HOT WORKING OF ALUMINUM ALLOY 7075

by

Shoichi Hashimoto

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF
MASTER OF SCIENCE
IN MECHANICAL ENGINEERING
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 1986

© Shoichi Hashimoto 1986

The author hereby grants to M.I.T. permission to reproduce and
to distribute copies of this thesis document in whole or in parts.

Signature of Author

Department of Mechanical Engineering
May 1986

Certified by

Professor Lallit Anand
Thesis Supervisor

Accepted by

Professor Ain Ants Sonin
Departmental Committee on Graduate Students
ABSTRACT

Large deformation, constant true strain rate, isothermal compression tests have been conducted on the aluminum alloy 7075 at strain rates which ranged from $10^{-3}$ to $1 \text{ sec}^{-1}$ and temperatures which spanned the practical forging temperature range of $325^\circ C - 425^\circ C$. In this strain rate and temperature regime the stress-strain curves show very little strain hardening or softening, and the relationship between the (visco) plastic strain rate $\dot{\varepsilon}^p$, the absolute temperature $T$, and the flow stress $\sigma$ can be represented well by the classical one-dimensional equation:

$$\dot{\varepsilon}^p = \left\{ A \exp \left( -\frac{Q}{kT} \right) \right\} \left( \frac{\sigma}{\sigma_0} \right)^{\frac{1}{m}} \text{sgn} (\sigma),$$

with $A = 6.544 \times 10^7 \text{ (sec}^{-1})$, $Q = 2.076 \times 10^{-19} \text{ (J)}$, $m = 0.141$, and where $\sigma_0 = 50 \text{ (MPa)}$ is a reference stress, $k$ is Boltzmann's constant and $\text{sgn}(\cdot)$ is the signum function. This constitutive equation should be of wide utility in analyzing isothermal forgings made from this commercially important alloy. To this end, a simple three dimensional generalization of this equation based on isotropy is incorporated via a user defined material subroutine, developed by L. Anand et al. [1], into the general purpose finite element computer program ABAQUS [2]. Then, using this program, a miniature closed-die, plane-strain, isothermal hot-forging operation which converts a cylindrical billet with a circular cross-section to one with a cross-section in the form of a cruciform is numerically analyzed. The prediction from this analysis concerning the forging load as a function of ram travel and material flow patterns are in excellent agreement with measurements made for a similar experiment.

Thesis Supervisor: Professor Lallit Anand
BIOGRAPHICAL NOTE ON AUTHOR

Institutions attended:

1. Osaka University, Osaka City, Japan
   (April 1969 to March 1973), Degree Received: B.S., Mech. Eng.

2. Osaka University, Osaka City, Japan
   (April 1973 to March 1975), Degree Received: M.S., Mech. Eng.

Professional experience:

1. Mitsubishi Heavy Industries, Ltd., Hiroshima Shipyard & Engine Works, Japan
   (April 1975 to present)
ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my thesis advisor Professor Lallit Anand for his guidance and counsel in many aspects of my research. A special thanks to Stuart Brown for his helpful suggestions and discussions both in my experimental works and analyses. As this work formed part of a large group effort, I would like to also thank to Charlie White, Kwon Hee Kim and Bill Henry. Special gratitude is also due to Mitsubishi Heavy Industries, Ltd. for the support throughout the course of my graduate education. The experimental and computational work reported here was supported by NSF Grant No.MEA8315117 under the supervision of Prof. L. Anand.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Introduction</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Background Information</td>
<td>-6-</td>
</tr>
<tr>
<td>2. Characterization of Al 7075-O Microstructure</td>
<td>-8-</td>
</tr>
<tr>
<td>3. Hot Compression Experiments</td>
<td>-11-</td>
</tr>
<tr>
<td>4. Constitutive Relations and Material Parameters</td>
<td>-14-</td>
</tr>
<tr>
<td>5. A Closed-Die Forging and Heat Treatment Test</td>
<td>-21-</td>
</tr>
<tr>
<td>Conclusion</td>
<td>-23-</td>
</tr>
<tr>
<td>References</td>
<td>-29-</td>
</tr>
</tbody>
</table>

| Appendix A: Chemical Composition of Al 7075 | -32- |
| Appendix B: Physical Properties of Al 7075 | -33- |
| Appendix C: Previous Hot Compression Experiments on Al 7075 | -35- |
| Appendix D: Strengthening Mechanism and Heat Treatment of Al 7075 | -38- |
| Appendix E: ABAQUS Input and UMAT Files | -42- |

List of Figures | -53- |

Figures | -57- |
INTRODUCTION

Aluminum alloy 7075 (Al 7075) is a widely used engineering material, especially in the aerospace industry, because of its high strength relative to other aluminum alloys, its good resistance to stress-corrosion cracking, and its ease of fabrication.

Structural forgings made from this alloy are beginning to be made using the process of “isothermal forging”. In this process the dies and the workpiece are heated to almost the same temperature, and because of a reduction in the effects of die-chilling, the workpiece can be precision forged into near net or final shapes. This can eliminate the need for finish-machining, which in turn can result in tremendous savings in costs.

In order to reduce the trial and error stages of the design of forging processes, it is anticipated that finite element modeling of such processes will increase in the future. Central to such modeling is the availability of accurate constitutive equations for the alloy under hot-working conditions. Unfortunately, in spite of the fairly long history of practical application of Al 7075, experimental data based on which such constitutive equations may be developed are either lacking, or have simply not been published.

Accordingly, the purpose of this study is to:

1. Conduct large deformation, constant true strain rate, isothermal compression tests at strain rates and temperatures spanning the ranges $10^{-3}$ to $10^0$ sec$^{-1}$ and 325 to 425°C, respectively.

2. Develop a constitutive equation for the (visco) plastic part of the strain rate as a function of flow stress and temperature based of these data.

3. Implement this equation via a user defined material subroutine [1] into the finite element computer program ABAQUS [2].
4. Analyze a simple closed-die, plane-strain, isothermal forging process using this program.

5. Conduct a similar forging experiment, and compare the predictions of the forging load versus ram displacement from the finite element analysis against the result from experiment.

This report is arranged in the following manner. The first section entitled Background Information provides the typical mechanical properties and basic information about this material and a brief description of isothermal and closed-die forging. A detailed description of the chemical composition, physical properties, previous hot-compression data, strengthening mechanisms, and heat treatment of Al 7075 is provided in the appendixes for further reading. In the second section, photo micrographs of the Al 7075-O used in this study are presented. In the third section our experimental results on hot-compression are presented. Based on these data, in the fourth section, the proposed constitutive relations and material parameters are presented. In the last section, a plane strain hot-forging is numerically analyzed and the predictions of the analysis compared against experiments. It is shown that the ABAQUS finite element code using the proposed constitutive relations can satisfactorily model the complicated closed-die forging process.
1 BACKGROUND INFORMATION

Aluminum alloy 7075 (Al 7075), which was introduced in 1943, is widely used in the aero-space industry, especially for highly stressed attachment forgings, airplane skins, and cowls because of its high strength and easy fabrication [3].

1.1 MECHANICAL PROPERTIES

The alloy in the T6 temper has a tensile strength 570 MPa, which is amongst the highest attainable for aluminum alloys. This strength is achieved through adequate solution heat treating and precipitation heat treating. Due to this high strength, this alloy is widely used for aircraft structural parts and other highly stressed structural applications.

In order to increase resistance to stress-corrosion cracking, the over-aged tempering condition (T73 tempers) is sometimes used, but the tensile strength due to this tempering decreases to 503 MPa. Elongation is 11% at T6 tempers and 13% at T73 tempers. The fracture toughness is 26.4 to 30.8 MPa√m at T651 tempers and 29.7 to 38.5 MPa√m at T7352 tempers.

Transverse mechanical properties of many products, particularly tensile strength and ductility in the short transverse direction, are generally less than those in the longitudinal direction.

1.2 MICROSTRUCTURE

In the solution heat treated and aged condition, most of the zinc, magnesium and copper is in solid solution or is precipitated in an extremely fine form. As a result, discrete particles of phase containing these elements are generally not observable in the optical microscope [5].
1.3 ISOTHERMAL AND CLOSED-DIE FORGING

Aluminum and its alloys are forged into a wide variety of products by open-die, ring-rolling, and closed-die methods. For forging in closed dies, the dies are ordinarily heated to minimize chilling the work-piece. Higher die temperatures are customarily employed in closed-die forging with presses, especially for producing close-tolerance or intricate parts. Closed and precise shaped die forging can significantly reduce later machining and consequently wasted material. As a result, machining costs and material costs are reduced [6].

Isothermal forging (dies at the same temperature as the workpiece) or hot-die forging (dies at a temperature approaching, but below, the workpiece temperature) offers the following potential advantages [7]:

1. Elimination of die chilling allows forging to closer tolerance than is possible with conventional forging. As a result, machining and material costs are reduced.
2. Elimination of die chilling allows a reduction in the number of pre-forming and blocking dies necessary for forging a given part. As a result, die costs are reduced.
3. Since die chilling is not a problem, a slow ram speed can be used. This lowers the strain rate and the flow stress of the forged material. As a result, the forging pressure is reduced and larger parts can be forged in existing hydraulic presses. The lower forging loads reduce die pressure and die wear and distortion.

Closed-die forging is, however, an extremely complex deformation process from the viewpoint of deformation mechanics. The metal flow and friction at the die-material interface vary continuously during the forging operation, and they are difficult to an-
alyze and predict. That is why there are, so far, no general and accurate methods of analyzing practical forging processes.

Dies should be lubricated, because aluminum-rich materials have a pronounced tendency to adhere to steel at elevated temperatures and pressures; colloidal graphite suspended in water is commonly sprayed on the dies for press forging. Lubricants containing graphite have serious disadvantages, however, for aluminum and magnesium. Their residues are difficult to remove, and particles embedded in the surface may cause staining, pitting, and corrosion. Friction coefficients estimated from upsetting tests with a variety of lubricants (oil, water, graphite, oleic acid, chlorinated paraffin, etc.) ranged from 0.06 to 0.24 compared with 0.48 for bare conditions. Friction coefficients tend to increase with the severity of reduction [6,14].

Aluminum-alloy forging stock is normally wrought material produced by press-forging and rolling from cast ingots. It is ordinarily supplied in the as-fabricated condition (F temper), for which mechanical properties are neither specified nor determined.

After forging, Al 7075 is heat-treated, generally solution heat treating and precipitation heat treating (aging), to obtain the adequate strength and resistance to stress-corrosion cracking.
2 CHARACTERIZATION OF THE MICROSTRUCTURE OF AL 7075-O

The aluminum alloy 7075 used in this study was purchased from a commercial source. The as-received condition was a 12.7mm diameter round bar of T6 temper (solution heat treated and aged). Handbook value of some mechanical properties and chemical composition of this material are [3]:

- Tensile strength: 572 MPa
- Yield strength: 503 MPa
- Elongation: 11%
- Hardness: 150 HB

Chemical composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Amount (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc:</td>
<td>5.6</td>
</tr>
<tr>
<td>Copper</td>
<td>1.6</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.5</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.23</td>
</tr>
<tr>
<td>Manganese</td>
<td>&lt; 0.30</td>
</tr>
<tr>
<td>Silicon</td>
<td>&lt; 0.40</td>
</tr>
<tr>
<td>Iron</td>
<td>&lt; 0.50</td>
</tr>
<tr>
<td>Titanium</td>
<td>&lt; 0.20</td>
</tr>
<tr>
<td>Aluminum</td>
<td>balance</td>
</tr>
</tbody>
</table>
The microstructure of Al 7075-T6 was recorded with micrographs in the as-received condition for referential purposes. Figure 2.1 and 2.2 show surfaces perpendicular and parallel, respectively, to the rolling direction at two magnifications. The average grain size was 0.1 mm in perpendicular direction and 0.4 mm in parallel direction to rolling direction. The etchant used to reveal the microstructure was Keller's reagent (HF 2 ml, HCl 3 ml, HNO₃ 5 ml, and water 190 ml. Immerse for 10 – 20 sec, wash in stream of warm water, blow dry).

Aluminum alloy forging stock is normally wrought material produced by press-forging and rolling from cast ingots. It is ordinarily supplied in the as-fabricated condition (F temper), for which the mechanical properties are neither specified nor determined. In order to start from a well characterized state, the received material was fully annealed before machining test specimens to eliminate the effect of prior unknown heat treating. The material was heated to 450°C, and kept at this temperature for one hour, then cooled down slowly in the furnace. After the temperature of the material decreased to a value lower than 200°C, the material was heated again to 230°C and kept at this temperature for four hours and then cooled to room temperature. The latter heating was done in order to eliminate any partly reprecipitated alloying elements [4]. The hardness of material before annealing was 51.5 – 53.5 on the Rockwell A scale. The hardness after annealing was 9 – 13.5 on the Rockwell A scale, which is too small for that scale. The fully annealed material had a hardness of 30 – 32 on the Rockwell F scale.

Figure 2.3 and 2.4 show surfaces perpendicular and parallel, respectively, to rolling direction after annealing at two magnifications. The fine particles of MgZn₂ were precipitated at lower temperatures, during heating to or cooling from the annealing
temperature. Figure 2.3 shows the platelets of MgZn₂ precipitated at grain boundaries during slow cooling [4].
3 HOT COMPRESSION EXPERIMENTS

It is very important in compression testing to ensure that the compression specimens are homogeneously deformed. For this purpose, many preliminary tests were necessary to select the proper specimen dimensions, that is, proper height-to-diameter ratio, specimen end grooves, and proper lubricants for a wide temperature range. Platen and loading rods of compression testing equipment were also very important factors in obtaining the homogeneous and stable specimen temperatures during testing as well as homogeneous deformation. Preliminary observations and results are shown before giving the results of the constant true strain rate tests. In the constant true strain rate test results section, stress-strain curves at various temperatures as well as observations of compressed specimens are shown.

3.1 METHODOLOGY

3.1.1 Compression Specimens

A height-to-diameter ratio of 1.5 was used. This ratio has been previously used by others (e.g. [9],[11]), and it provided uniform deformation and relatively little shearing of the compression specimen.

The as-received material was first fully annealed, then compression specimens were cut out from the annealed bar. The diameter of the specimens was chosen to be the same as the diameter of bar, 12.7 mm. The height of these specimens were 19.05 mm. For some specimens which were tested at 225°C the specimen diameter was reduced to 7.9 mm in order to be able to compress these specimens by using the available load cell on the test machine. These specimens had a height of 11.85 mm.

After machining, both ends of compression specimen were polished with 240, 320,
400, and 600 grit silicon carbide papers in succession, and then examined to assure that both ends were flat, smooth, and parallel to each other. Concentric grooves were cut into the ends of compression specimen in order to retain lubricant at the platen-specimen interface during the deformation process. At the first stage of preliminary tests, five grooves per each end for 12.7 mm diameter specimen and one groove for 7.9 mm diameter specimen were used satisfactorily to some extent. But, later, for whole constant true strain rate tests at temperatures 225 - 525°C with various types of lubricants, nine grooves per each end for 12.7 mm diameter specimen and four grooves for 7.9 mm diameter specimen were chosen. Figure 3.1.1 shows the precise dimension of these grooves.

At the center of specimen height, a small hole of diameter 0.7 mm x depth 0.14 mm was made to insert a chromel-alumel thermocouple which monitored specimen temperature before and during a compression test. The thermocouple wires were insulated with high-temperature ceramic insulators. It is generally difficult to spot weld a thermocouple onto aluminum and its alloys. Therefore it is common to make a small hole in each specimen and insert a thermocouple to measure temperature [8–10]. Figure 3.1.2 shows the final figure of a compression specimen.

3.1.2 Lubricant

In order to obtain good compression test results, homogeneous deformation of compression specimens is necessary. Lubricant as well as groove geometry of specimen, and choice of compression platen is most important to obtain homogeneous compression deformation.

A commercial oil-based graphite lubricant (DAG 41 produced by Acheson Colloids
Co. worked very well up to temperatures of 370 – 400°C, at which point the oil decomposed and the lubricant no longer worked well. A water-based graphite lubricant is also widely used as aluminum forging lubricant at temperatures at which oil lubricant can no longer be used. Two water-based graphite lubricants (DAG 137 and DELTAFOREG 182 recommended by Acheson Colloids Co.) were used in vain. I did not conduct a systematic testing for various types of lubricants, but I suppose that solid-type lubricants alone like graphite or boron-nitride do not work well as compression testing lubricants. Instead a combination of such lubricants with liquid-type lubricant like oil or melting metal or glass is necessary. A water-based graphite lubricant, therefore, does not work well at a high temperature because the water has evaporated, and graphite only remains at such a high temperature.

Since J. F. Alder and V. A. Philips obtained homogeneous compression deformation using glass-type lubricants [12], various types of glass lubricants for high temperature compression testings have been widely used. The combination of boron oxide B₂O₃ 20 % in weight and lead oxide PbO 80 % which J. F. Alder recommended for a temperature 450 - 600°C, however, did not work well for Al 7075 at a temperature 525°C. Commercial glass powder 8463 (high lead) and 7570 (lead borosilicate) produced by Corning Glass Works were satisfactory for 425°C and 525°C respectively. Viscosity of these glass powders, however, are very sensitive to temperature. By the company’s data sheet, for example, the viscosity of 8463 drops from 10⁷ poise to less than 10⁵ poise as the temperature increases from 400°C to 450°C. Homogeniety of the compressed specimen was very sensitive to the viscosity of the glass lubricant. Therefore a combination of glass lubricant and boron nitride was very successful. Boron nitride has a lubricating mechanism very similar to that of graphite, and is very stable at a high
temperature. It was used to adjust the viscosity of lubricant at a required temperature. Glass composition 8463 95 % in weight and boron nitride 5 % was finally used for a temperature 425°C, and glass composition 7570 90 % and boron nitride 10 % was used for a temperature 525°C. A summary of the lubricant which worked for Al 7075 is given below.

<table>
<thead>
<tr>
<th>temperature (°C)</th>
<th>lubricant</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>DAG41</td>
</tr>
<tr>
<td>325</td>
<td>DAG41</td>
</tr>
<tr>
<td>375</td>
<td>DAG41</td>
</tr>
<tr>
<td>425</td>
<td>glass 8463 95% in weight + boron nitride 5% in weight</td>
</tr>
<tr>
<td>525</td>
<td>glass 7570 90% in weight + boron nitride 10% in weight</td>
</tr>
</tbody>
</table>

Compression platens of Astroloy, a nickel-based super alloy, were used. Before each test, the platens were polished by 240, 320, 400, and 600 grit silicon carbide grinding papers. If the lubricant between specimen and platen did not work well, the aluminum alloy specimen directly contacted to the platen under a combination of a high temperature and a high pressure, and stuck to it so strongly that it was very difficult to separate them after a test.

3.1.3 Equipment for High Temperature Tests

All high temperature tests were conducted on a model 1350 INSTRON servo-hydraulic mechanical test machine. A logarithmic function generator (constructed by Mehrdad Haghi of our laboratory) was used to provide an exponentially decaying command signal for constant true strain rate compression tests. A tungsten filament type radiant heating chamber, Research Inc. model E4-5, was used to heat the specimens. The heating chamber and top and bottom Astroloy loading rods were water-cooled. Data acquisition was accomplished with the use of an IBM PC/XT, a Metrabyte data acquisition board, and a software program called UNKELSCOPE, which has been
developed by Professor W. Unkel of M. I. T. Figure 3.1.3 shows a photograph of the test equipment, and a schematic of the load train.

The Astroloy platens with specimens were put between top and bottom alumina (96 % Al₂O₃) rods and also top and bottom Astroloy loading rods. These were all put into the furnace heat zone. Outer parts of Astroloy loading rods were water-cooled to protect the connected load-cell.

The low thermal conductivity of the alumina rods placed between each platen and each Astroloy loading rod was satisfactory to keep specimen temperature uniformity within about ±1 – 2°C.

3.2 CONSTANT TRUE STRAIN RATE TEST

The Al 7075-O was tested at four strain rates, five temperatures, and compressed to approximately 100 % true strain. The strain rates were 10⁻³, 10⁻², 10⁻¹, 1 sec⁻¹, and the temperatures were 225, 325, 375, 425, and 525°C. Temperatures recommended for forging Al 7075 are around 382 – 438°C [6]. Test temperatures covered this actual forging temperature range. Compression tests at temperature 225°C, where strain hardening clearly appeared, are much lower than the practical forging temperatures, but are shown for reference. On the other hand, the test temperature 525°C was much higher than typical temperatures, and was also higher than the solidus temperature 477°C. According to ASM Handbook [3], the incipient melt temperature for Al 7075 is 532°C. M. Kiuchi et al. [10] found that the flow stress in compression changed greatly around 524°C. Therefore test temperature 525°C was critical and, in this sense, compression test data at this temperature will be important for future research.
3.2.1 Inspection of Compression Specimen

The compression specimen in this study were relatively homogeneously deformed. Those data which showed macroscopic localized shearing and non-homogeneous deformation such as barrelling were carefully eliminated. Compression tests at a high temperature, that is 525°C, were relatively unstable and frequently showed macroscopic localized shearing. Figure 3.2.1 shows two sets of compression specimens in the before and after condition compressed to 100 % true strain. Figure 3.2.2 shows a batch of specimens compressed to approximately 100 % true strain grouped together by their testing temperatures. In each of these groups, the profiles of the specimens deformed at strain rates of $10^{-3}, 10^{-2}, 10^{-1},$ and $1 \text{ sec}^{-1}$ are compared. Overall, the deformation was well behaved. The test matrix corresponding to figure 3.2.2 is:

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Strain rate (sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10$^{-3}$</td>
</tr>
<tr>
<td>225</td>
<td>X</td>
</tr>
<tr>
<td>325</td>
<td>X</td>
</tr>
<tr>
<td>375</td>
<td>X</td>
</tr>
<tr>
<td>425</td>
<td>X</td>
</tr>
<tr>
<td>525</td>
<td>X</td>
</tr>
</tbody>
</table>

3.2.2 Stress-Strain Curves

Figure 3.2.3 through 3.2.11 show all stress strain curves obtained in this study. In figures 3.2.3 through 3.2.7, are four stress-strain curves having different strain rates are plotted together by common testing temperatures. Similarly, figures 3.2.8 through 3.2.11 contain the stress-strain curves having different temperatures but grouped together by common strain rates. The graphs in figures 3.2.3 through 3.2.7 show the
strain rate sensitivity of the deformation behavior of Al 7075 at high temperatures. The graphs in figures 3.2.8 through 3.2.11 show the temperature dependency. Figure 3.2.3 shows that at a fairly lower temperature 225°C, strain hardening appeared and the flow stress depends on strain. On the other hand, in the temperature range 325°C through 525°C, including the practically important temperature around 400°C, and also at the strain rates spanned in this study, the flow stress revealed to be relatively independent of strain. Figure 3.2.6 and 3.2.7 show that at the relatively high temperatures of 425°C and 525°C and also at a high strain rate 1 sec⁻¹, the flow stress decreases as the strain increases. Three data of same test condition of the temperature 425°C and strain rate 1 sec⁻¹ showed the same result and its repeatability. These specimens looked compressed homogeneously as shown in figure 3.2.2. Figure 3.2.12 shows the macroetched cross section of the specimen which shows the shear band. This localized shearing was due to the strain softening observed.
4 CONSTITUTIVE RELATIONS AND MATERIAL PARAMETERS

In the practically important range of temperature 325°C – 425°C, the flow stress of Al 7075 revealed to be independent of strain as mentioned in the last section. A constant value of the flow stress, therefore, was used in determining the constitutive relations for each constant true strain rate test. If the constitutive equation predicts the actual data within acceptable tolerances, then one simple equation which can cover the entire regime, that is, temperatures from 325°C through 425°C and strain rates from $10^{-3}$ through 1 sec$^{-1}$ would be very useful and important for engineering use, especially for complicated non-linear finite element analysis.

The following classical constitutive equation proved adequate to model the temperature and strain rate sensitivity of the flow stress:

$$\dot{\varepsilon}^p = \left\{A \exp\left(-\frac{Q}{kT}\right)\right\} \left(\left|\frac{\sigma}{\sigma_0}\right|\right)^m \text{sgn}(\sigma)$$

(1)

Here

- $\dot{\varepsilon}^p$: Plastic true strain rate (sec$^{-1}$);
- $T$: Temperature (°K);
- $\sigma$: Flow stress (MPa);
- $\sigma_0$: Representative stress, here taken to be 50 MPa;
- $A$: Pre-exponential material constant (sec$^{-1}$);
- $m$: Strain rate sensitivity (dimensionless);
- $Q$: Activation energy (J);
- $k$: Boltzmann’s constant = 1.381x10$^{-23}$ (J/K).
By a nonlinear least-square fit (IMSL routine ZXSSQ) of all data except 225 & 525°C for each deformation condition, the constant A, Q and m determined for aluminum alloy 7075 are listed in the table below.

**Material Parameters**

\[
\begin{align*}
A &= 6.544 \times 10^7 \text{ (sec}^{-1}) \\
Q &= 2.076 \times 10^{-19} \text{ (J)} \\
m &= 0.141
\end{align*}
\]

Figure 4.1 through 4.3 show that the flow stress predicted by this viscoplastic equation agree reasonably well with the actual stresses.

If the temperature sensitivity in equation (1) is expressed as \( \exp \left( -\frac{Q^*}{RT} \right) \) instead of \( \exp \left( -\frac{Q}{RT} \right) \), where \( R=8.31 \times 10^{-3} \) (kJ/mole-K) is the Universal gas constant, then \( Q^*=125 \) (kJ/mole). This value compares reasonably well with the activation energy for lattice self diffusion of 142 (kJ/mole) tabulated by H.J.Frost & M.F.Ashby [15].
5 A CLOSED-DIE FORGING AND HEAT TREATMENT TEST

As mentioned in the first section, cast ingots in the as-fabricated condition (F-temper) are forged and then heat-treated to obtain the specified material properties in the forged products. In order to simulate such a forging process, an isothermal closed-die forging was conducted using fully annealed Al 7075 as the starting material. The forged material was then heat-treated to T6-temper condition. The macrostructure and microstructure after heat-treatment were observed and compared with the original one.

The constitutive equation of Al 7075 obtained in this study was implemented in the ABAQUS finite element code (version # 4-5-159) via a user material subroutine developed by L. Anand et al. [1]. Then a process of isothermal closed-die forging test was simulated numerically using this finite element program. The forging configuration studied here developed large nonhomogeneous deformations within the work piece. These conditions were substantially different from those from which the constitutive relations were developed. Consequently, the usefulness of the constitutive relations for actual applications will be substantiated if they can predict the actual response under these nonhomogeneous time-varying conditions.

5.1 A CLOSED-DIE FORGING TEST

A miniature closed-die, plane-strain, isothermal forging test which converts a cylindrical billet with a circular cross section to one with a cross section in the form of a cruciform was conducted. Drawings of the forging dies and the cylindrical starting material are shown in figure 5.1.1. The cylindrical material was placed between the top and bottom
dies. The inside volume between top and bottom dies was made a little smaller than that of the cylindrical material so that the material would fill forging dies and produce a small amount of flash. To ensure plane strain conditions, in other words, to protect the material from extruding in the axial direction, the top and bottom forging dies assembly with material was placed in the C-shaped restraining block. A combination of glass lubricant 8463 95% and boron nitride 5% which worked well for compression testings at a temperature 425°C was applied on both material and forging dies. The material was forged at 425°C at a constant ram speed of 0.1 mm/sec. The theoretical total travel between top and bottom dies is about 6 mm, but the actual stroke was 5.4 – 5.5 mm due to flash. Figure 5.1.2 shows the actual top and bottom dies and C-shaped block. Figure 5.1.3 shows the before and after condition of the cylindrical material. The hardness after heat-treatment T6-temper was 51.5 – 53.5 of Rockwell A scale which was the same as that of the as-received material (Section 2).

Figure 5.1.4 shows the macrostructure of the material after forged and heat-treated of T6 condition. This shows the material flow lines along the forging die surface. This figure shows the asymmetry of top and bottom forging dies. This is due to the loose tolerance between top and bottom dies and the difficulty of machining the small dies accurately in our laboratory.

Figure 5.1.5 through 5.1.8 show the microstructure of the same material. Figure 5.1.5 shows its center part. Even at the center part where strain seems to be smaller than other parts, the grains were stretched vertically and became smaller from the original homogeneous grain size (see figure 2.1). Figure 5.1.6 shows the region with the most severe deformation. Grains were stretched largely along the forging die surface. Figure 5.1.7 shows its top part where strains were not large and grains remained fairly
large. Figure 5.1.8 shows the flash region where grains were again heavily stretched, just as in figure 5.1.6.

5.2 FINITE ELEMENT ANALYSIS OF CLOSED-DIE FORGING

The closed-die forging was analyzed by a finite element analysis. The constitutive relation obtained in this study for Al 7075 was implemented into a user material subroutine (UMAT) which is an option provided in ABAQUS where the user has the freedom to define a constitutive model to be used in the finite element analysis. The constitutive model used in this analysis was developed by Professor Lallit Anand and co-workers [1]. The UMAT subroutine is shown in Appendix E.

Figure 5.2.1 shows the finite element mesh used to model the starting billet and dies. This model is a quadrant of forged cylindrical material and shows the section perpendicular to the cylindrical axis. As mentioned in the last section, this closed-die forging can be treated as a plane strain problem. The two straight lines are, consequently, center lines which divide a circle into four quadrants. Figure 5.2.1 shows a grid of 29 8-node plane strain elements. The element used was CPE8RH, which is an 8-node biquadratic displacement, linear pressure element with reduced integration. Finer grids are used for the surface section of the material which deformed more than the central section.

The dies were modeled with a rigid surface option available in ABAQUS. The boundary conditions on the center lines were restriction of displacement in the direction perpendicular to each line. The forging load was obtained by summing the reaction forces on the horizontal boundary line.

Two models which have the same mesh shown figure 5.2.1 were analyzed: model
Model #1 was frictionless, and model #2 used classical Coulomb friction with a coefficient of friction of 0.3. 2 hours 51 minutes of CPU time and 318 increments were required to complete model #1 on a Data General MV 10000, and 4 hours 13 minutes of CPU time and 424 increments were required to complete model #2. The input file of model #2 is listed in Appendix D. The input file of model #1 is similar to that of model #2 except that the friction coefficient is 0.0 and the minimum increment time step of calculation $10^{-2}$ sec is greater than the previous value of $10^{-3}$ sec.

Figure 5.2.2 shows the progressively deformed meshes for model #1 (frictionless) and #2 (friction coefficient $\mu = 0.3$). Note that the frictionless model #1 fills the die in the horizontal direction faster than does the model #2 as shown between ram stroke 4.6 mm and 5.0 mm. This shows that the model #2 with friction rubs the forging die and has a large frictional force resisting horizontal extrusion. This is the main reason that model #1 has the larger forging load than does model #2 between ram stroke 4.6 mm and 5.0 mm. The final deformed figure is similar to the experimental one (figure 5.1.3), except for the length of the flash. A mesh refinement procedure seems to be necessary to analyze the flash part.

Figure 5.2.3 and 5.2.4 show shear strain rate $\dot{\gamma}^p$, and shear strain $\gamma^p$ contours of both models. These contours confirm that deformation is highly inhomogeneous. Such information is important and useful especially for strain-history-dependent material to create schemes for thermomechanical processing, which is the process to utilize thermo and mechanical means to produce desired microstructures for optimal mechanical properties.

Comparing these final deformed figures and strain contours to the experimentally obtained microstructure of forged material (see figure 5.1.5 through 5.1.8), the following
coincidences between the analysis and the experiments were found:

1. Highly compressed concave parts were observed in figure 5.1.6 and 5.2.2 and 5.2.4.

2. Vertically stretched central part was observed in figure 5.1.5 and 5.2.2.

3. Fairly small strain and almost non-deformed top part was observed in figure 5.1.7 and 5.2.4.

4. Highly compressed flash part was observed in figure 5.1.8 and 5.2.2 and 5.2.4.

Figure 5.2.5 shows the load verses ram stroke of both the experimental data and the two finite element results. It is found that for ram stroke in the range 0 - 4.6 mm, those three data are in good agreement, and for ram stroke 4.6 - 5.46 mm, the experimental data are at first close to the frictionless model #1, and then the friction model #2 is in better agreement with the experiment. In the forging experiment, the combination of glass lubricant and boron nitride which worked quite well for homogeneous compression testing was applied of both the cylindrical material and forging dies. In this sense the experimental data should be close to the frictionless model #1. Up to ram stroke around 4.25 mm, both coincide very well. After the material horizontally filled up the dies, (ram stroke around 5 mm), the actual force increased rapidly and the model #2 with friction captures this behavior. This indicates that after a ram stroke of \( \approx 4.6 \) mm, the material was constrained horizontally, and then it had to be extruded upward (see \( \gamma^p \) contours in figure 5.2.3). The contact pressure between the dies and the material increased highly, and the lubricant film was broken and could no longer work well. The friction coefficient finally increased.

This good accordance between experimental closed-die forging and its finite element analysis verifies the validity of constitutive equations obtained in this study as well as
the effectiveness of ABAQUS finite element analysis. This good agreement indicates that the constitutive equation developed here can be used successfully to predict forging loads, and material flow patterns.
CONCLUSIONS

A constitutive relation for Al 7075 has been developed in this study based on data obtained from isothermal homogeneous constant true strain rate compression tests. This constitutive equation has been implemented into the ABAQUS finite element code. A finite element model was constructed to simulate a closed-die forging that was conducted in the laboratory. The predicted forging loads and material flow patterns were in good agreement with the experimental data. These results show that the constitutive relation developed here can be used effectively to predict the response of complicated deformations. This constitutive equation makes it possible to predict forging loads, shapes, and material flow patterns within the forging piece with an accuracy which has not been possible previously. This equation can be used in numerical modeling to reduce the trial-and-error stage of the design of isothermal, precision forgings made of Al 7075.
REFERENCES


## APPENDIX A. CHEMICAL COMPOSITION OF AL 7075

<table>
<thead>
<tr>
<th>Element</th>
<th>Amount (Wt%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal</td>
<td>limits</td>
</tr>
<tr>
<td>Zinc</td>
<td>5.6</td>
<td>5.1 to 6.1</td>
</tr>
<tr>
<td>Copper</td>
<td>1.6</td>
<td>1.20 to 2.0</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.5</td>
<td>2.1 to 2.9</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.23</td>
<td>0.18 to 0.28</td>
</tr>
<tr>
<td>Manganese</td>
<td>-</td>
<td>0.30 max</td>
</tr>
<tr>
<td>Silicon</td>
<td>-</td>
<td>0.40 max</td>
</tr>
<tr>
<td>Iron</td>
<td>-</td>
<td>0.50 max</td>
</tr>
<tr>
<td>Titanium</td>
<td>-</td>
<td>0.20 max</td>
</tr>
<tr>
<td>Residual Elements</td>
<td>-</td>
<td>each: 0.05 max</td>
</tr>
<tr>
<td></td>
<td></td>
<td>total: 0.15 max</td>
</tr>
<tr>
<td>Aluminum</td>
<td>90.0</td>
<td>balance</td>
</tr>
</tbody>
</table>

APPENDIX B. PHYSICAL PROPERTIES OF AL 7075

Elastic Modulus

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>71.0 GPa</td>
</tr>
<tr>
<td>Compression</td>
<td>72.4 GPa</td>
</tr>
<tr>
<td>Shear</td>
<td>26.9 GPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Density</td>
<td>2.80 Mg/m³ at 20°C</td>
</tr>
</tbody>
</table>

Thermal Expansion

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Coefficient of Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 - 100°C</td>
<td>23.2x10⁻⁶</td>
</tr>
<tr>
<td>20 - 400°C</td>
<td>27x10⁻⁶</td>
</tr>
</tbody>
</table>

Liquidus Temperature | 635°C
Solidus Temperature  | 477°C
Incipient Melting Temperature | 532°C

Specific Heat | 960 J/Kg°C at 100°C

Hardness

<table>
<thead>
<tr>
<th>Temper</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>O temper</td>
<td>60 HB</td>
</tr>
<tr>
<td>T6, T651 temper</td>
<td>150 HB</td>
</tr>
</tbody>
</table>

(data obtained using 500 kg load, 10 mm dia. ball and 30 sec duration of loading)

Fatigue Strength

<table>
<thead>
<tr>
<th>Temper</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6, T651, T73</td>
<td>159 MPa at 5x10⁸ cycles</td>
</tr>
</tbody>
</table>

Fracture Toughness

<table>
<thead>
<tr>
<th>Temper</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T651</td>
<td>26.4 - 30.8 MPa√m</td>
</tr>
</tbody>
</table>
Tensile Properties

<table>
<thead>
<tr>
<th>temperature (°C)</th>
<th>tensile strength (MPa)</th>
<th>yield strength (MPa)</th>
<th>elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-196</td>
<td>703</td>
<td>634</td>
<td>9</td>
</tr>
<tr>
<td>-80</td>
<td>621</td>
<td>545</td>
<td>11</td>
</tr>
<tr>
<td>24</td>
<td>572</td>
<td>503</td>
<td>11</td>
</tr>
<tr>
<td>100</td>
<td>483</td>
<td>448</td>
<td>14</td>
</tr>
<tr>
<td>204</td>
<td>110</td>
<td>87</td>
<td>55</td>
</tr>
<tr>
<td>316</td>
<td>55</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>371</td>
<td>41</td>
<td>38</td>
<td>70</td>
</tr>
</tbody>
</table>

T73 tempers

<table>
<thead>
<tr>
<th>temperature (°C)</th>
<th>tensile strength (MPa)</th>
<th>yield strength (MPa)</th>
<th>elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-196</td>
<td>634</td>
<td>496</td>
<td>14</td>
</tr>
<tr>
<td>-80</td>
<td>545</td>
<td>462</td>
<td>14</td>
</tr>
<tr>
<td>24</td>
<td>503</td>
<td>434</td>
<td>13</td>
</tr>
<tr>
<td>100</td>
<td>434</td>
<td>400</td>
<td>15</td>
</tr>
<tr>
<td>204</td>
<td>110</td>
<td>90</td>
<td>55</td>
</tr>
<tr>
<td>316</td>
<td>55</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>371</td>
<td>41</td>
<td>32</td>
<td>70</td>
</tr>
</tbody>
</table>

APPENDIX C. PREVIOUS HOT COMPRESSION EXPERIMENTS ON AL 7075

Constitutive relations or flow stress data based on experiments on Al 7075 are necessary to predict forging loads. Despite Al 7075’s history of more than forty years, there are very few experimental data and associated constitutive relations.

T. Altan et al. in his book for forging [6] cited J. A. Bailey and A. R. E. Singer’s data [8] as Al 7075 equivalent. In fact only their data had been obtained systematically, and the power law type relation had been obtained between flow stress and strain rate at a certain temperature. Unfortunately, Bailey’s material is slightly different from Al 7075 (no chromium), and the temperature range is higher than the practical forging temperature range. The measured flow stresses are found to be close to the experimental data of Al 7075 to be presented here. Some references in the literature describing Al 7075 compression tests follow:


| material: | Al 89.6, Cu 1.31, Mg 2.21, Si 0.21, Fe 0.3, Mn 0.34, Zn 5.75, Pb 0.01 |
| (composition wt %) | |
| initial heat treatment: | solution heat treating and overaging |
| temperature: | 400 - 550°C |
| strain rate: | constant true strain rate 0.4 - 311 sec\(^{-1}\) |
| strain: | up to 2.3 (plane strain compression test) |

The flow stress and strain rate relation.

\[ \sigma = \sigma_0 \varepsilon^n \]
where $\sigma$ is flow stress (MPa) and $\dot{\varepsilon}$ strain rate (sec$^{-1}$) and other constants:

<table>
<thead>
<tr>
<th>temperature ($^\circ$C)</th>
<th>n</th>
<th>$\sigma_0$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.090 - 0.115</td>
<td>79.3 - 77.2</td>
</tr>
<tr>
<td>450</td>
<td>0.135 - 0.120</td>
<td>47.6 - 49.6</td>
</tr>
<tr>
<td>500</td>
<td>0.150 - 0.115</td>
<td>31.0 - 38.6</td>
</tr>
<tr>
<td>550</td>
<td>0.170 - 0.115</td>
<td>23.4 - 21.4</td>
</tr>
</tbody>
</table>

The comparison of flow stresses between Bailey’s and this study’s.

<table>
<thead>
<tr>
<th>temperature ($^\circ$C)</th>
<th>strain rate (sec$^{-1}$)</th>
<th>Bailey’s stress (MPa)</th>
<th>this study’s stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.4</td>
<td>103 - 90</td>
<td>91.7</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>138 - 110</td>
<td>142.3</td>
</tr>
</tbody>
</table>

Both Bailey’s equation and the constitutive equation in this study cover the temperature 400$^\circ$C. At this temperature, the strain rate sensitivity of $n=0.090 - 0.115$ in Bailey’s equation is smaller than that of this study $m=0.141$. The equivalent $\sigma_0$ calculated from the constitutive equation in this study comes to 92.2 MPa which is larger than that of Bailey’s equation $\sigma_0=79.3 - 77.2$ MPa.


- material: aluminum alloy 7075
- temperature: 371 / 427$^\circ$C
- strain rate: constant speed (0.31 - 0.49 sec$^{-1}$ equivalent strain rate)
- strain: up to 0.9 (ring compression test)

material: aluminum alloy 7075-T6
temperature: 487 – 590°C
strain rate: constant strain rate 0.2 sec⁻¹
strain: up to 0.1 (axisymmetric compression test)


material: aluminum alloy 7075-F (ingot)
temperature: room temperature – 500°C
strain rate: constant speed (0.05–0.06 sec⁻¹ equivalent strain rate)
strain: up to 0.7
APPENDIX D. STRENGTHENING MECHANISM AND HEAT TREATMENT OF AL 7075

Aluminum alloy 7000 series or the Al-Zn-Mg-Cu alloys have the highest strength of any aluminum alloy groups. Despite their attractive tensile properties and good fabricating characteristics, originally they were not used commercially because of their unsatisfactory resistance to stress-corrosion cracking. The success of aluminum alloy 7075 widely used in aircrafts was associated with the beneficial effect of chromium, which imparted good resistance to stress-corrosion cracking.

Alloying Elements for Hardening

Copper is one of the most important alloying ingredients for aluminum, because of its appreciable solubility and its strengthening effect. Many commercial alloys contain copper, either as the major addition or among the principal alloying elements. It imparts substantial precipitation-hardening characteristics to many of these alloys.

Magnesium is used in combination with copper, to accelerate and increase age hardening at room temperature. Magnesium provides substantial strengthening and high work-hardening characteristics. The combination of copper and magnesium in aluminum is the basis for a variety of heat treatable alloys. This combination, together with other elements, yields a series of alloys of great versatility because of their response to thermal treatment.

As an alloying ingredient, zinc is employed mostly along with magnesium in wrought alloys. The principal use of the binary alloys is for electrolytic protection against corrosion.
Solution Heat Treating

The objective of solution heat treatment is to allow the maximum practical amounts of the soluble hardening elements of the alloy to dissolve into solid solution, thus obtaining a solid solution that is nearly homogeneous. Because solubility and diffusion rate both increase with temperature, it usually is desirable to use the highest treatment temperature that will not cause remelting.

The temperature range 460 – 477°C is generally used for solution heat treatment, but higher range (up to 500°C) may be allowable for Al 7075.

To avoid types of precipitation detrimental to mechanical properties or to corrosion resistance, the solid solution formed during solution heat treatment must be rapidly cooled (quenched) to produce a supersaturated solution at room temperature—the optimum condition for precipitation hardening. Most frequently, quenching is done by rapid immersion in cold water. For aluminum alloys relatively high in sensitivity to quenching rate, such as 7075, quenching rates of about 330°C/sec or higher through the critical temperature range are required in order to obtain maximum strength after precipitation heat treating.

Precipitation Heat Treating

One essential attribute of a precipitation-hardening alloy system is a temperature-dependent solid solubility equilibrium characterized by decreasing solubility with decreasing temperature. Precipitation heat treatment or artificial aging produces maximum strength and hardness. If alloy is heated at too high temperature or for too long a time, the increase in strength and hardness will be followed by a decrease of these properties; this is called overaging.
Precipitation heat treatment or artificial aging following solution heat treatment and quenching produces T6- and T7-type tempers. Alloys in T6-type tempers generally have the highest strength possible without sacrifice of the other properties and characteristics found by experience to be satisfactory and useful for engineering applications. Alloys in T7-type tempers are stabilized by overaging which means that some degree of strength has been sacrificed to improve one or more other characteristics. Certain properties in the T6, T76 and T73 type temper are shown below:

<table>
<thead>
<tr>
<th>Property</th>
<th>Type of Temper</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T6</td>
</tr>
<tr>
<td>Strength</td>
<td>Highest</td>
</tr>
<tr>
<td>Resistance to stress-corrosion cracking</td>
<td>Lowest</td>
</tr>
<tr>
<td>Resistance to exfoliation corrosion</td>
<td>Low</td>
</tr>
</tbody>
</table>

Remarks: Temper designation

**T6** Solution heat treated and artificially aged. Applies to products that are not cold worked after solution heat treatment, and for which mechanical properties or dimensional stability, or both, have been substantially improved by precipitation heat treatment. If the products are flattened or straightened, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.

- T651: Stress relieved by stretching after solution heat treatment of T6
- T652: Stress relieved by compressing after solution heat treatment of T6
**T7** Solution heat treated and stabilized. Applies to products that have been precipitation heat treated to the extent that they are overaged. Stabilization heat treatment carries the mechanical properties beyond the point of maximum strength to provide some special characteristics, such as enhanced resistance to stress-corrosion cracking or exfoliation corrosion. Two important groups of T7-type tempers, T73-type and T76-type tempers, have been developed specially to improve resistance to exfoliation corrosion and stress-corrosion cracking.

Typical temperature of these heat treatments are shown below:

<table>
<thead>
<tr>
<th>Temper</th>
<th>Solution heat treatment (°C)</th>
<th>Precipitation heat treatment (°C)</th>
<th>Holding time for precipitation (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6, T651</td>
<td>470</td>
<td>120</td>
<td>24</td>
</tr>
<tr>
<td>T73</td>
<td>470</td>
<td>107</td>
<td>6</td>
</tr>
</tbody>
</table>
APPENDIX E. ABAQUS INPUT AND UMAT FILES

ABAQUS Input File

Friction coefficient = 0.3

*HEADING
ALUMINUM 7075 FORGING TEST, 425°C, 0.1MM/S, FRC, 0-5.6MM, MODEL-9J

*NODE
1, 0.0, 0.0
101, 0.001, 0.0
201, 0.002, 0.0
276, 0.00275, 0.0
351, 0.0035, 0.0
426, 0.00425, 0.0
501, 0.005, 0.0
651, 0.005675, 0.0
801, 0.00635, 0.0
102, 0.0, 0.001
209, 0.0, 0.002
284, 0.0, 0.00275
367, 0.0, 0.0035
442, 0.0, 0.00425
533, 0.0, 0.005
683, 0.0, 0.005675
833, 0.0, 0.00635

*NEST, NSET=CNTLINE
1, 102, 209, 284, 367, 442, 533, 683, 833

*NEST, NSET=HFLINE
1, 101, 201, 276, 351, 426, 501, 651, 801

*NGEN, LINE=C
201, 209, 1, 1
276, 284, 2, 1
351, 367, 1, 1
426, 442, 2, 1
501, 533, 1, 1
651, 683, 2, 1
801, 833, 1, 1

*MPC
2, 202, 201, 203, 205
2, 204, 201, 203, 205
2, 206, 205, 207, 209
2, 208, 205, 207, 209
2, 352, 351, 353, 355
2, 354, 351, 353, 355
2, 356, 355, 357, 359
2, 358, 355, 357, 359
2, 360, 359, 361, 363
2, 362, 359, 361, 363
2, 364, 363, 365, 367
2, 366, 363, 365, 367
2, 502, 501, 503, 505
2, 504, 501, 503, 505
2, 506, 505, 507, 509
2, 508, 505, 507, 509
2, 510, 509, 511, 513
2,512,509,511,513
2,514,513,515,517
2,516,513,515,517
2,518,517,519,521
2,520,517,519,521
2,522,521,523,525
2,524,521,523,525
2,526,525,527,529
2,528,525,527,529
2,530,529,531,533
2,532,529,531,533
*ELEMENT, TYPE=CPE8RH, ELSET=BODY
1,1,201,205,209,101,203,207,102
201,201,351,355,203,276,353,278,202
202,203,355,359,205,278,357,280,204
203,205,359,363,207,280,361,282,206
204,207,363,367,209,282,365,284,208
351,351,501,503,353,426,502,428,352
351,501,801,803,503,651,802,653,502
351,351,501,505,353,426,502,428,352
352,353,505,509,355,428,507,430,354
353,355,509,513,357,430,511,432,356
354,357,513,517,359,432,515,434,358
355,359,517,521,361,434,519,436,360
356,361,521,525,363,436,523,438,362
357,363,525,529,365,438,527,440,364
358,365,529,533,367,440,531,442,366
*ELGEN, ELSET=BODY
501,16,2,1
*ELSET, ELSET=HFBBAND
1,201,351,501
*ELEMENT, TYPE=IR322, ELSET=Surface
801,801,802,803
*ELGEN, ELSET=Surface
801,16,2,1
*RIGID SURFACE, ELSET=Surface, TYPE=SEGMENTS, SMOOTH=0.00005
START, 0.0119, 0.001996
LINE, 0.0119, 0.002996
LINE, 0.009145, 0.002996
CIRCLE, 0.00889, 0.003251, 0.009145, 0.003251
CIRCLE, 0.007841, 0.004501, 0.00762, 0.003251
LINE, 0.004053, 0.005169
CIRCLE, 0.001993, 0.007229, 0.004494, 0.00767
LINE, 0.00145, 0.010307
CIRCLE, 0.0002, 0.011356, 0.0002, 0.010086
LINE, 0.0, 0.011356
*MATERIAL, ELSET=BODY
*USER MATERIAL, CONSTANTS=1
1.0
*DEPVAR
4
*MATERIAL, ELSET=Surface
*FRICCTION
0.3, 1.0E+13
*BINARY
CNTLINE, 1
*BOUNDARY
*HLINE,2
*PLOT
UNDEFORMED MESH
*DRAW
*RESTART,WRITE,FREQUENCY=20
*STEP,NLGEOM,INC=500,CYCLE=10,AMP=RAMP
*VISCO,PTOL=100.0,CETOL=0.005
0.1,20.0,1.0E-3,3.0
*VALUE,TYPE=RIGID SURFACE
SURFACE,0.0,-0.001
*EL PRINT,FREQ=100,ELSET=HFBAND
2,1,1,1,1
2,1,1
*NODE PRINT,FREQ=4
1,1,1,1,1,2
*PRINT,FREQUENCY=4
*PLOT,FREQUENCY=100
FORGING TEST,425C,0.1MM/S,FRC,0-2.0MM,MODEL-9J
*DISPLACED
1,1,0,1
*END STEP
*STEP,NLGEOM,INC=300,CYCLE=10,AMP=RAMP
*VISCO,PTOL=100.0,CETOL=0.005
0.1,10.0,1.0E-3,3.0
*VALUE,TYPE=RIGID SURFACE
SURFACE,0.0,-0.001
*EL PRINT,FREQ=100,ELSET=HFBAND
2,1,1,1,1
2,1,1
*NODE PRINT,FREQ=4
1,1,1,1,1,2
*PRINT,FREQUENCY=4
*PLOT,FREQUENCY=100
FORGING TEST,425C,0.1MM/S,FRC,2.0-3.0MM,MODEL-9J
*DISPLACED
1,1,0,1
*END STEP
*STEP,NLGEOM,INC=300,CYCLE=10,AMP=RAMP
*VISCO,PTOL=100.0,CETOL=0.005
0.1,10.0,1.0E-3,3.0
*VALUE,TYPE=RIGID SURFACE
SURFACE,0.0,-0.002
*EL PRINT,FREQ=100,ELSET=HFBAND
2,1,1,1,1
2,1,1
*NODE PRINT,FREQ=4
1,1,1,1,1,2
*PRINT,FREQUENCY=4
*PLOT,FREQUENCY=100
FORGING TEST,425C,0.1MM/S,FRC,3.0-4.0MM,MODEL-9J
*DISPLACED
1,1,0,1
*END STEP
*STEP,NLGEOM,INC=300,CYCLE=10,AMP=RAMP
*VISCO,PTOL=100.0,CETOL=0.005
0.1,10.0,1.0E-3,3.0

*VALUE, TYPE=RIGID SURFACE
SURFACE, 0.0, -0.0025
*EL PRINT, FREQ=100, ELSET=HFBAND
2,1,1,1,1
2,1,1
*NODE PRINT, FREQ=4
1,1,1,1,1,2
*PRINT, FREQUENCY=4
*PLOT, FREQUENCY=20
FORGING TEST, 425C, 0.1MM/S, FRC, 4.0-5.0MM, MODEL-9J
*DISPLACED
1,1,0,1
*END STEP
*STEP, NLGEOM, INC=300, CYCLE=10, AMP=RAMP
*VISO, PTOL=100.0, CETOL=0.005
0.1,4.6,1.0E-3,2.0
*VALUE, TYPE=RIGID SURFACE
SURFACE, 0.0, -0.00273
*EL PRINT, FREQ=100, ELSET=HFBAND
2,1,1,1,1
2,1,1
*NODE PRINT, FREQ=4
1,1,1,1,1,2
*PRINT, FREQUENCY=4
*PLOT, FREQUENCY=20
FORGING TEST, 425C, 0.1MM/S, FRC, 4.0-5.0MM, MODEL-9J
*DISPLACED
1,1,0,1
*PLOT, FREQUENCY=100
FORGING TEST, 425C, 0.1MM/S, FRC, 5.46MM, MODEL-9J
*DISPLACED
1,1,0
PLASTIC SHEAR STRAIN RATE, 425C, 0.1MM/S, FRC, 5.46MM, MODEL-9J
*CONTOUR
83
*PLOT, FREQUENCY=100
PLASTIC SHEAR STRAIN, 425C, 0.1MM/S, FRC, 5.46MM, MODEL-9J
*CONTOUR
84
*END STEP
*STEP, NLGEOM, INC=300, CYCLE=10, AMP=RAMP
*VISO, PTOL=100.0, CETOL=0.005
0.1,1.4,1.0E-3,1.4
*VALUE, TYPE=RIGID SURFACE
SURFACE, 0.0, -0.0028
*EL PRINT, FREQ=100, ELSET=HFBAND
2,1,1,1,1
2,1,1
*NODE PRINT, FREQ=4
1,1,1,1,1,2
*PRINT, FREQUENCY=4
*PLOT, FREQUENCY=20
FORGING TEST, 425C, 0.1MM/S, FRC, 5.46-5.6MM, MODEL-9J
*DISPLACED
1,1,0,1
*END STEP
ABAQUS UMAT File

SUBROUTINE UMAT(STRESS, STATEV, DDSDDE, SSE, SPD,
1 SC, STRAN, DSTRAN, TIME, DTIME, TEMP, DTEMP, DPREDEF,
2 DPRED, MATERL, NDI, NSHR, NTENS, NSTATV, PROPS,
3 NPROPS, COORDS)

C******************************************************************************
IMPLICIT REAL*8(A-H,O-Z)
C******************************************************************************

COMMON/CERROR/RESMAX(30), JNREMX(30), ERRMAX(2), CETOL, CSLIM,
1 CMAX, PCTOL, TLIMIT, PSUBIN, RESMIN, DUMAX(30), JNDLNX(30),
2 ERRPRE, UDELSS, PTOL, AMTOL, DMKET, DMRETL, SIGTOL, DSIGM,
3 UTOU, UMAX, UMAXXMAX, AMAX, A4MAX, TMAX, EPPMAX, RMAX, RMAX,
4 NGOPEN, NGCLOS, ROTTOL, ROTFAC, JRIKND, NINCCS, RIKUB, RIKLM, RIKMU,
5 RIKLAM, RIKDLO, RIKRO, RIKOLD, RIKLM, QMAX, DUMAXP
6, STRAT, PCUT, RIKDLO
DIMENSION STRESS(NTENS), STATEV(NSTATV),
1 DDSDDE(NTENS, NTENS), STRAN(NTENS),
2 DSTRAN(NTENS), DPREDEF(1), DPRED(1),
3 PROPS(NPROPS), CODIDS(3)
C******************************************************************************

DIMENSION DSTRES(6), STRES(6)

CELASTIC SHEAR AND BULK MIXED (SUGGESTED UNITS: N/m2)
C******************************************************************************

AMU=5.64E+9
AKAPPA=14.7E+9

C COEFFICIENT OF THERMAL EXPANSION (SUGGESTED UNITS m/m per degree K)
C******************************************************************************

ALPHA=27. E-6

C INITIAL VALUES OF STATE VARIABLES (SUGGESTED UNITS: S0 IN N/m2, T0 IN DEG. K)
C******************************************************************************

S0=100.0E+6/1.7321
T0=698.0

C THE PARAMETER PHI CONTROLS THE DEGREE OF IMPLICITNESS OF
C THE INTEGRATION PROCEDURE:
C PHI=0.0 ---- EXPLICIT
C PHI=1.0 ---- IMPlicit
C******************************************************************************

PHI=0.75

C FOR ISOHERMAL DEFORMATIONS SET OMEGA EQUAL TO ZERO.
C FOR ADIABATIC DEFORMATIONS THE PARAMETER OMEGA MUST BE
C SET TO A NON-ZERO VALUE OF APPROXIMATELY 0.9.
C RHO ---- MASS DENSITY (SUGGESTED UNITS: Kg/m3)
C C ---- SPECIFIC HEAT (SUGGESTED UNITS: J/Kg./DEG. K)
C******************************************************************************

OMEGA=0.0
RHO=2800.0
C=960.0
C******************************************************************************

46
DO 10 K1=1,NTENS
DSTRES(K1)=0.0
10 CONTINUE
C*******************************************************************************
DO 20 K1=1,NTENS
DO 20 K2=1,NTENS
DDSDDE(K1,K2)=0.0
20 CONTINUE
C*******************************************************************************
CALL SINV(STRESS,SINV1,SINV2)
C*******************************************************************************
DO 30 K1=1,NDI
STRESS(K1)=STRESS(K1)-SINV1
30 CONTINUE
C IF(NSHR.EQ.0) GO TO 50
C I1=NDI
DO 40 K1=1,NSHR
I1=I1+1
STRES(I1)=STRESS(I1)
40 CONTINUE
C 50 CONTINUE
C*******************************************************************************
S=STATEV(1)
T=STATEV(2)
C IF(STATEV(1).EQ.0.0) THEN
S=S0
T=T0
STATEV(1)=S0
STATEV(2)=T0
STATEV(4)=0.0
END IF
C*******************************************************************************
TAUB=SINV2/1.73205081
PB=-SINV1
C THE NEXT CALL TO SBETA IS TO DETERMINE THE VALUE OF THE
C THE PLASTIC DILATANCY FACTOR BETA
C*******************************************************************************
CALL SBETA(TAUB, PB, T, S, BETA)
C THE NEXT CALL TO GAMDOT IS TO DETERMINE THE EQUIVALENT
C PLASTIC SHEAR STRAIN RATE F AND THE PARTIAL DERIVATIVES
C PDA, PDB, PDC, PDD OF F WITH RESPECT TO TAUB, PB, T AND S,
C RESPECTIVELY.
C*******************************************************************************
CALL GAMDOT(TAUB, PB, T, S, F1, PDA, PDB, PDC, PDD)
EDOT1=F1/1.732050808
C*******************************************************************************
EDOT1=F1/1.732050808
C THE NEXT CALL TO SDOT IS TO DETERMINE THE HARDENING RATE H,
C THE STATIC RESTORATION RATE RDOT AND THE PARTIAL
C DERIVATIVES PDE AND PDF OF H AND RDOT, RESPECTIVELY, WITH
C RESPECT TO S.
CALL SDOT(TAUB,PB,T,S,F1,H,RDOT,PDD,PDE,PDF)

PDG = PDE*F1 + PDD*H - PDF
PDH = PHI*DTIME*PDG

HB = H/(1. + PDH)
DR = RDOT*DTIME/(1. + PDH)

G = AMU - (PDD*HB + PDB*AKAPPA*BETA + PDC*(OMEGA/(RHO*C))*(TAUB-BETA*PB))/PDA

V = PHI*DTIME*PDA*G

IF(PHI.EQ.0.0) THEN
  AMUB = AMU
  GO TO 55
END IF

H1 = TAUB/(PHI*DTIME*F1)

AMUB = ((AMU*H1)/(AMU+H1))

55 CONTINUE

C THE NEXT BLOCK CALCULATES T' .DSTRAN

W1 = 0.0
DO 60 K1 = 1,NDI
  W1 = W1 + STRESD(K1)*DSTRAN(K1)
60 CONTINUE

C IF(NSHR.EQ.0) GO TO 80

I1 = NDI
DO 70 K1 = 1,NSHR
  I1 = I1 + 1
  W1 = W1 + STRESD(I1)*DSTRAN(I1)
70 CONTINUE

80 CONTINUE

C THE NEXT BLOCK CALCULATES TR(DSTRAN)

W2 = 0.0
DO 90 K1 = 1,NDI
  W2 = W2 + DSTRAN(K1)
90 CONTINUE

V1 = (F1*DTIME)/(1.+V)
V2 = (V/(1.+V))*((1./G)

DGAMPB = V1 + V2*((AMU/TAUB)*W1 + AKAPPA*(-PDB/PDA)*W2)
C******************************************************************************
C THE NEXT BLOCK CALCULATES THE INCREMENTS DS AND DT IN THE
C STATE VARIABLES S AND T, AND UPDATES THE VALUES OF THE
C STATE VARIABLES.
C******************************************************************************
DS=HB*DGAMPB-DR
DT=(OMEGA/(RHO*C))*(TAUB-BETA*PB)*DGAMPB
C
STATEV(1)=S+DS
STATEV(2)=T+DT
C******************************************************************************
C THE NEXT BLOCK CALCULATES THE STRESS INCREMENTS AND
C UPDATES THE VARIOUS COMPONENTS OF THE STRESS TENSOR.
C******************************************************************************
V3=2.*AMUB
V4=(AKAPPA-(2./3.)*AMUB)*W2
V5=3.*AKAPPA*ALPHA*DT
V6=AKAPPA*BETA*DGAMPB
V7=V4-V5-V6
V8A=(AMJ/TAUB)*DGAMPB
V8B=(AMJ-AMUB)*W1/(TAUB**2)
V8=V8A-V8B
V9=AMUB
C
DO 100 K1=1,NDI
DSTRES(K1)=V3*DSTRAN(K1)+V7-V8*STRESD(K1)
STRESS(K1)=STRESS(K1)+DSTRES(K1)
100 CONTINUE
C
IF(NSHR.EQ.0)GO TO 120
C
I1=NDI
DO 110 K1=1,NSHR
  I1=I1+1
DSTRES(I1)=V9*DSTRAN(I1)-V8*STRESD(I1)
STRESS(I1)=STRESS(I1)+DSTRES(I1)
110 CONTINUE
C
120 CONTINUE
C******************************************************************************
C THE NEXT BLOCK CALCULATES THE (IN GENERAL NON-SYMMETRIC)
C JACOBIAN MATRIX.
C******************************************************************************
V10=AKAPPA
V11=V10-(2./3.)*V9
V12=(V2*(AMJ/TAUB)**2)-(AMJ-AMUB)/(TAUB**2)
V13=V2*V10*(-PDB/PDA)*(AMJ/TAUB)
V14=V2*V10*BETA*(AMJ/TAUB)
V15=V2*(V10**2)*BETA*(-PDB/PDA)
V16=V11-V15
C
DO 130 K1=1,NDI
DDSDDE(K1,K1)=V3+V16
1   -V12*STRESD(K1)**2
2   -(V13+V14)*STRESD(K1)
130 CONTINUE
IF(NDI.EQ.1)GO TO 160

C DO 150 K1=2,NDI
N2=K1-1
DO 140 K2=1,N2
DDSDDE(K2,K1)=V16-V12*STRESD(K2)*STRESD(K1)
1-V13*STRESD(K2)-V14*STRESD(K1)
DDSDDE(K1,K2)=V16-V12*STRESD(K1)*STRESD(K2)
1-V13*STRESD(K1)-V14*STRESD(K2)
140 CONTINUE
150 CONTINUE
160 CONTINUE
C
IF(NSHR.EQ.0)GO TO 200
C
DO 180 K1=1,NDI
I1=NDI
DO 170 K2=1,NSHR
I1=I1+1
DDSDDE(K1,I1)=-V12*STRESD(K1)*STRESD(I1)
1-V14*STRESD(I1)
DDSDDE(I1,K1)=-V12*STRESD(K1)*STRESD(I1)
1-V13*STRESD(I1)
170 CONTINUE
180 CONTINUE
C
I1=NDI
DO 190 K1=1,NSHR
I1=I1+1
DDSDDE(I1,I1)=V9-V12*STRESD(I1)*STRESD(I1)
190 CONTINUE
C
IF(NSHR.EQ.1) GO TO 200
C
IF(NSHR.EQ.2) THEN
I=NDI+1
J=NDI+2
DDSDDE(I,J)=-V12*STRESD(I)*STRESD(J)
DDSDDE(J,I)=DDSDDE(I,J)
END IF
C
IF(NSHR.EQ.3) THEN
I=NDI+1
J=NDI+2
K=NDI+3
DDSDDE(I,J)=-V12*STRESD(I)*STRESD(J)
DDSDDE(J,I)=DDSDDE(I,J)
DDSDDE(I,K)=-V12*STRESD(I)*STRESD(K)
DDSDDE(K,I)=DDSDDE(I,K)
DDSDDE(J,K)=-V12*STRESD(J)*STRESD(K)
DDSDDE(K,J)=DDSDDE(J,K)
END IF
C
200 CONTINUE
C***************************** Calculation of the Plastic Strain Rates Before and After
C the Time Step, to be Used by the Automatic Integration
C Scheme of Abaqus
C***********************************************
S=STATEV(1)
T=STATEV(2)
CALL SINV(STRESS,SINV1,SINV2)
TAUB=SINV2/1.732050808
PB=-SINV1
CALL GAMDOT(TAUB,PB,T,S,F2,PDA,PDB,PDC,PDD)
STATEV(3)=F2
STATEV(4)=STATEV(4)+DTIME*(F+PHI*(F2-F1))
EDOT2=F2/1.732050808
DIFF=DTIME*DABS(EDOT1-EDOT2)
CMAX=MAX1(CMAX,DIF)
RETURN
END
C***********************************************
C***********************************************
SUBROUTINE SBETA(TAUB,PB,T,S,BETA)
***************************************************************
IMPLICIT REAL*8(A-H,O-Z)
C*****************************************************
BETA=0.0
RETURN
END
C*****************************************************
SUBROUTINE GAMDOT(TAUB,PB,T,S,F,PDA,PDB,PDC,PDD)
IMPLICIT REAL*8(A-H,O-Z)
C MATERIAL PARAMETERS DEFINING THE FUNCTION F FOR THE
C EQUIVALENT PLASTIC SHEAR STRAIN RATE:
C A ---- PRE-EXPONENTIAL FACTOR
C Q ---- ACTIVATION ENERGY (SUGGESTED UNITS:kJ/mol.)
C R ---- UNIVERSAL GAS CONSTANT (SUGGESTED VALUE: 8.314E-3kJ/mol./Deg. K)
C AM ---- STRAIN RATE SENSITIVITY
C PALPHA -- PRESSURE SENSITIVITY PARAMETER (SUGGESTED UNITS: (N/m2)-1)
C PALPHA2 -- SHEAR MODULUS AT ZERO PRESSURE (SUGGESTED UNITS: N/m2)
C PALPHA2 -- PRESSURE DEPENDENCY OF SHEAR MODULUS
C SS ---- REPRESENTATIVE STRESS
C**************************************************************************
A=6.544E+7
Q=2.076E-19
R=1.381E-23
AM=0.141
PALPHA=0.0
SS=50.0E+6
C**************************************************************************
IF(TAUB.LT.0.001) THEN
  TAUB=.001
END IF

C A1=A*DEXP(-Q/(R*T))

C SSR3= SS/1.73205
  F=A1*(TAUB/SSR3)**(1./AM)
C
IF(F.LT.1.D-10)THEN
  F=1.D-10
END IF

C PDA=F/(AM*TAUB)
PDB=0.
PDC=F*(Q/(R*T**2))
PDD=0.

C RETURN
END

C***********************************************************************
C***********************************************************************
C***********************************************************************

SUBROUTINE SDOT(TAUB,PB,T,S,F,H,RDOT,PDD,PDE,PDF)
C***********************************************************************
C***********************************************************************
C***********************************************************************

IMPLICIT REAL*8(A-H,O-Z)
C***********************************************************************
C***********************************************************************
C***********************************************************************

H=0.0
PDE=0.0
RDOT=0.0
PDF=0.0
RETURN
END
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Surface perpendicular to rolling direction of 7075-T6 in the as-received condition. Etchant: Keller’s reagent</td>
<td>57</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Surface parallel to rolling direction of 7075-T6 in the as-received condition. Etchant: Keller’s reagent</td>
<td>58</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Surface perpendicular to rolling direction of 7075 after annealing. Etchant: Keller’s reagent</td>
<td>59</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Surface parallel to rolling direction of 7075 after annealing. Etchant: Keller’s reagent</td>
<td>60</td>
</tr>
<tr>
<td>Figure 3.1.1</td>
<td>Groove geometries of test specimens</td>
<td>61</td>
</tr>
<tr>
<td>Figure 3.1.2</td>
<td>Dimensions of test specimens</td>
<td>61</td>
</tr>
<tr>
<td>Figure 3.1.3</td>
<td>Test equipment</td>
<td>62</td>
</tr>
<tr>
<td>Figure 3.2.1</td>
<td>Before and after condition of specimens compressed to 100 % true strain</td>
<td>63</td>
</tr>
<tr>
<td>Figure 3.2.2</td>
<td>A matrix of aluminum alloy 7075 specimens compressed to approximately 100 % true strain. Testing temperatures vary from row to row, and strain rates vary from column to column</td>
<td>63</td>
</tr>
<tr>
<td>Figure 3.2.3</td>
<td>Experimental data: Stress-strain curves</td>
<td>63</td>
</tr>
</tbody>
</table>

53
Testing temperature: 225°C
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1 \text{ sec}^{-1}$

Figure 3.2.4 Experimental data: Stress-strain curves

Testing temperature: 325°C
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1 \text{ sec}^{-1}$

Figure 3.2.5 Experimental data: Stress-strain curves

Testing temperature: 375°C
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1 \text{ sec}^{-1}$

Figure 3.2.6 Experimental data: Stress-strain curves

Testing temperature: 425°C
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1 \text{ sec}^{-1}$

Figure 3.2.7 Experimental data: Stress-strain curves

Testing temperature: 525°C
Strain rates: $10^{-2}, 10^{-1}, 1 \text{ sec}^{-1}$

Figure 3.2.8 Experimental data: Stress-strain curves

Testing temperature: 225, 325, 375, 425°C
Strain rates: $10^{-3} \text{ sec}^{-1}$

Figure 3.2.9 Experimental data: Stress-strain curves

Testing temperature: 225, 325, 375, 425, 525°C
Strain rates: $10^{-2} \text{ sec}^{-1}$

Figure 3.2.10 Experimental data: Stress-strain curves

Testing temperature: 225, 325, 375, 425, 525°C
Strain rates: $10^{-1} \text{ sec}^{-1}$

Figure 3.2.11 Experimental data: Stress-strain curves
Testing temperature: 225, 325, 375, 425, 525°C
Strain rates: 1 sec\(^{-1}\)

**Figure 3.2.12** Cross section of compressed specimen
at temperature 425°C, strain rate 1 sec\(^{-1}\)

**Figure 4.1** Stress-strain data curves compared to
consitutive relations

Testing temperature: 325°C
Strain rates: 10\(^{-3}\), 10\(^{-2}\), 10\(^{-1}\), 1 sec\(^{-1}\)

**Figure 4.2** Stress-strain data curves compared to
consitutive relations

Testing temperature: 375°C
Strain rates: 10\(^{-3}\), 10\(^{-2}\), 10\(^{-1}\), 1 sec\(^{-1}\)

**Figure 4.3** Stress-strain data curves compared to
consitutive relations

Testing temperature: 425°C
Strain rates: 10\(^{-3}\), 10\(^{-2}\), 10\(^{-1}\), 1 sec\(^{-1}\)

**Figure 5.1.1** Dimension of forging dies and cylindrical material

**Figure 5.1.2** Forging dies for performed closed-die
forging

**Figure 5.1.3** Before and after condition of closed-die
forging

**Figure 5.1.4** Macroetched surface of forged material
Etchant: caustic etch

**Figure 5.1.5** Surface of the forged material (1/4)
Etchant: Keller’s reagent

Figure 5.1.6  Surface of the forged material (2/4)
Etchant: Keller’s reagent

Figure 5.1.7  Surface of the forged material (3/4)
Etchant: Keller’s reagent

Figure 5.1.8  Surface of the forged material (4/4)
Etchant: Keller’s reagent

Figure 5.2.1  Finite element model

Figure 5.2.2  Progressively deformed meshes of finite element models

Figure 5.2.3  Plastic shear strain rate $\dot{\gamma}^p$ contours of finite element model

Figure 5.2.4  Plastic shear strain $\gamma^p$ contours of finite element models

Figure 5.2.5  Load-stroke curves of the performed closed-die forging comparing the experimental data and the finite element analyses
Figure 2.1  Surface perpendicular to rolling direction of 7075-T6 in the as-received condition.  
Etchant: Keller’s reagent
Figure 2.2 Surface parallel to rolling direction of 7075-T6 in the as-received condition. 
Etchant: Keller's reagent
Figure 2.3  Surface perpendicular to rolling direction of 7075 after annealing.  
Etchant: Keller's reagent
Figure 2.4  Surface parallel to rolling direction of 7075 after annealing.  
Etchant: Keller’s reagent
Figure 3.1.1  Groove geometries of test specimens

Figure 3.1.2  Dimensions of test specimens
Figure 3.1.3  Test equipment
Figure 3.2.1  Before and after condition of specimens compressed to 100 % true strain

Figure 3.2.2  A matrix of aluminum alloy 7075 specimens compressed to approximately 100 % true strain. Testing temperatures vary from row to row, and strain rates vary from column to column
Aluminum 7075

$T=225°C$

Figure 3.2.3  Experimental data: Stress-strain curves
Testing temperature: $225°C$
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1 \text{ sec}^{-1}$
Figure 3.2.4 Experimental data: Stress-strain curves
Testing temperature: 325°C
Strain rates: $10^{-3}$, $10^{-2}$, $10^{-1}$, 1 sec$^{-1}$

Aluminum 7075

T=325°C

Strain rates: 10$^{-3}$, 10$^{-2}$, 10$^{-1}$, 1 sec$^{-1}$
Aluminum 7075

Figure 3.2.5 Experimental data: Stress-strain curves
Testing temperature: 375°C
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1$ sec$^{-1}$
Aluminum 7075

T=425°C

Figure 3.2.6 Experimental data: Stress-strain curves
Testing temperature: 425°C
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1$ sec$^{-1}$
Aluminum 7075

T=525°C

Figure 3.2.7
Experimental data: Stress-strain curves
Testing temperature: 525°C
Strain rates: $10^{-2}$, $10^{-1}$, 1 sec$^{-1}$
Aluminum 7075
Sr=0.001

Figure 3.2.8 Experimental data: Stress-strain curves
Testing temperature: 225, 325, 375, 425°C
Strain rates: $10^{-3}$ sec$^{-1}$
Aluminum 7075
Sr=0.01

Figure 3.2.9 Experimental data: Stress-strain curves
Testing temperature: 225, 325, 375, 425, 525°C
Strain rates: $10^{-2}$ sec$^{-1}$
Aluminum 7075
Sr=0.1

Figure 3.2.10 Experimental data: Stress-strain curves
Testing temperature: 225, 325, 375, 425, 525°C
Strain rates: $10^{-1}$ sec$^{-1}$
Figure 3.2.11  Experimental data: Stress-strain curves
Testing temperature: 225, 325, 375, 425, 525°C
Strain rates: 1 sec^{-1}
Figure 3.2.12  Cross section of compressed specimen at temperature 425°C, strain rate 1 sec$^{-1}$
Figure 4.1  Stress-strain data curves compared to constitutive relations
Testing temperature: 325°C
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1 \text{ sec}^{-1}$
Aluminum 7075
T=375°C

Figure 4.2 Stress-strain data curves compared to constitutive relations
Testing temperature: 375°C
Strain rates: $10^{-3}$, $10^{-2}$, $10^{-1}$, 1 sec$^{-1}$
Aluminum 7075

T=425°C

Stress-strain data curves compared to constitutive relations
Testing temperature: 425°C
Strain rates: $10^{-3}, 10^{-2}, 10^{-1}, 1 \text{ sec}^{-1}$

Figure 4.3
Cylindrical material

Top die

Bottom die

C-shaped restraining block
(half scale of above)

Figure 5.1.1  Dimension of forging dies and cylindrical material
Figure 5.1.2  Forging dies for performed closed-die forging

Figure 5.1.3  Before and after condition of closed-die forging
Figure 5.1.4
Macroetched surface of forged material
Etchant: caustic etch

x11.25
Figure 5.1.5 Surface of the forged material (1/4)
Etchant: Keller’s reagent
Figure 5.1.6  Surface of the forged material (2/4)
Etchant: Keller's reagent
81
Figure 5.1.7  Surface of the forged material (3/4)
Etchant: Keller’s reagent

82
Figure 5.1.8 Surface of the forged material (4/4)
Etchant: Keller’s reagent
Figure 5.2.1 Finite element model
Figure 5.2.2  Progressively deformed meshes of finite element models
Model # 1 (frictionless)

Ram stroke = 4.6 mm

Model # 2 (friction $\mu = 0.3$)

Ram stroke = 5 mm

Ram stroke = 5.46 mm

Ram stroke = 5.55 mm

Figure 5.2.2 Progressively deformed meshes of finite element models (Continued)
Model # 1 (frictionless)

Ram stroke = 2 mm

Ram stroke = 3 mm

Ram stroke = 4 mm

Figure 5.2.3 Plastic shear strain rate $\dot{\gamma}^p$ contours of finite element models
Figure 5.2.3 Plastic shear strain rate $\dot{\gamma}^P$ contours of finite element models (Continued)
Model #1 (frictionless)

STATE V. 4
I.D. VALUE
1 +0.00E+00
2 +0.00E+00
3 +0.00E+00
4 +0.00E+00
5 +0.00E+00
6 +0.00E+00
7 +0.00E+00
8 +0.00E+00
9 +0.00E+00
10 +0.00E+00
11 +0.00E+00

Ram stroke = 2 mm

Model #2 (friction $\mu=0.3$)

STATE V. 4
I.D. VALUE
1 +0.00E+00
2 +0.00E+00
3 +0.00E+00
4 +0.00E+00
5 +0.00E+00
6 +0.00E+00
7 +0.00E+00
8 +0.00E+00
9 +0.00E+00
10 +0.00E+00
11 +0.00E+00

Ram stroke = 3 mm

Ram stroke = 4 mm

Figure 5.2.4 Plastic shear strain $\gamma^p$ contours of finite element models
Model # 1 (frictionless)

Ram stroke = 4.6 mm

Model # 2 (friction \( \mu = 0.3 \))

Ram stroke = 5 mm

Ram stroke = 5.46 mm

Ram stroke = 5.55 mm

Figure 5.2.4 Plastic shear strain \( \gamma_p \) contours of finite element models (Continued)
Figure 5.2.5  Load-stroke curves of the performed closed-die forging comparing the experimental data and the finite element analyses.

ALUMINUM 7075

T=425°C, SP=0.1MM/S

1 — Experiment
2 — Model # 2  
   (friction $\mu=0.3$)
3 — Model # 1  
   (frictionless)