPa^{-1}
n, n' stress exponent
m strain rate sensitivity,
σ_0 flow stress, MPa

INTRODUCTION

One of the major limitations of high strength aluminium alloys is their relatively low elastic modulus compared with other structural alloy system, e.g., steels and titanium alloys. Metal-Matrix composites (MMC) of stiff ceramics in aluminium alloy matrices currently are being developed to overcome this limitation, with strength sometimes being simultaneously improved [1].
Particulate-reinforced metal-matrix composites (MMCs) are attractive materials due to their excellent combination of properties, e.g. light weight, high elastic modulus, high-temperature resistance, good wear resistance, good workability, and desirable coefficient of thermal expansion and isotropy [1,2].

Discontinuously reinforced MMCs can be fabricated via conventional metal working techniques, for example, extrusion, forging, and rolling, providing great potential for commercial applications. The disadvantages are that MMCs have a high flow stress, which results in very high extrusion pressures; the limited hot ductility in MMCs can cause surface breakup during hot working. Studies to improve the hot working behaviour of MMCs have important commercial objectives. In hot working, increasing temperature leads to lower stresses via increasing dynamic recovery, which reduce the stress concentrations at the crack nucleation sites [3-19].

Hot ductility is improved by applying higher strain rates for the following reasons:-

1- There is sufficient time for strain induced precipitation.
2- The amount of grain boundary sliding is reduced, i.e. $\varepsilon_s / \varepsilon_t$, decreased as the strain rate is increased, where ε_s is the strain due to grain boundary and ε_t the total strain to fracture.,
3- There is insufficient time for the formation and diffusion controlled growth of voids next to the precipitates and inclusions present at the grain boundary.
4- It has also been suggested, that increasing the strain rate, prevents the formation of deformation induced ferrite [3].

Hot workability relates to the ability of a metal or alloy to be deformed under conditions of high temperature (> 0.6 T_m, where T_m is the melting temperature). The two characteristics that govern hot workability are strength and ductility.

To increase the achievable deformation for a particular process and to be able to model the process, it is essential to know the flow behaviour of the material, which is determined by process factor such as the true strain, strain rate and the deformation temperature, and material factor such as the flow stress , strain rate sensitivity and the deformation activation energy.
Examination of the deformation and fracture behaviour of Al6061 alloy /SiC reinforced metal matrix composites over a wide range of microstructure and temperature have been performed in order to improve their mechanical properties [11-19].
Nevertheless, more experimentation and investigation are still needed for better understanding of the responses between temperature, strain and strain rate during the plasticity processing of (MMCs) aluminium alloy /SiCp composites.

The main purpose of this study is to present the general nature of the influence of strain, strain rate and temperature on the compressive deformation behaviour and fracture characteristics of 6061Al alloy/SiCp composites. Also, the apparent activation energy for hot working has been determined.

MATERIALS AND EXPERIMENTAL PROCEDURES

Materials

The material used in this study is a Al 6061 alloy with composition (in wt%) is: 0.65Si-0.19Fe-0.19Cu-0.21Mn-0.82Mg-0.017Zn-0.068Cr-0.018Ti 0.003Ni-Al(ball). Silicon carbide (SiC) particles with an average size of 90 μm. The volume fraction of SiC particles in the is about 0.15. The fabrication procedure for the composite was mentioned in details in ref.[5]. The composite was produced in the form of cast ingots of dimensions 20x20x110 mm. The particle distribution in the matrix was examined using an optical microscope.

Test procedure

Hot workability was investigated via compression tests. The compression tests were performed using a computer-controlled servohydraulic Instron machine which had been modified to carry out uniaxial compression over a range of temperature and true strain rates.

Fig.1 depicts the furnace used in this investigation. Specimens 10 mm in diameter and 15mm in length were machined from the ingot, see ref. [4] for more details. Tends of each specimen were carefully machined to ensure that the faces were parallel. After polishing the specimens down with 1200 grit emery paper, the surface of both ends is sprayed with lubricants of two different kinds: molybdenum-disulfide is used for lubrication at the temperatures of 300 and 500 °C and Teflon film at temperatures below 300°C. During testing, all specimens were heated to the required test temperature by a radiation furnace enclosing the test rig . The temperature of each specimen was monitored continuously during the test by a thermocouple bonded to the specimen. The specimens were maintained at the required temperature for 10 min. before deformation to ensure uniform temperature distribution within the specimens. The testing temperature was controlled thermostatically to within ±3 °C of the required temperature. Specimens were deformed at temperatures ranging from 100 to 500 °C at constant strain rates from 0.1 to 5.0 s^{-1}. All specimens were deformed using nickel-based tape as a lubricant, which was found to keep its integrity at elevated temperatures. All samples were deformed to a total strain of 60% reduction in single pass. After fracture had occurred, the furnace was moved away from the test specimen and one of the halves of the specimen quenched without delay for about 8 s in water, to retain the specimen structure existing at the instant of fracture.

RESULTS AND DISCUSSION

Flow stress curves

Figure 2 summarizes the relationship between the true stress as a function of true strain for both the Al6061 alloy and Al6061+15vol.%SiCp composite tested at temperatures ranging from 100 to 500 °C, and strain rates of 0.1, 1.0, and 5.0 s^{-1} (as example at $\dot{\varepsilon}$ = 5.0 s^{-1}). As observed from this figure, the flow curves is similar for both the alloy and the composite. Stress decreases with the increase of temperature, but its variation with strain rate is low. Under all deformation conditions the flow stress of the composite was greater than that of the alloy. Other workers [6-7] for composite materials compared with their unreinforced matrixes as a function of deformation temperature have observed higher flow stress values. Clearly, the SiC particles influence the deformation behaviour at lower temperatures, but at temperatures above 400 °C, their influence is negligible. On further deformation, the work-hardening rate is equal to the material-softening rate caused by dynamic recovery and/or

recrystallisation and therefore the flow stress remains constant with increasing strain at a steady compression temperature.
A higher flow stress in these composites compared with the matrix alloys, for a given set of deformation conditions, has important particle consequences. For example, higher mill loads would be required during industrial processing, particularly at lower temperatures, to accommodate the additional resistance to deformation imparted by the reinforcement phase.

Strain rate sensitivity *(m)*

Strain rate sensitivity *m* was calculated assuming the following relation applies [10] :

$$\sigma_0 = C\,\dot{\varepsilon}^{m}|_{\varepsilon,T} \quad \text{--------------------------------(1)}$$

Where:

C = constant,
T = absolute temperature, and
$\dot{\varepsilon}$ = tensile strain rate.

Figs.3 shows log-log plots of flow stress against strain rates for both the alloy and the composite. The slope of each curve, which is defined as the strain rate sensitivity *m*, increased slightly with deformation temperature for both the Al6061 alloy and Al6061+15vol.%SiCp composite. At any given temperature the value of *m* was slightly higher for the alloy than for the composite. M.Guden et. al. [11] observed the same effect for the short fiber reinforced aluminium composite and suggested that the higher rate sensitivity of the composite is due to the imposed strain rate rather than the changing of the internal structure.

Activation energy Q

The activation energy of deformation Q was computed assuming that the following creep law equation applies [12] :

$$\dot{\varepsilon} = A\,\sigma_0^{1/m} \exp(-Q/RT) \quad \text{--- --------------------------(2)}$$

where:

R is the gas constant, T is the absolute temperature, and A is the material constant.
Consequently, the following constitutive relation, proposed by Sellars and Tegart [13], can be used:

$$\sigma_0 = A''(\sinh \alpha\sigma)^{n'} \operatorname{Exp}(-Q/RT) \quad \text{---------------------(3)}$$

Where:

A″ is the frequency factor of the stress term (s^{-1}), n' was determined from Fig.3, and α was determined from the expression $\alpha = \beta / n'$. Fig.4 shows the relation between the log sinh ($\alpha\sigma$) and log $\dot{\varepsilon}$. The slope of these curves providing a refined values of n'.The evaluated constants of Eq. (3) calculated from this procedure are given in table1.

The Logarithm of flow stress versus the reciprocal test temperature (1000/T) curves is shown in Fig.5. The slopes of the log σ_0 versus 1000/T curves present the activation energy of the alloy and the composite.

By using Eq.3 the activation energy of deformation Q for both the alloy and the composite are 166 kJ mol^{-1} and 290 kJ mol^{-1} respectively. This appears to be a result of the increased difference in the magnitude of the flow stress between the materials as the deformation temperature decreases, resulting in a greater temperature dependence of the stress for the composite. McQueen et al [6]. speculated that the higher activation energy for the composite was attributed to the SiC particles forcing the matrix to undergo additional strain hardening during deformation at lower temperatures. The activation energy for the particulate reinforced MMCs was higher than the activation energy for selfdiffusion in pure aluminium (Q ~150 kJ mol^{-1}). Perhaps the grain and subgrain sizes for the metal matrix composite are much finer than those of Al6061 alloy. Grain boundary diffusion might then be higher for the composite, which could cause the activation energies to be lower.

Table 1 Values of constants determined from Eq. (3).

Material	n'	β (MN/m^2)	α (MN/m^2)	Q $Kjmol^{-1}$
Al6061	5.85	0.0589	9.05×10^{-3}	166
Al6061/15%SiCp	6.11	0.0622	9.88×10^{-3}	290

Fracture strain behaviour

The fracture strain ε_f versus test temperature curves of Al6061 alloy and Al6061 alloy/15vol.%SiCp reinforced MMC are shown in Fig.6. It can be seen that ε_f for the 6061Al alloy goes through a maximum at 350°C, but for the MMC it can appears as a much lower value at the same test temperature and strain rate. The ε_f of the specimen at 0.1 S^{-1} shows a marginally higher value than that of the 1.0 and $5S^{-1}$ conditions in the 200-350°C temperature ranges, but in the 350- 500°C range, ε_f of the 5 S^{-1} is higher than other strain rate conditions. This behaviour agrees with the 20vol.%SiC whisker and particle reinforced Al6061 composite [9]. The much lower ductility in MMCs is interpreted to result from its high dislocation density and imperfect dynamic recovery during hot deformation. The flow constraints between particles and matrix lead to stress concentration and crack initiation and this is absent in the 6061Al alloy. These results suggest that it is necessary to find the appropriate strain rate to improve the hot ductility of composites, which affects load transfer and void formation and propagation at the interface during hot deformation.

Microstructure of the fractured specimens

Longitudinal sections of compression samples deformed to 60% reduction at temperature of 500°C ,and strain rate $5S^{-1}$are shown in Fig.7, for both the alloy and the composite. Slip lines present within grains do not form at any specific angle to the loading axis. Grains appear to move towards the lateral surface, with the central grains moving away to a greater extent; this creates a barrel-like shape of flow lines.

Forming-limit line (FLL)

Bulk workability is defined as the amount of deformation that a material will withstand fracture in a particular metal working process. It is not a unique property of a material but depends on process variables like strain rate, geometrical factors, temperature, and material variables like inclusion content and grain size.

The forming limit line is obtained by plotting tensile against compressive strain at the point of failure. The plot is said to be linear and the intercept of the FLL on the tensile strain (Y) axis has been defined as the workability index of the material. Additive information is given in [4].

Fig.8 demonstrates the variation of hoop strain ε_θ (tensile) with axial strain ε_z (compressive) were plotted for both Al 6061 alloy and Al6061/15% SiCp composite under a temperature ranging from 200 to 500 ^{0}C. The strain rate was constant at $1.0s^{-1}$. It is shown that the relation between the axial and hoop strains untile fracture are linear and parallel to the line of homogeneous deformation for specimens. The forming limit increases with increasing temperature. The variation in strain rate has a significant effect on hot workability. The shape of the curves is similar to that observed in cold forming [4]. So ductile fracture under homogeneous compression would not be expected. The improve in hot workability with increase deformation temperature is attributed to the various softening processes associated with high temperature. Furthermore, the transition of mechanical behaviour is related to be the deformation temperature. At low temperature (20 C^0 to 200 C^0), slide dislocation accumulate at particles, on consequence is high work hardening and low ductility. At high temperatures, it is possible for a dislocations to accumulate at particles and climb out, especially is high socking fault energy methods. If rate of climb around the particles is greater than rate of dislocation accumulation, then there will be no build up of stress at particles, leading to a lower more hardening rate without any ship increase in flow stress [20].

Sources of failure and their criteria

Many types of defects were traced by McQueen [21] as being well-known causes of failure and emphasized that process and quality controls should be applied to eliminate them. Prevention of component failures depends on the avoidance of discontinuity introduction and the provision of microstructure, which is resistant of failure propagation. Processing can lead to variety of macro discontinuities, like cracks, voids and second phase inclusions. Internal mechanisms and deformation conditions may give rise to finer defects. Intergranular pores produced in some temperature ranges, and hydrostatic tension components near centerline or in the surface (in upsetting and heading) can produce small discontinuities leading to cracking. Ashby [22], cleavage, void nucleation and growth, and rupture listed three types of fracture. Such types at both room and creep temperature are given in Fig.9. It is clear from this figure that temperature affects the details of the mode of fracture, however, strain in the warm and hot deformation regimes becomes important.

CONCLUSIONS

--Hot deformation was performed on a particulate metal matrix composite based on a 6061Al matrix reinforced with SiCp and also on the unreinforced 6061Al alloy. It was shown that the flow stress of the composite was consistently higher than for the alloy for a given set of deformation conditions. The activation energy of hot deformation was also higher, which suggests that the ceramic particles force the matrix to undergo additional strain hardening during deformation,

particularly at lower temperatures. This was attributed to the localised increase both in strain and strain rate in regions of the matrix adjacent to the particulate.
--The fracture strain of the Al6061/15vol.%SiCp composite marginally increases from 200 to 500 °C: these much lower values than those of the Al6061 alloy are due to the high dislocation density in MMC causing stress concentration at particle interfaces.
-- The forming limit increases with increasing temperature and the variation in strain rate has a significant effect on hot workability.

REFERENCES

1- W.C.Harrigan, Jr., "Discontinuous silicon fiber MMCs", Engineering Materials Handbook, Vol. 1, ASM, Metals Park, OH, pp. 889-895,(1987).
2- R.K.Everett & R.J.Arsenault, Metal Matrix Composites: Processing and Interfaces, Academic Press, Boston,pp.83-87,(1991).
2- A. M.Khourshid, S. Ayyad, S. Serag and B. Mintz "effect of cooling rate on the hot ductility of oil platform steel",Sci. Bull. Fac. Ain Shams Univ.Vol.33, No.1, March 31, (1998) EGYPT.
3- A.M .Khourshid & A.M.Assar,"Workability of Al 6061Alloy/SiCp Composites in Cold Compression", Alex. Engg. Journal, Vol.38, No.3, pp.A179-A186, May (1999).EGYPT.
5- A.M. Assar and A. M. Khourshid, "Fabrication and Properties Of Aluminium Alloy 6061/SiCp Composite" ,4th In. Conf. On Measurement and Control of Granular Materials (MCGM '1997) Sept. 17-19 (1997) Shenyang, CHINA.
6-H.J.Mcqueen, P.Sakaris, and J.Bowles: in Proc. Conf. "Advanced composites' 93 , (ed.T.Chandra and A.B.Dhingra), 1193-1198; 1993, warrendale, PA,TMS.
7-D.Yu and T.Chandra: : in Proc. Conf. "Advanced composites'93', (ed.T.Chandra and A.B.Dhingra), 1073-1077; 1993, warrendale, PA, TMS.
8-J.R.Pickens, T.J.Langan, R.O.England and M.Libson: Metall. Trans., 18A, pp. 303-312., 1987.
9-F.R.Tuler, J.T.Beals, C.Demetry, and D.Zho : in Cast reinforced metal matrix composite", (ed.S.G.Fishman and A.K.Dhingra) ,321-325: 1099. Chicago,IL.ASM.
10-I.LeMay: "Principles of Mechanical Metallurgy", Elsecier Nort-Holland, Inc., New York, NY, p.70., 1981.
11-M.Guden and I.W.Hall, "High strain rate compression testing of a short fiber reinforced aluminium composite"Mat. Sci. Eng. A232, pp.1-10, (1997).
12-G.E.Dieter: in "Mechanical metallurgy", 3 edn, 306-307; 1986,

New York, McGraw-Hill.
13-C.M.Sellars and W.G. Tegart; "Hot workability" rev.158, International Metall. Vol. 17 , pp.1-23. (1972).
14-X.Xia, P.Sakaris, H.J.McQueen, Mater. Sci. Technol. Vol.10, pp.487- 496, (1992).
15-K.C.Chan,G.Q.Tong and L.Gao, " Hot formability of an Al20SiCw Composite sheet" J.of Mater. Proc. Tech. 74, pp.142-148, (1998)
16-Woei-Shyan Lee and Ming-Tong Lin,"The effect of strain rate and Temperature on the compressive deformation behaviour of Ti-6Al-4V alloy" J.of Mater. Processing Tech. 71, pp.235-246, (1997)
17-Xiaoxin Xia, P.Sakaris, and H.J.McQueen," Hot deformation, dynamic recovery, and recrystallisation behaviour of Al 6061-SiCp composite" Mater.Sci. and Techn. Vol.10, pp.487-496, (1994).
18- Cerri.E., Evangelista E., Forcellese A., and NcQueen H.J. "Comparative hot workability of 7012 and 7075 alloys after different pretreatments" Mat.Sci.Eng. A197, pp.181-198, (1995).
19- Ko B.C., Park K., and Yoo Y.C."Hot deformation behaviour of SiCp/2024Al alloy composites reinforced with various sizes of SiCp." Mater.Sci. and Techn. Vol.14, pp.765-769, (1998).
20-Y.Li and S.T.Langdon,"High temperature deformation of a 6061Al composite with alumina particulate reinforcement creep and Fracture" Engineering Materials and Structures, Eds.J. Earthman S.F.Mohamed , The Minerals, Metal. And Materials Society, pp.227-236, (1997).
21- McQueen h.J.,"Discontinuity sources in manufacturing processes" 2nd Inter. conf. On defect and fractures, , PP. 1-14, Mont Gabriel, Quebec, May (1982)Canada
22- Ashby M.F., Prog.Mat.Sci., Chalmers Anniversary Vol., pp. 1-25, (1981).

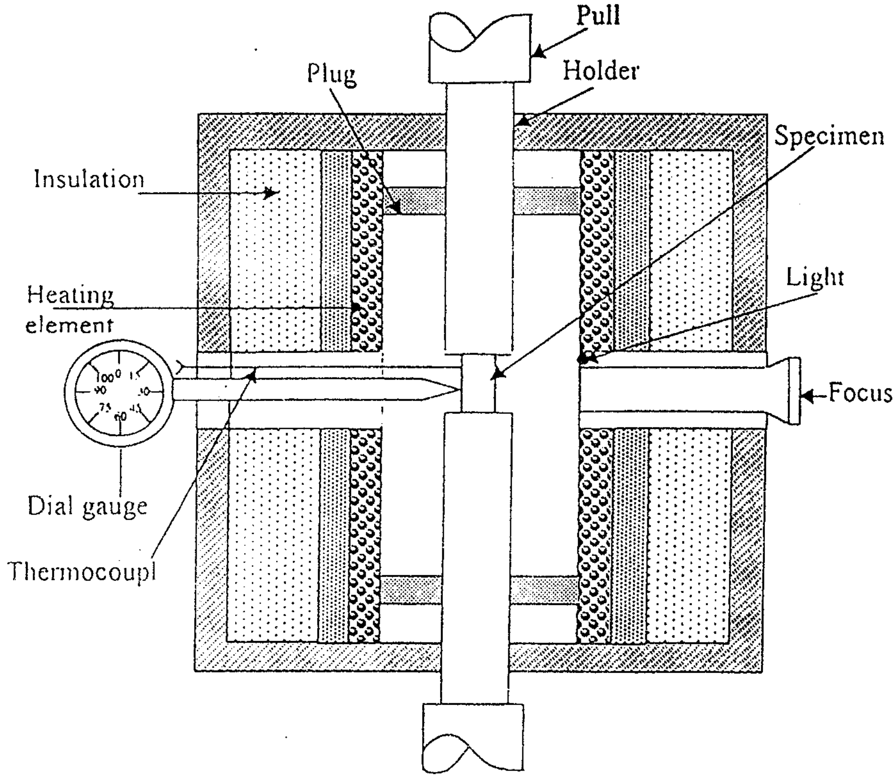
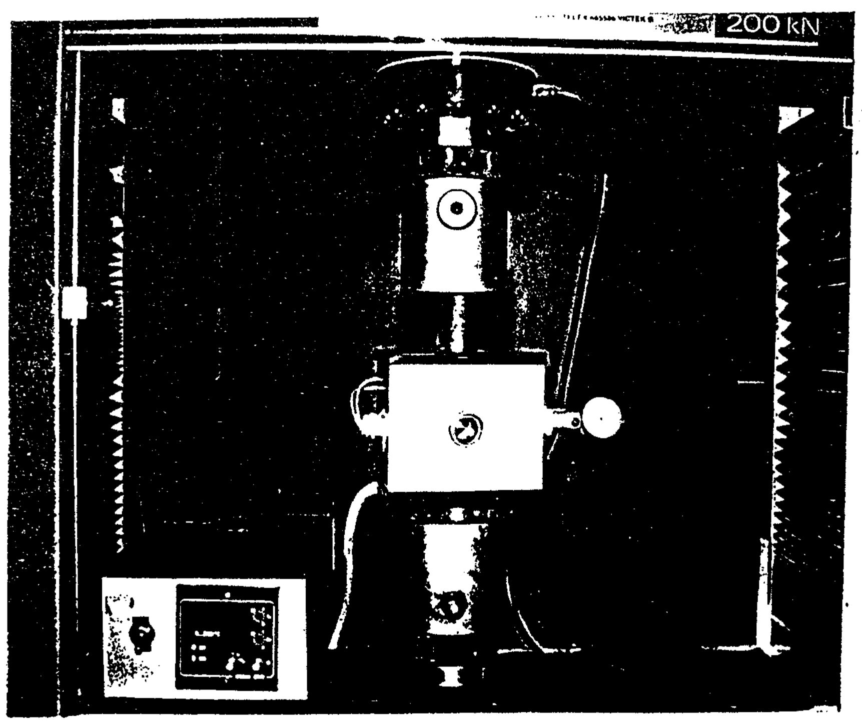
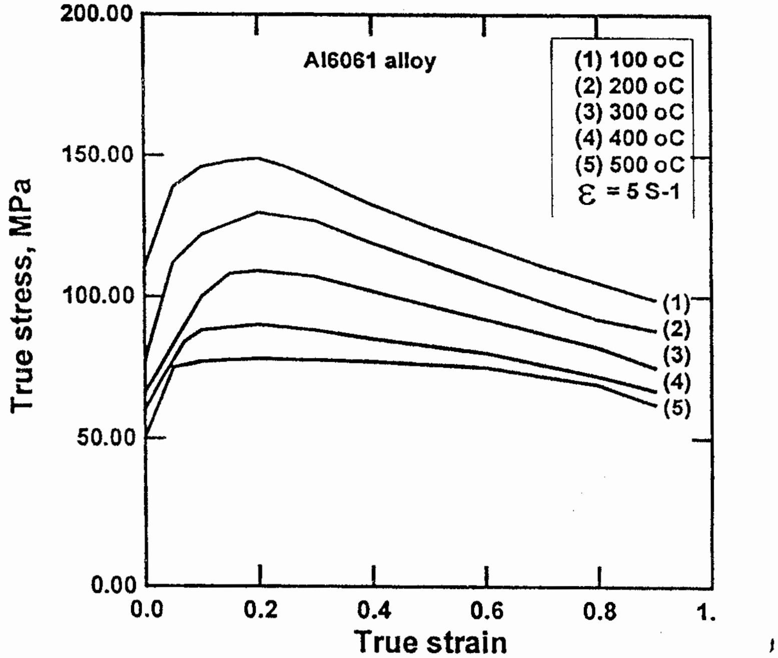


Fig.1 Schematic illustration of induction heating equipment for high temperature universal testing machine



universal testing machine



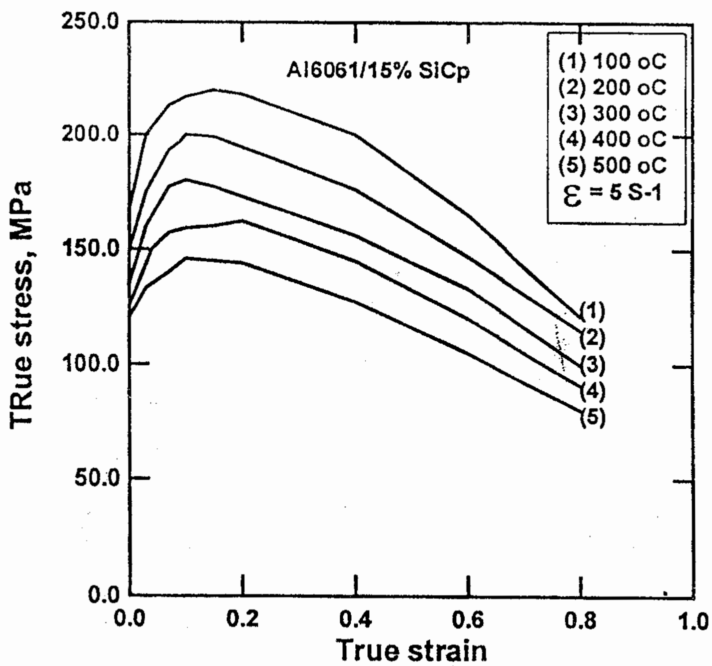


Fig.2. True stress-true strain curves of alloy and composite obtained at ε̇ and different temperatures.

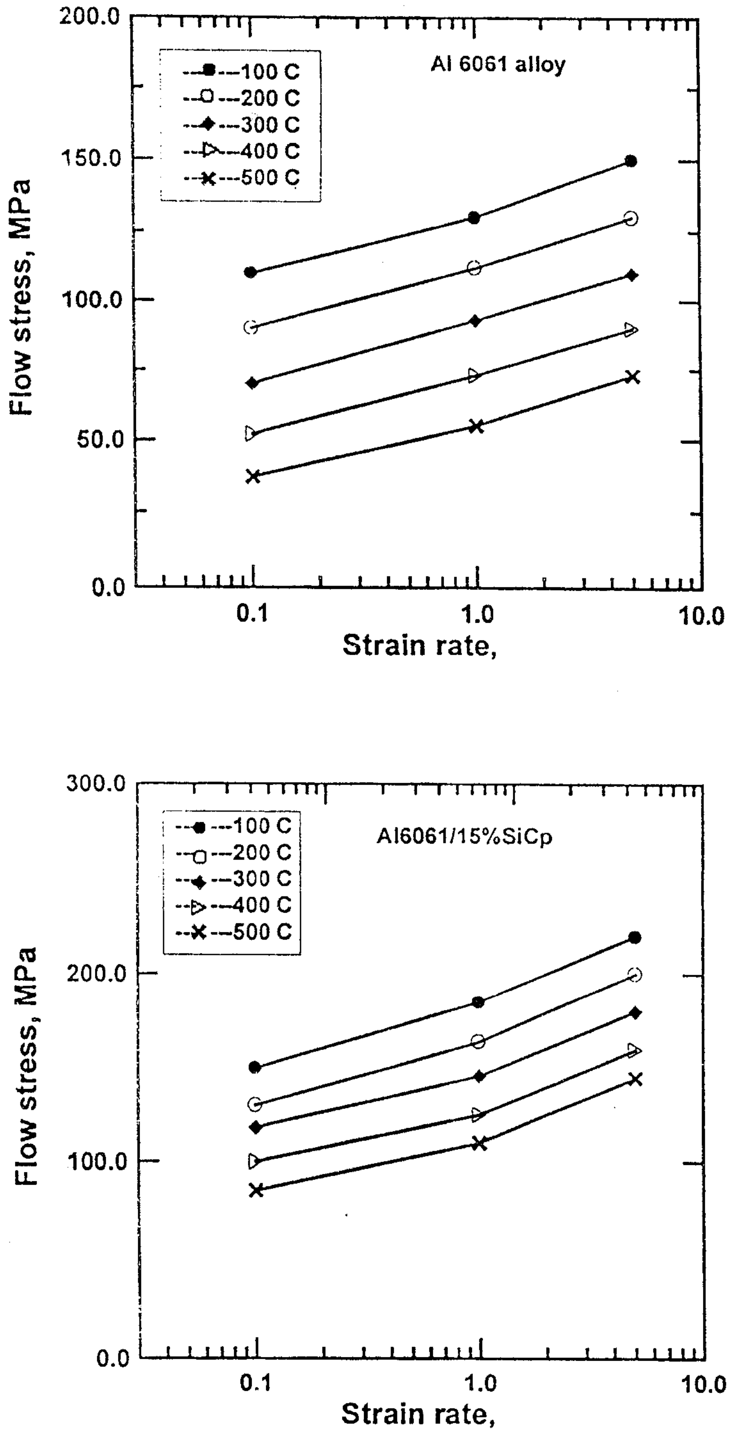


Fig. 3 Effect of the strain rate on the flow stress at a plastic strain of 0.3 for all of the temperatures tested

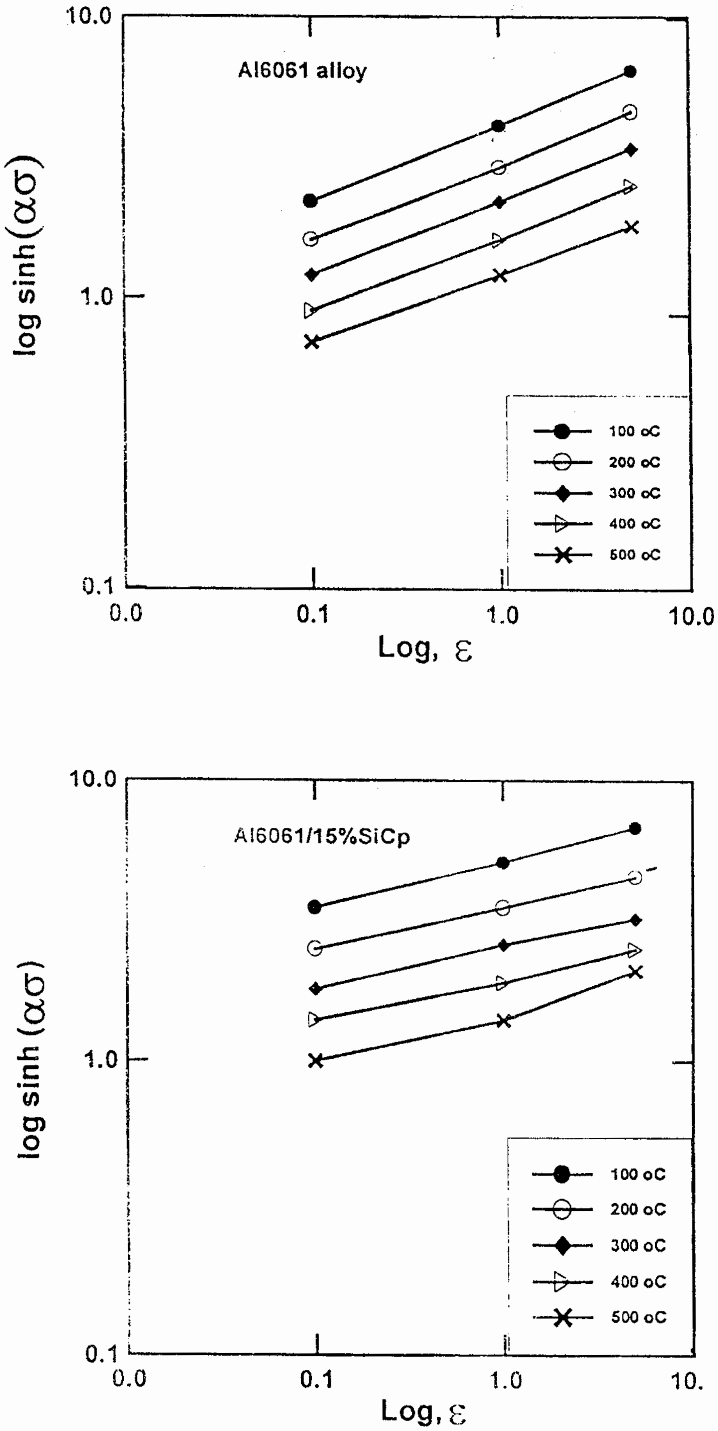
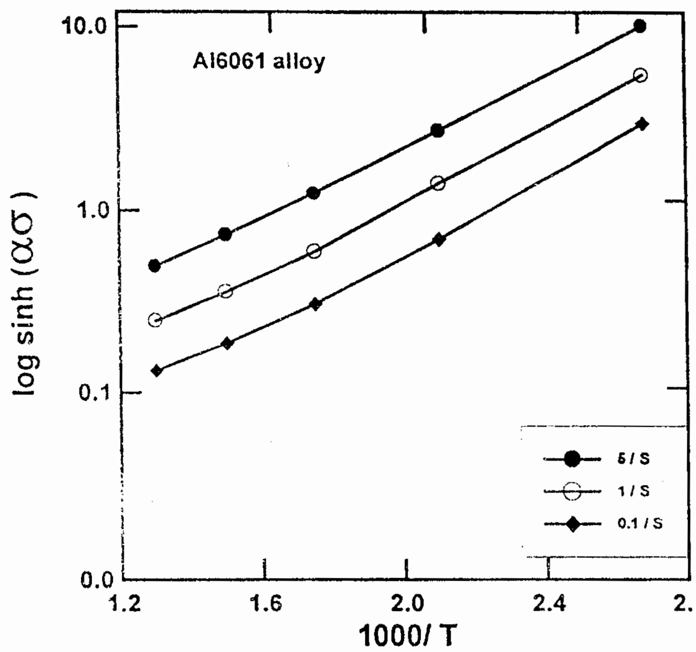


Fig.4 True stress dependence of strain rate in compression for Al6061 alloy and composite.



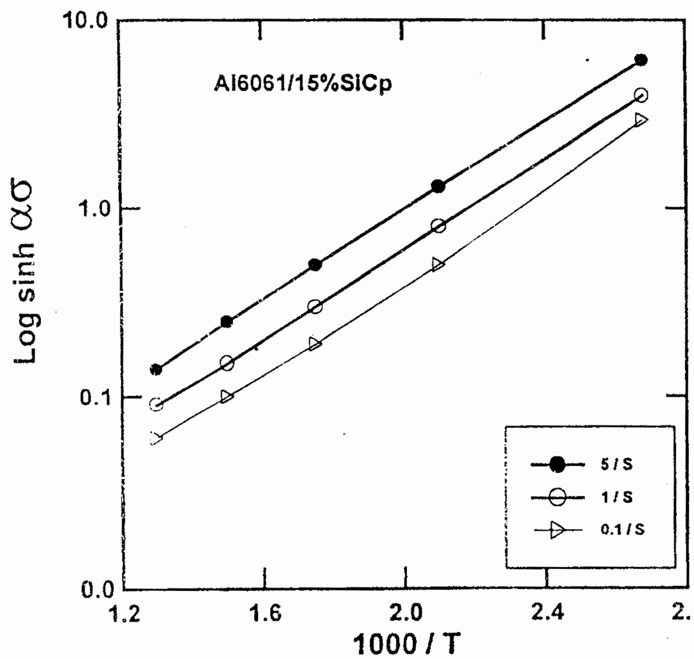


Fig.5 The relation between log sinh (α σ) and 1000/T for the three tested strain rates

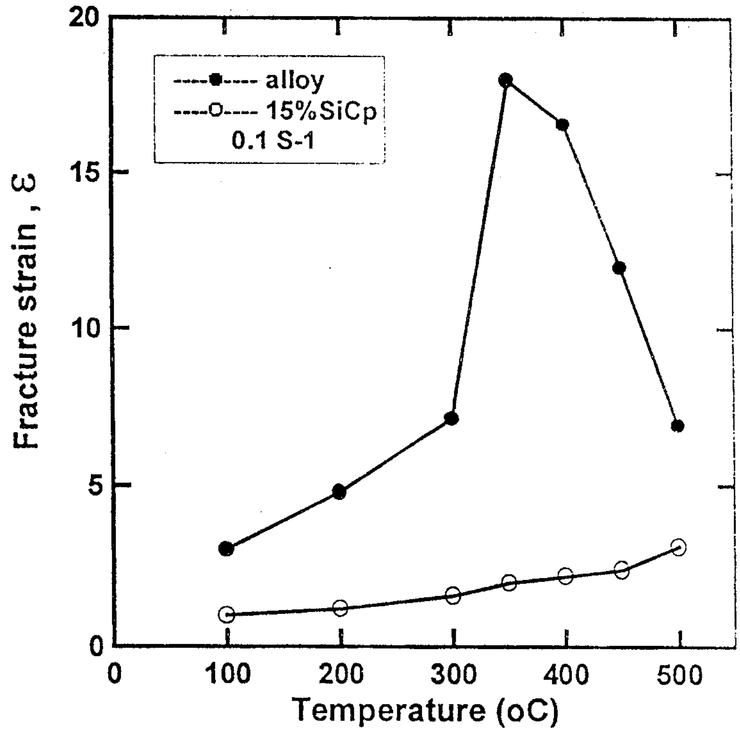


Fig.6 Fracture strain versus test temperature for Al6061 alloy and composite at $0.1S^{-1}$

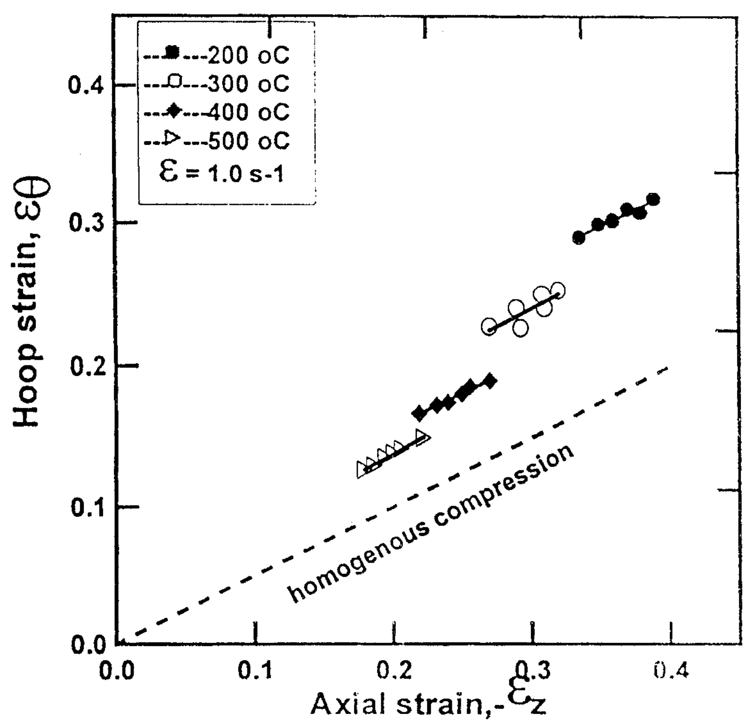
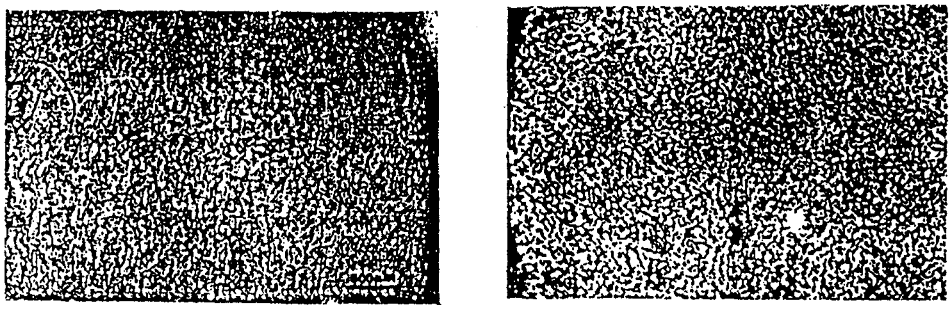
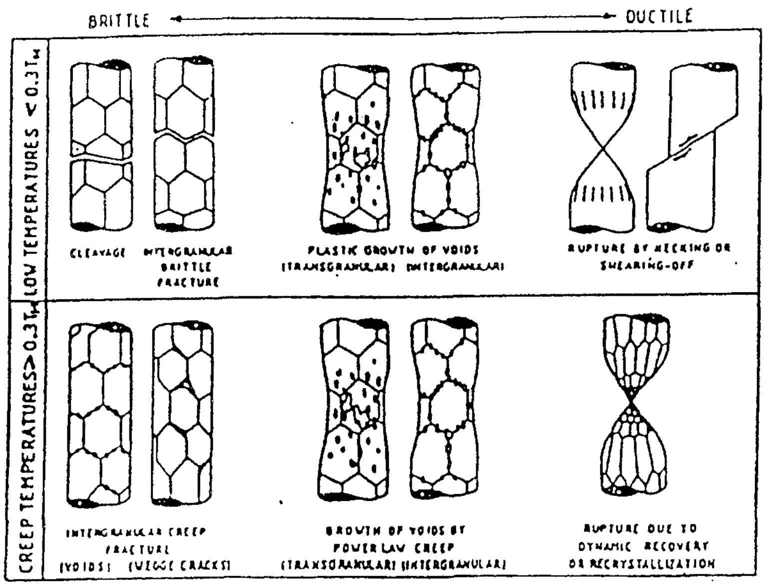


Fig. 8 Fracture limit lines, corresponding to different temperature for Al 6061 alloy/15% SiCp.



Al 6061alloy Al 6061alloy/15%SiCp

Fig.7 Longitudinal sections of compression samples deformed to 60% reduction at temperature of 500°C ,and strain rate $5S^{-1}$.



high strain rate low strain rate high strain rate

Fig.9. Types of fractures mechanisms in both low and creep temperatures after Ashby[22]. Ductile fracture at 20 C° usually includes internal void formation to give a cup/cone fracture. At higher T, the recovery mechanisms (DRV and DRX) impede the fracture mechanisms.

بسم الله الرحمن الرحيم

الملخص باللغة العربية

عنوان البحث :

"سلوك التشكيل الساخن لمؤتلف سبيكة الألومونيوم ٦٠٦١ المدعمة بحبيبات كربيد السيلكون"

الغرض من البحث:

فى هذا البحث تم دراسة سلوك التشكيل الساخن لسبيكة الألومونيوم ٦٠٦١ و كذلك لمؤتلف سبيكة الألومونيوم ٦٠٦١ باختبار الضغط تحت معدلات انفعال ($0.1, 1.0, 5\ Sec^{-1}$) و عند درجات حرارة تتراوح بين ١٠٠–٥٠٠ درجة مئوية بنسب انخفاض تتغير من ١٠%–٦٠% وذلك لتوصيف قابلية التشكيل على الساخن.

لإنجاز هذا البحث تم تصميم فرن لهذا الغرض. تم تحليل بيانات اجهادات الانسياب وتأثرها بمعدل الانفعال ودرجة الحرارة.

-أوضحت التجارب أن اجهادات الانسياب تنخفض مع زيادة درجة الحرارة ويتأثر قليلا بمعدل الانفعال.

-منحنيات حد التشكيل لمؤتلف سبيكة الألومونيوم ٦٠٦١ تم تحديدة.

أوضحت النتائج زيادة حد التشكيل مع ارتفاع درجة الحرارة وكذلك أوضحت أن التغير فى معدلات الانفعال له تأثير ملحوظ على قابلية التشكيل على الساخن.