Al 7075: Feasibility Study of Near-Net Shape Superplastic Forging

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FIERF Graduate Fellowship 2009/10

1. Background

For almost three decades, superplastic forging has been proven to be cost effective to commercially produce complex shaped components and unitized structure from sheets.

Due to the traditionally low forming rates and the high cost of producing fine grained materials, superplastic forging found very little application in the forging industry. This study evaluates the feasibility of forging a small connecting rod from raw material that had been friction stir processed. The 12.5 mm thick plate of ultra-fine grained Al 7075 was then superplastically forged at a temperature of 490 C.

Friction stir processing is based on the idea of a rotating tool being inserted in a monolithic work piece for localized microstructural modification to create ultra-fine grains via high local strain rates.

2. Project Description

This thesis focused on two areas. First, it targeted the optimization of FSP parameters such as tool traverse speed and rotational rates to create ultra-fine grain structures and second, forging temperature and strain rate.

The forged FSP connecting rod is then compared to unprocessed, but forged parent material as well as FSP processed & forged - T6 heat treated forging, in means of fatigue life, yield strength, crack nucleation and crack growth.
3. Summary of Conclusions

It was found that for higher temperatures and low strain rates the flow stress was at a minimum. The two charts below provide a overview of flow stress and elongation data:

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*Summary of flow stresses at different temperatures and strain rates*

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*Elongation at different temperatures and strain rates*

FSP proved to be effective in refining grains in aluminum alloys via dynamic recrystallization and subsequent formation of annealed, very fine equiaxed grains. The grain size in the FSP nugget zone was found to be 5.3±0.86 µm. In order to evaluate thermal stability of the grain, the FSP material was heated at 490°C for 1 hr and quenched. The microstructure after the heat treatment was reasonably stable with grain sizes of 8.99±1.19 µm.
Comparison of the microstructure from the FSP processed zone and the raw material.

Backscattered images from a Hitachi S-570 SEM were used to analyze the changes in the constituent particles and voids due to FSP and subsequent compression. The parent material showed larger constituent particles which were not uniformly distributed and larger voids. Below images show the FSP zone compared to the unprocessed zone.

Many studies have come to the conclusion that larger, Fe rich constituent particles were responsible for crack nucleation. The constituent particles are formed when some of the alloying elements solidify faster than aluminum. They are inherent to the material and largely dictated by the level of impurity of the raw material.

The chart below provides an overview of the preliminary fatigue life data.
Preliminary data for fatigue life of superplastically forged 7075 Al alloy

It was further observed that the coefficient of friction at 490°C and a strain rate of $10^{-2}$s$^{-1}$ for the FSP material was ~0.02 while the coefficient of friction for the parent material for the same temperature and strain rate was more than double with ~0.05. For closed die forging this reduction in friction coefficient one would assume a better die life and fill behavior.

*For more information please find full report on the following pages*
Feasibility Study of Al7075 Near-net Shape Superplastic Forging

FIERF Fellowship 2009-10 Report

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Abstract
The current work involved superplastic forging of fine grained Al 7075 to produce near-net shape components. Friction stir processing (FSP) of Al7075 produced a homogeneous microstructure with recrystallised fine grains of the size of 5.3±0.86 µm. This microstructure exhibited high strain rate superplasticity. The constituent particles in the stock material were also refined by FSP. The energy efficiency as well as material utilization in making near-net shape components was better compared to conventional high temperature 7075 forgings. The low compressive forces used in the process as well as the low coefficient of friction observed while forging FSP 7075 is expected to enhance the die life. The finer constituent particles and homogeneous microstructure of the final product are expected to lead to higher fatigue life, but that work has not been completed.
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1. Introduction

One of the main features of most types of forging processes is the use of high compressive forces applied to forge a component. The compressive force in turn dictates the amount of energy utilized for the process as well as the type of die material used. Since improving the die life as well as decreasing the energy input is a main concern to the forging industry [1], it is attractive to find means to reduce the compressive forces required for the forging process. Superplastic forging is one of the means by which the above stated goal can be achieved. Superplastic forging, as the name suggests, utilizes the superplastic property of materials in the forging process. Superplasticity results in enhanced ductility (>200%) and low flow stress in a certain temperature and strain rate range. This phenomenon is related to the microstructural behavior of the material and the primary mechanism of deformation is grain boundary sliding. Superplastic forming (SPF) has been in use for almost three decades to commercially produce complex shaped components and unitized structure from sheets. SPF is an attractive, cost effective near-net shape forming process in industry. Due to its potential impact on manufacturing sector, a number of national reports have identified superplastic forming as critical research area [2-4].

Superplastic forging is therefore a process which tries to merge the forging process with superplastic properties, in which forging can be done under significantly lower compressive forces. In spite of the advantages of superplastic forming, there are two main disadvantages from an industrial point of view. The forming rates are slow and the cost of producing fine grained materials via thermo-mechanical treatment is high. Also, because the fine grain size was historically obtained by rolling, the superplastic properties were observed in thin sheets. But in the recent years the concept of high strain rate superplasticy has been developed. It is now established that by reducing the grain size it is possible to decrease superplastic temperature and increase superplastic strain rate. Friction Stir Processing (FSP) which is an offshoot of a solid state welding technique called Friction Stir Welding (FSW) helps to address precisely these two disadvantages. FSP is a generic tool for microstructural modification based on the basic principles of FSW (figure 1). In this case, a rotating tool is inserted in a monolithic work piece for localized microstructural modification for specific property enhancement [5].
To demonstrate the feasibility of the superplastic forging process for producing near-net shape components, close die forging at superplastic temperature (~490°C) was done to produce a small connecting rod. This report discusses the various steps undertaken to achieve this objective.

2. Near–net shape superplastic forging of Al7075 component

The work done to produce a superplastic component can be mainly grouped into the following steps,

1. Optimization of FSP parameters,
2. Optimization of forging temperature and strain rate,
3. Additional characterization of the material processed under optimized parameters, and
4. Superplastic forging of near-net shape component.

2.1 Optimization of FSP parameters

The important microstructural features that govern overall superplastic behavior are fine grain size, equiaxed grain shape, presence of very fine second phase particles to inhibit grain growth and large fraction of high angle grain boundaries. High temperature deformation based on grain boundary sliding can be given by a constitutive relation [6]

\[ \dot{\varepsilon} = \frac{ADGb}{kT} \left( \frac{\sigma}{G} \right)^n \left( \frac{b}{d} \right)^p \]

where \( \dot{\varepsilon} \) is the strain rate, G is shear modulus, \( \sigma \) is applied stress, d is the grain size, D is the
diffusivity, $p$ is the inverse grain size exponent, $n$ is the stress exponent, $T$ is the temperature and $A$ is a microstructural and mechanism dependent dimensionless constant.

FSP is a very effective grain refinement process in 7075 alloys [7-9]. In addition to fine grain size, FSP 7075 alloys also have a large fraction of high angle gain boundaries and fine distribution of second phase particles. These microstructural modifications in 7075 alloy have resulted in highly enhanced superplasticity. But FSP have several process parameters, each of which can have a very different effect on the processed material in terms of the final microstructure. Therefore it is very important to optimize the FSP parameters. In the current work FSP was done on a 12.5mm thick Al7075-T651 plate. The tool used for FSP had a diameter of 12mm and length of 10mm (figure 2).

Figure 2. FSP tool used in this study.

Several combinations of tool traverse speed and tool rotational rates were tried for the FSP run. The tilt angle for all runs was 2.5 degrees. By controlling the rotational rate (rotation per minute, rpm), linear travel speed (inches per minute, ipm), the tilt angle of the tool and the plunge depth, one can control the heat input into the parent material that is processed by FSP. The grain size of the processed material depends on the heat input during FSP. In addition to the heat input, material flow in the processed zone also varies with the processing parameters, which in turn affects the size of the broken down constituent particles. Figure 3 shows three different combination of parameters, 400rpm/2ipm, 400rpm/4ipm and 600rpm/4ipm, used for FSP. The 600rpm/4ipm run had defects in the processed zone. The other two conditions were defect-free. Higher linear travel speed/tool rotational rate ratio resulted in lower heat input and thereby finer grain size [7]. The 400rpm/2ipm and 400rpm/4ipm produced average grain sizes of $6.2 \pm 1.1 \mu m$
and 5.3±0.86µm, respectively. The 400rpm/4ipm processing condition was therefore selected as the optimum FSP parameter among the three combinations as it produced a defect-free zone with the finest grain size.

Figure 3. FSP nuggets for the three different process parameters used in this study.

2.2 Optimization of forging temperature and strain rate

As can be noted from equation (1), temperature and strain rate influences the flow stress which in turn affects the superplastic behavior of the material. The optimum temperature and strain rate suitable for forging was decided after analyzing the data obtained from high temperature tensile tests, high temperature compression tests, optical microscopy and scanning electron microscopy done on the 400rpm/4ipm FSP 7075.

2.2.1 High temperature tensile tests

Data for high temperature tensile tests was used from Ma et al’s work on superplasticity of FSP 7075 [7]. The grain sizes of the FSP nugget used by Ma et al for the study were 3.8 µm and 7.5 µm. Rolled parent material was also tested. The relevant data is summarized in Table 1.
Table 1. A summary of flow stresses at different temperatures and strain rates.

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It was noted that for higher temperature and lower strain rate, the flow stress was the minimum. Finer grained material was having lower flow stress compared to coarser grained material. Strain rate sensitivity, m, of both FSP 7.5µm and FSP 3.8 µm was found to be 0.5 for the strain rate range of $3 \times 10^{-3}$ s⁻¹ to $10^{-1}$ s⁻¹ which indicated grain boundary sliding. Grain boundary sliding is the primary deformation mechanism in fine grain superplasticity. Strain rate sensitivity was determined from the following equation

$$m = \frac{\log \sigma}{\log \varepsilon},$$

(2)

where $\varepsilon$ is the strain rate and $\sigma$ is the flow stress. As the optimized FSP parameter (400rpm/4ipm) produced grains of size 5.3±0.86µm, it was assumed that the superplastic property of the material selected for current work will lie between that of FSP 3.8 µm and FSP 7.5 µm. The elongation data for the same materials at various strain rates and temperatures are summarized in Table 2.
Table 2. Elongation at different temperatures and strain rates.

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Elongations were higher when grains were finer and strain rates were lower. Elongation of the optimized material (400rpm/4ipm) will be therefore better than FSP 7.5 µm.

2.2.2 High temperature compression tests

Compression tests were done with a 100 kN MTS machine. Samples of dimensions 10 mm x 10 mm x 10 mm were used for both parent and nugget materials. Samples from unprocessed material were compressed at 490°C to a height of 2 mm at strain rates of 1x10^{-2} s^{-1}, 3x10^{-2} s^{-1} and 1x10^{-1} s^{-1}. Figure 4 shows the images of the compressed samples of parent material. At lower strain rates the material flow was not symmetrical along the X and Y directions. It becomes more symmetrical at higher strain rates. But at the highest strain rate, edge crack was observed. This can be attributed to the lower ductility of unprocessed Al 7075 at higher strain rate.

![Figure 4. Photographs of parent material compressed at 490°C and various strain rates.](image)
The samples for compression tests from nugget region were tested at strain rates of $1 \times 10^{-2} \text{ s}^{-1}$ and $1 \times 10^{-1} \text{ s}^{-1}$. Figure 5 shows the images of compressed samples. It is observed that the material has flowed symmetrically along the X and Y axes at both lower and higher strain rates owing to the superplastic behavior of the nugget region. The samples are also crack-free at the two strain rates.

![Figure 5](image)

Figure 5. Photograph of FSP material compressed at 490°C and various strain rates.

Figure 6 shows the true compressive stress-strain curves of base material and FSP material at various strain rates tested at 490°C. There was a significant difference between the yield stresses of FSP and parent material.

![Figure 6](image)

Figure 6. True stress–true strain plots for compression tests done at 490°C.
2.2.3 Microstructural characterization

FSP is very effective in refining grains in aluminum alloys. FSP of aluminum alloys result in dynamic recrystallization and subsequent formation of annealed, very fine equiaxed grains [7-9]. Optical microscopy of the nugget region and the parent material was done. Figure 7 shows the transverse section of the FSP plate. The nugget of the weld had fine dynamically recrystallized grains. Parent material microstructure is also shown in the same figure. The grain size in the FSP nugget zone was 5.3±0.86 µm. In order to check the thermal stability of the grain, the FSP material was heated at 490°C for 1 hr and quenched. The microstructure after the heat treatment was reasonably stable with grain sizes of 8.99±1.19 µm in the nugget.

Figure 7. Comparison of the microstructure from the nugget zone of an FSP run and the parent material.

Similarly the optical micrographs of compressed samples of parent material and FSP material were taken. Compared to the coarse grained microstructure in the as-received condition, fine recrystallized grains started to appear in the microstructure of compressed samples (figure 8). On
the other hand no further grain refinement was observed in the case of the compressed FSP material. Instead figure 9 showed that the grains were slightly elongated in the direction normal to the direction of compressive forces.

Figure 8. Microstructure of the parent material after compression at 490°C and various strain rates.

Figure 9. Microstructure of the FSP material after compression at 490°C and various strain rates.
2.2.4 Characterization of constituent particles and voids

Backscattered images from a Hitachi S-570 SEM were used to analyze the changes in the constituent particles and voids due to FSP and subsequent compression. Figure 10 showed that the constituent particles in the parent material were bigger and not uniformly distributed. The voids were also bigger. FSP of the plate refined the constituent particles as well as distributed them uniformly in the nugget region. The voids were also smaller in the nugget region. At this stage it is being assumed that the voids form due to particle pull-out or drop out during mechanical polishing for metallography.

![Nugget and Voids](image)

Figure 10. Constituent particles and voids in nugget zone of an FSP material and parent material.

Compressive stresses during forging lead to break down of the constituent particle in parent material to smaller size (figure 11). It also reduced the void area. The sample compressed at higher strain rate had less void area compared to samples compressed at lower strain rate. It is not clear if this difference results from better matrix/particle bonding after forging or there are indeed open voids in as-rolled material that get compresses during forging. In the case of
compressed FSP material, the constituent particles remained fine and homogenously distributed as in the uncompressed FSP material (figure 12). Again higher strain rates showed lower number of voids.

Figure 11. Constituent particles and voids in the parent material compressed at 490°C and various strain rates.

Figure 12. Constituent particles and voids in FSP material compressed at 490°C and various strain rates.
After the analyses of the high temperature tensile and compressive data along with the optical micrographs and SEM images, the temperature of 490°C and strain rates ranging from $10^{-3}$ s$^{-1}$ to $10^{-2}$ s$^{-1}$ was selected as the optimum condition for superplastic forging a near-net shape component. Consideration was also given to the limited capacity of the MTS press (100kN) before arriving at the optimum temperature and strain rate range for superplastic forging of a component for the current work.

2.3 Additional characterization of the material processed under optimum parameters

In addition to the characterization mentioned so far, fatigue life and coefficient of friction of the optimally processed material were determined.

2.3.1 Determination of coefficient of friction

Coefficient of friction was determined by doing the ring compression test (figure 13). Boron Nitride was used as the lubricant for elevated temperatures. For the test, rings of outside diameter (OD): inside diameter (ID): thickness (t) ratio 6:3:2 were compressed at 490°C and $10^{-2}$ s$^{-1}$. $\mu$ was then determined by measuring the change in ID ($\Delta$ID), plotting $\Delta$ID against ($\Delta$t) and comparing with the calibration curve [10].

It was observed that the coefficient of friction at 490°C and strain rate of $10^{-2}$ s$^{-1}$ for the FSP material was ~0.02 and the coefficient of friction for the parent material for the same temperature and strain rate was ~0.05, which was more than double of the FSP material. In closed die forging frictional forces play a critical role in determining the forging loads as well the die life. The lower frictional coefficient of the FSP material hence would be beneficial with respect to forging loads and die life.
2.3.2 Fatigue life analysis

Fatigue life degradation is a major concern in any aging structural component subject to fatigue cycles, including that of aircraft. Very often fatigue life is one of the main criteria which determine how long such structural component should be in service. Since forging is one of the primary manufacturing process for such fatigue critical components, increasing fatigue life of end products will go a long way to make forging a more efficient and attractive process.

The focus of the fatigue analysis was on studying the effect of microstructure of both stock material and end product on fatigue life of the superplastically forged component. There are many models which try to deal with fatigue life. The four stage model which captures the microstructural details and correlates it with fatigue, has been summarized by Suresh [11] as

\[ N_{\text{total}} = N_{\text{inc}} + N_{\text{MSC/PSC}} + N_{\text{LC}} \]  

(2)

where incubation period (inc), microstructurally small crack (MSC) growth, physically small crack (PSC) growth and a long crack (LC) growth are the four stages of this model. \( N_{\text{total}} \) is the total fatigue life which is a sum total of the number of fatigue cycles required for each of the four stages.

Xue [12] reported that final fatigue failure originated from a single crack. He also mentioned that even though all the four stages were distinguished in high cycle fatigue regime, the first three were not as apparent as LC. Hence for ease of discussion the first three stages will be clubbed
together as crack nucleation stage and the LC as the crack growth stage.

(i) **Crack Nucleation**

Many studies have come to the conclusion that larger Fe rich constituent particles were responsible for crack nucleation [12, 13, 14]. The constituent particles are formed when some of the alloying elements solidify faster than aluminum. They are inherent to the material and largely dictated by the level of impurity elements in the material.

![Figure 14. SEM micrographs of the surface of the specimen after it was subjected to cycles of 10% of the total life under the loading of ea = 0.4%, R = 0. The initial cyclic damage formed at the fractured large particles [12].](image)

From literature it is also seen that crack nucleates from large particles. Xue [12] had observed ~4-8 µm x ~8-12 µm Fe rich particles nucleating the cracks (figure 14). Merati had reported fatigue crack nucleation on particles at high end of size distribution. He had reported sizes of 167.1 µm² and 225.7 µm² responsible for the cracks [13]. The grain shape, aspect ratio and large defects near crack nucleation sites were the main factors in the advance of MSC and PSC [12]. FSP had the advantage of generating equiaxed dynamically recrystallized grains in the nugget as well as breaking down constituent particles and voids, thereby eliminating both the prime reasons for advancement of MSC / PSC cracks. It is also interesting to note [13] that the larger particles were rich in Fe, where as smaller particles were not.
(ii) Crack Growth

The LC stage can be considered as the crack growth stage. The grain boundaries normally block crack growth and reduce crack driving forces due to energy induced by the piled up dislocations [12]. So a fine grained structure could provide more barriers to crack propagation compared to coarse grained structure. FSP generates finer grain sizes compared to coarse grained parent material. Fatigue life of FSP 7075 in high cycle fatigue regime is seen to have increased compared to base material [15]. This was ascribed to reduced crack propagation rates due to grain boundaries and a crack closure effect due to crack deflection.

In the current work in order to capture the microstructural effect on fatigue life of the superplastically forged component, miniature fatigue samples was machined on a mini CNC machine from as-forged FSP and parent samples as well as from forged samples of FSP material subjected to T6 treatment. Fatigue samples were prepared from samples forged at 490°C and $10^2 \text{s}^{-1}$. They were tested on a custom build fatigue testing machine (figure 15).

![Figure 15. Custom built mini fatigue machine at Missouri S&T [16].](image)

The advantage of using mini-fatigue samples is that a larger ASTM sized samples would not be able to find establish the variation in fatigue life from point to point of a forged sample. The results of fatigue testing of subsize fatigue specimens were compared to handbook [11] data and were seen to be very close to it [7]. The subsize specimen used in this work (figure 16) is a hybrid version of Krouse type sheet or strip fatigue specimen [12].
Figure 16. Sub size fatigue specimen used in this study. Dimensions in inches and [mm].

The maximum bending stress experienced by the fatigue sample was calculated by the Euler-Bernoulli beam formula,

\[ S = \frac{6PL}{bd^2} \]  

where \( S \) was the bending stress encountered once the loading cycle was stabilized, \( P \) was the applied point load, \( L \) was the distance between axis of point load application and axis of stress calculation, \( b \) was the sample width and \( d \) was the sample thickness. Figure 17 shows the preliminary fatigue data. Uniform distribution of second phase particles and finer grain size result in higher fatigue life of superplastically forged specimens.
2.4 Superplastic forging of connecting rod

2.4.1 Die design

A die was designed for flashless closed die forging from H13 tool steel (figure 18 (a) and (b)). Flashless forging would produce a near-net shape connecting rod. Superplasticity of the FSP material along with its low frictional coefficient would permit high flowability of the material, thereby making flashless forging process suitable for producing the near-net shape (figure 18(c)). The forging die was designed for a MTS press of 75kN. The forging force was calculated using’

$$F = K_f \sigma_f A$$

(4)

where $F$ is the maximum force during forging (N), $\sigma_f$ is the flow stress of material (MPa), $A$ is the projected area of work piece (mm$^2$) and $K_f$ is the forging shape factor. $K_f$ for a simple shape without flash is between 5 and 8 [17, 18]. The split die had a cavity of ~20mm depth. A suitable punch of approximately the same shape and height of the cavity was made to forge the material in the die.
Figure 18. (a) and (b) Top view and side views of the die assembly. (c) The dimensions of connecting rod forged in the die.

3. Conclusions

(i) FSP 7075Al had a homogeneous and very fine grain structure compared to the commercially available 7075Al. The constituent particle distribution was uniform in FSP material. It resulted in superplastic flow of the FSP material.
(ii) The final forged microstructure of FSP material was as homogenous as the initial microstructure. The relatively defect-free and homogenous microstructure of forged FSP material resulted in better fatigue and mechanical properties.
(iii) The FSP forging due to its ease of flow had less defects compared to non-FSP forgings.
(iv) Forging loads were lower for FSP material due to lower yield stress and frictional coefficient.
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