to analyze IR images in this study. When the background temperature of one image was subtracted from the previous image, the resulting image showed the temperature changes within 8 seconds (160 cycles). In one ULTIMET alloy specimen, the final IR image taken before failure was at 85,376 cycles. Figure 4(a) shows the difference image after the subtraction of the image of cycle 85,056 from that of cycle 85,216. The heat was generated from the crack and conducted to the surroundings. The last image before failure (*i.e.*, at 85,376 cycles) is shown in Figure 1(b). When the temperature at cycle 85,216 was subtracted from Figure 1(b), the resulting image (Figure 4(b)) clearly indicated that the source of heat was at the crack tip. The heat source is shown at a different location in Figures 4(a) and (b), indicating that the crack was propagating through the specimen. After the examination of the fracture surface, this crack was determined to be the one that caused the final failure of the specimen.

In summary, infrared imaging has been shown to add a new perspective to high-cycle fatigue analysis. Temperature mapping as a function of time can pinpoint the crack that causes the final failure of the test specimen. The application of IR thermography to ULTIMET alloy provided a new tool to dynamically monitor the crack initiation and propagation behavior in this material. The significant increase in temperature during different stages is likely to accelarate the failure process and shorten the measured fatigue life of the material.[13] More detailed studies are being conducted to explore further applications of this technique to fatigue analysis.

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Plastic Flow Behavior during the Forging of a 6061 Al/10 Vol Pct Al_2O_3 $_{(p)}$ Composite

M.S. YEH, W.P. WENG, S.C. WANG, and T.H. CHUANG

Aluminum matrix composites possess excellent properties such as higher specific strength, wear resistance, higher stiffness, and low cost. The commercial products of Al-matrix composites have been widely used in automobiles, aircraft, and bicycles.[1] For the manufacturing of these components, casting has been the popular industrial process. Since forging has also been used in the forming of a variety of metals, its applicability to Al-matrix composites should be evaluated. Many researchers have studied the mechanical properties and fracture behavior of Al-matrix composites. Kamat *et al.*[2] have found that the Al_2O_3 particulate-reinforced aluminum-matrix composites had better mechanical properties (yield strength, ultimate tensile strength, and J_{IC}) than those of the unreinforced Al alloy. For the 6061-SiC composites, Lloyd[3] and Arsenault *et al.*[4] showed that the fracture of the composite initiated at the corners of SiC particles, where a high dislocation density that increased with tensile strain existed. Singh and Lewandowski[5] reported that the Poisson ratios of Al-matrix composites varied with heat treatment and reinforcement volume fractions, and specimens exhibited cracked reinforcements, which would influence the mechanical properties of Al-matrix composites. In another work,[6] they reported that the number of cracked reinforcements increased with an increase in the global stress and global plastic strain. Liu *et al.*[7,8] further investigated the effects of superimposed hydrostatic pressure on the deformation and fracture of Al-matrix composites. They showed that applying superimposed hydrostatic pressure, regardless of the matrix aging condition, could significantly increase the ductility of Al-matrix composites. It was also observed that the matrix metal could flow in between the separate faces of the cracked Al_2O_3 particles. However, these studies still focused on the tensile behavior of Al-matrix composites. On the other hand, the plastic deformation of these materials under compressive stress was seldom reported, except in the

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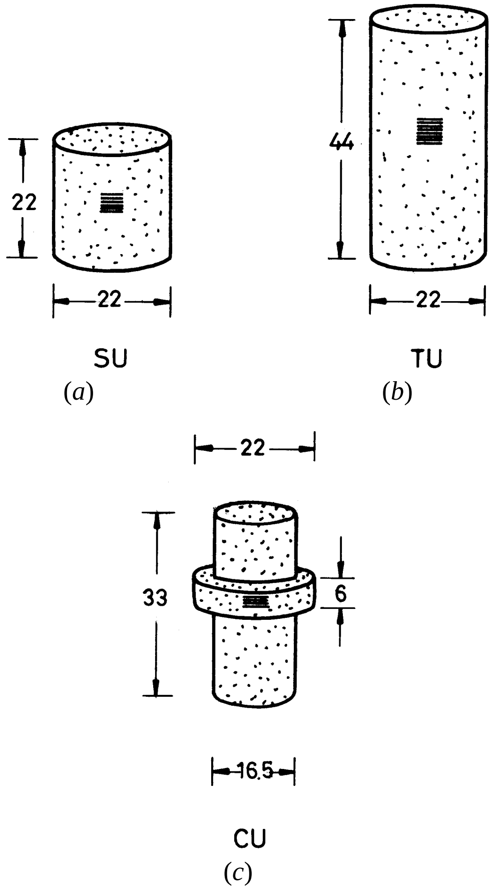


Fig. 1—The specimen geometries of aluminum matrix composites for forging test: (*a*) SU specimens, (*b*) TU specimens, and (*c*) CU specimens.

recent work of Syu and Ghosh.[9,10] They systematically studied the forging limits of a 2014 Al/15 vol. pct Al_2O_3 $_{(p)}$ composite with various cylindrical geometries through experimental tests and theoretical analyses. Their results showed that the forging temperatures and strain rates influenced the forging limits. In this study, the forgeability of a 6061 Al/10 vol. pct $Al_2O_{3\,(p)}$ composite has been evaluated using Gleeble tests. Also, the cracking of reinforcements reported by Liu and Lewandowski[7] during tensile tests with superimposed hydrostatic pressure has been evaluated through forging compressive tests.

The 6061 Al/10 vol pct Al_2O_3 composite used in this study was in the form of 200-mm-diameter cast ingots supplied by Duralcan Aluminum Composites Corporation (San Diego, CA). The ingot was extruded into rods with a diameter of 22 mm. Three types of upset specimens, *i.e.*, short upset (SU) specimens, tall upset (TU) specimens, and collar upset (CU) specimens, were used in these forging tests and the geometries are shown in Figure 1. Before the forging test, all specimens were treated to a T6 temper condition: solution treated at 520 °C for 1.5 hours, water quenched, and then aged at 175 °C for 8 hours.

The forging tests were carried out using a GLEEBLE 2000* dynamic testing machine. Specimens were tested in air at 350 °C, 400 °C, 450 °C, and 500 °C with a compressive strain rate of 0.5 s^{-1}. The average heating rate was about 10 °C/s, and the specimens were maintained at the forging temperatures for 3 minutes before tests. No lubricants between the workpiece and the tools were used during the forging process. A computer recorded the instantaneous compressive axial heights of specimens and superimposed loads. After forging, the specimens were cooled in air and then cut along the centerline for metallographic analyses by an optical microscope.

*GLEEBLE 2000 is the trademark of Duffers Scientific Inc., New York, NY.

No surface cracks were observed in any of the forged specimens tested in this study even after a very high compressive strain had been achieved. This implies that the 6061 Al/10 vol pct $Al_2O_{3\,(p)}$ composite possesses excellent forgeability at the compressive strain rate of 0.5 s^{-1} in the temperature range from 350 °C to 500 °C. Examination of the specimens after tests revealed a barrel appearance. This phenomenon was primarily due to the frictional forces at ram/specimen interfaces, which retarded the outward flow of material at such interfaces.

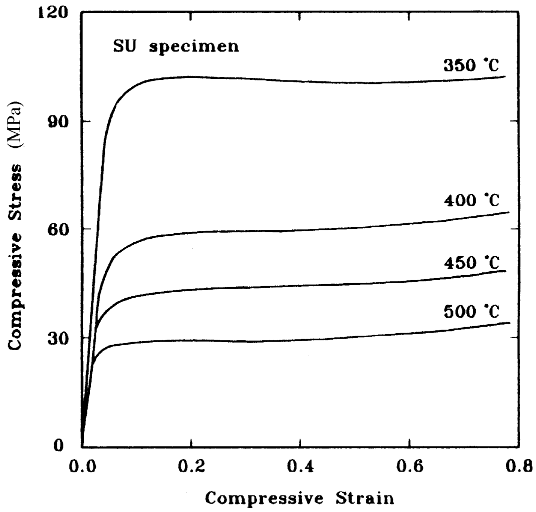
The σ–ε (compressive stress–compressive strain) curves for various specimens with different geometries tested at different forging temperatures are shown in Figure 2. For SU specimens, the compressive yield stress increased first with the compressive strain and then remained constant. For the specimens with a higher h/D (height to diameter) ratio, a greater axial pressure was required to result in the same compressive strain due to the larger deformed region. Such an effect became more noticeable at high compressive strains, which caused the elevation of σ–ε curves. Moreover, the CU specimens with a raised collar on the surface provide a positive plane strain; *i.e.*, the compressive strain will be zero in this region.[9] During the forging test, the raised collar resulted in the reduction of the effective h/D ratio of the specimens, causing a lower axial pressure to be required for CU specimens than that for TU specimens.

The compressive yield stresses (σ_y) and compressive yield offset (ε_y) could be obtained from the extrapolation intercept of σ–ε curves. The results were plotted in Figure 3 for the compressive yield stresses as a function of temperature. It can be seen that the compressive stresses of all the specimens decreased with an increase in temperature, which is attributed to the noticeable dynamic recovery effect at elevated temperatures.

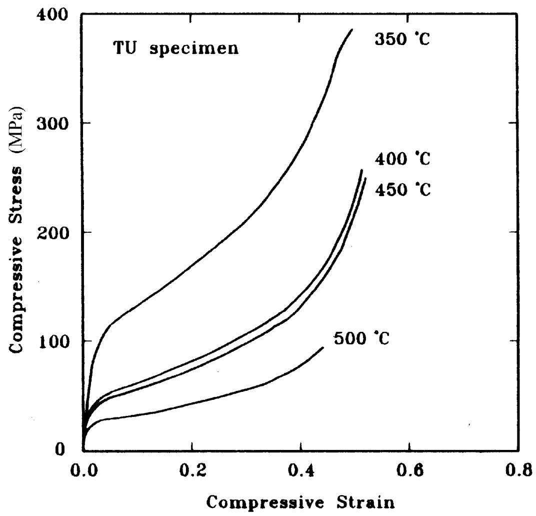
Observations of the cross sections of the specimens after tests showed that the Al_2O_3 particles turned around to array themselves along the plastic flow lines of 6061 Al matrix. The typical micrographs of the distribution of Al_2O_3 particles at different locations of a specimen were given in Figure 4. The local alignment of Al_2O_3 particles along the direction of flow lines alleviated the forging stress on them. Thus, cracking of Al_2O_3 particles in Al-matrix composites was not observed after forging tests. These results were quite different from those reported by Liu *et al.*[7,8] In their work, the specimens were tensile tested with a superimposed hydrostatic pressure. The monoaxial tensile stress applied through the Al matrix on the Al_2O_3 particles caused them to fracture.

Summarizing the results, some conclusions can be drawn.

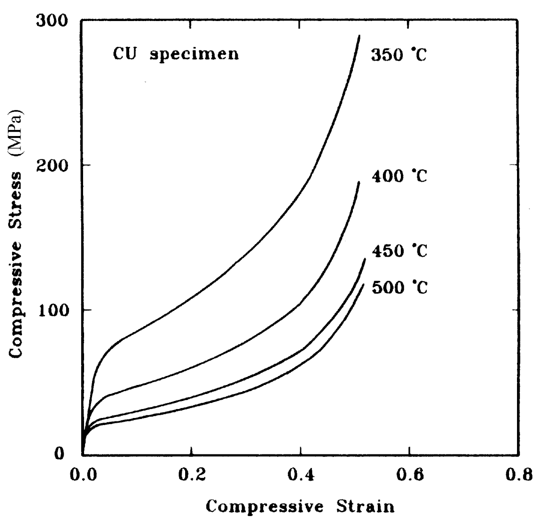
The 6061 Al/10 vol. pct $Al_2O_{3(p)}$ composite possesses excellent forgeability in the temperature range between 350 °C and 500 °C under the compressive strain rate of 0.5



(*a*)



(*b*)



(*c*)

Fig. 2—The σ-ε curves of a 6061 Al/10 vol. pct $Al_2O_{3\,(p)}$ composite with different geometries after forging tests at various temperatures: (*a*) SU specimens, (*b*) TU specimens, and (*c*) CU specimens.

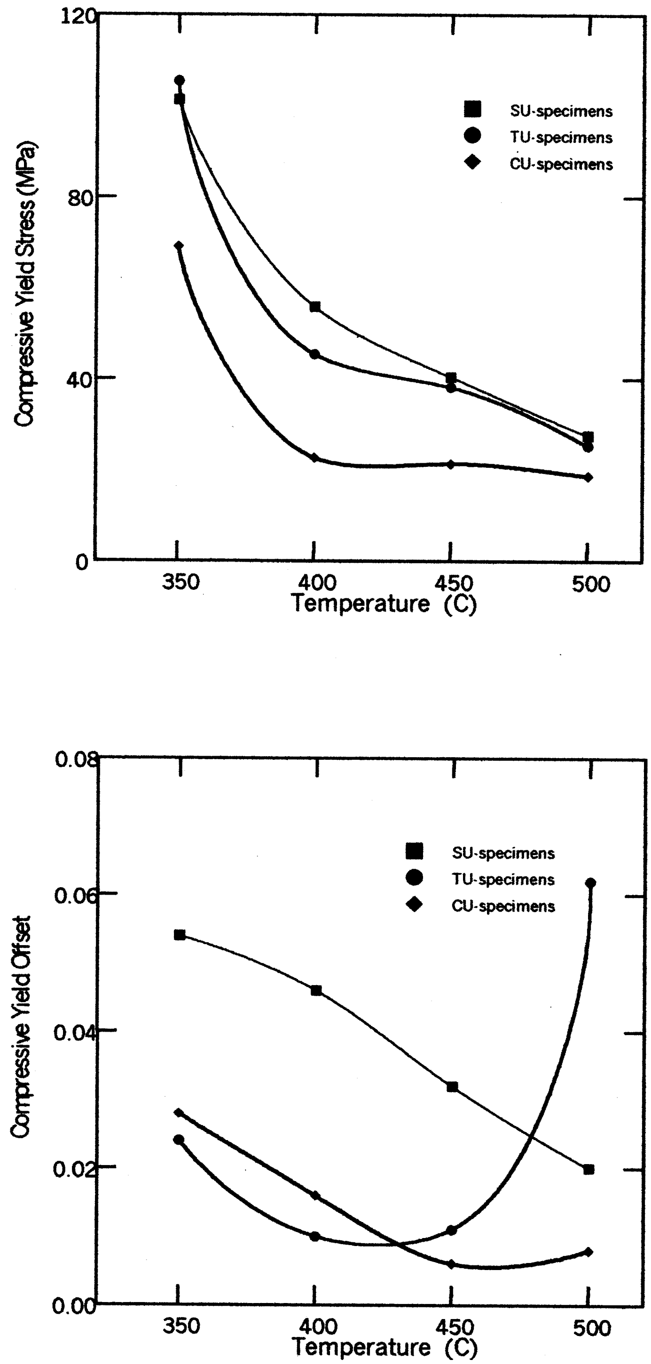


Fig. 3—Compressive yield stress in dependence of forging temperatures for 6061 Al/10 vol. pct $Al_2O_{3\,(p)}$ composite with different specimen geometries.

s^{-1}. The specimens did not crack even after a very high compressive strain had been achieved.

The compressive stresses of Al-matrix composites decreased with an increase in the forging temperature. Moreover, the compressive yield stresses were affected by the geometry of specimens and forging temperatures. During the forging process in this study, the Al_2O_3 particles can arrange themselves along the plastic flow lines of the 6061 Al matrix, and thus remain unbroken.

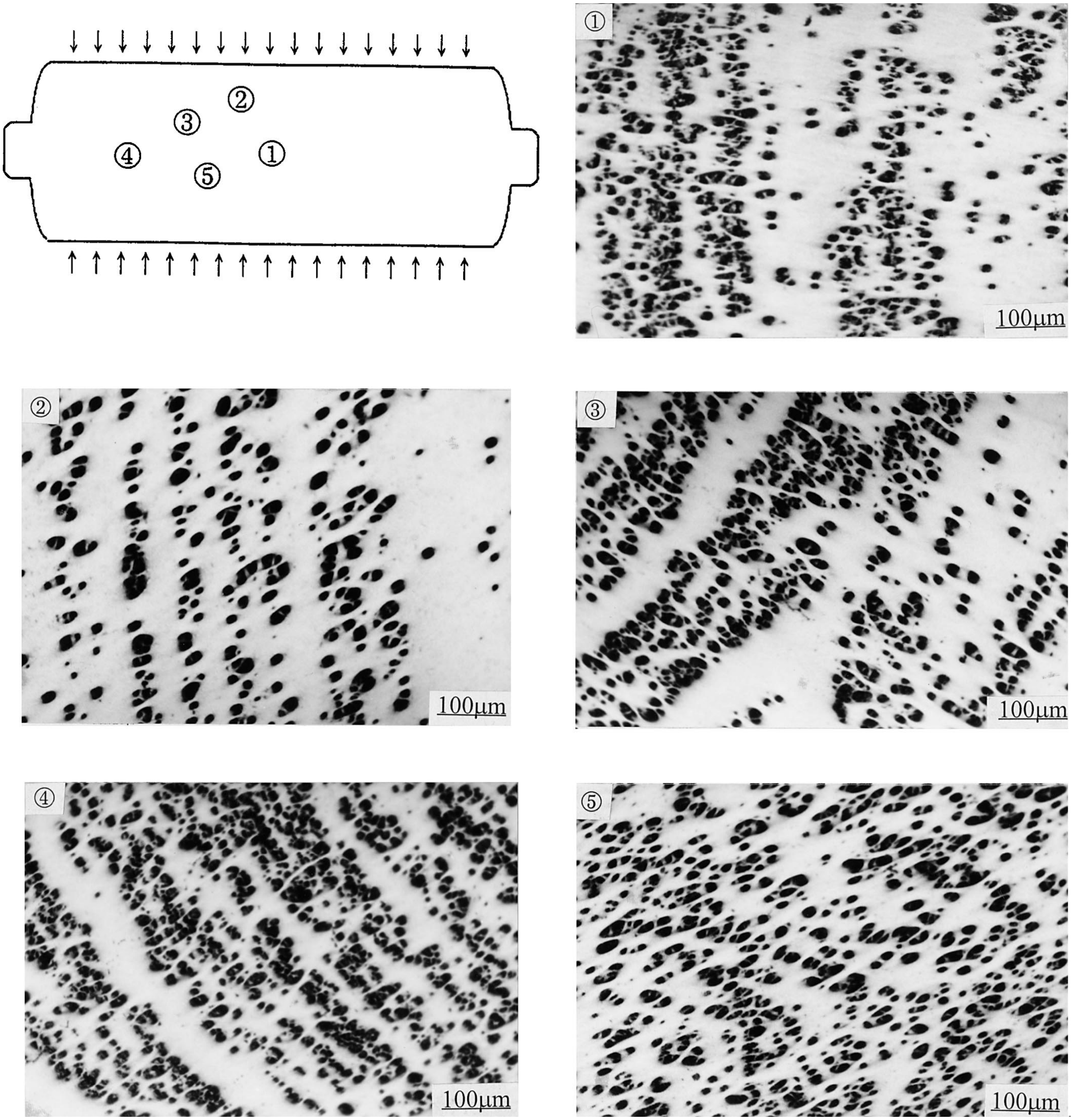


Fig. 4—A typical micrograph to show the distribution of alumina particles after forging test (specimen: TU 6061 Al/10 vol. pct $Al_2O_{3\,(p)}$; temperature: 500 °C).

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