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PRODUCING OF ULTRA-FINE GRAINED SHEET MATERIAL WITH COMBINATION OF MULTIPLE FORGING AND COLD ROLLING

Summary of the PhD theses

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This dissertation, the comments of the reviewers and the log recorded on the defense are on show in the Dean's office of the Faculty of Mechanical Engineering of the Budapest University of Technology and Economics

Introduction

Nano- and ultra-fine grained materials

In the past decades the nanotechnology become one of the most important areas of both the engineering and physical sciences. Some of the important areas of the nanotechnology researches are the investigation and produce of the so-called ultra-fine grained (UFG) and nano-grained (NG) materials which have an average grain size under 100 nm and between 100-1000 nm respectively. The NG and UFG materials differ in several properties from the coarse grained material (CGM):

- Higher strength and hardness
- Better Superplastic formability
- Low ductile-to-brittle transition temperature
- Good corrosion resistance
- Good electric and magnetic behavior

Although numerous methods exist to produce such materials, nowadays this can be done typically under laboratory circumstances. One of the most applied procedures is the so-called severe plastic deformation (SPD) method. SPD can be defined as metal forming processes in which the bulk metallic material is subjected to high hydrostatic pressure and undergo ultra-large shear plastic strain in order to create ultra-fine grained material. Several techniques were developed using the basic of SPD, for example high pressure torsion (HPT), equal channel angular pressing ECAP and multiple forging.

Motivations

1. The ultra-fine grained material has attracted high interest in the last decades of scientists and researchers because of their good properties such strength and corrosion resistant.
2. MF technique hasn't studied in the same level of intensity like other SPD techniques, although it produce the largest SPD bulk specimen.
3. Constitutive equations that describe and simulate material behavior are very important in the forming process design.

Objectives

1. Producing ultra-fine grained sheet material using closed die forging, and cold rolling form 7075 Al alloy.
2. Producing ultra-fine grained using closed die forging form 6082 Al alloy.
3. Investigate the mechanical properties after MF and cold rolling using several material testing processes.
4. Determine reliable constitutive equations in wide range of temperature and strain rate. The deformation temperature were between 250 and 450°C, and the strain rate were between (0.002 and 2 s^{-1}).

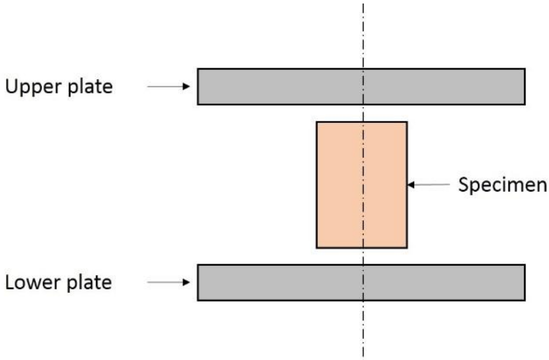

Figure 1 Schematic of open die forging

Multiple forging - MF

It is one SPD technique to obtain bulk ultra-fine grained material. SPD occurs by repeating the forging operation with the change of the axis of applied load. The method of multiple forging was successfully used for refinement of microstructures in a number of alloys, including pure Ti, titanium alloys VT8, VT30, Ti-6%Al-32%Mo, magnesium alloy Mg-6%Zr, aluminum alloy, high strength high alloyed nickel base alloys and others. The multiple forging method can be applied in a range of deformation temperature (0.1-0.5) T_m, where T_m is the melting temperature.

In fact the maximum strain in case of multiple forging is lower than at the ECAP and HPT, but largest SPD specimen can be produced. Two different dies are used open and closed die forging as they are illustrated in Figures 1 and 2.

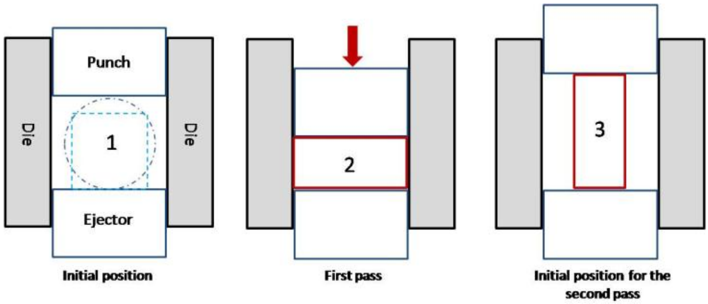

Figure 2 Schematic closed die forging

Constitutive equations

Hot compression tests are generally used to determine constitutive equation constants. Nowadays the finite element method (FEM) is widely used in metal forming to find out the optimal deformation parameters. Constitutive equation representing the flow behavior of materials is used as input to the FEM code for simulating the material's response under the specified loading conditions. The constitutive models for hot deformation proposed by Sellars and McTegart Equations (1 and 2) were used to summarize and extrapolate experimental data.

$$\dot{\varepsilon} = A\ sinh\,(\alpha\sigma)^n exp\left(\frac{Q}{RT}\right) \quad (1)$$

$$\dot{\varepsilon} = A\ exp(\beta\sigma)\ exp\left(-\frac{Q}{RT}\right) \quad (2)$$

where $\dot{\varepsilon}$ is the strain rate (s^{-1}), σ is the true stress (MPa), Q is the activation energy of deformation, R is the gas constant and T is the absolute temperature of deformation (K). A, β, n and a are material parameters.

All material parameters have been obtained by solving the equations as an over-determined problem, where we have a higher number of equations than the number of the unknown parameters. The obtained parameters were plotted with equivalent strain between 0.05 and 0.55 with an interval of 0.05. A fourth-order polynomial fitting function was applied to describe the relationship between the material parameters and equivalent strain.

Investigated materials

Pure aluminum and aluminum alloys belong to the most interesting materials in modern engineering, and they are the most used non-ferrous materials for engineering applications like automotive, aerospace, and construction engineering, because of their good corrosion resistance, mechanical properties, machinability, low weight, weldability and relatively low cost. Since work first started in the field of nanostructured material, Al alloys have advanced to be the most developed UFG materials. Because of all those interests going around the aluminum alloys, as it was previously reviewed, two aluminum alloys were chosen for this work 7075 and 6082 alloy:

1. Table 1 shows the chemical composition of this 7075 Al alloy. The row material was received as rod 40 mm in diameter and 3m in length. The received rod was annealed at 450°C for 30 minutes, and then it was cooled down to room temperature in the furnace in order to allow the precipitation process to complete.

Table 1 Chemical composition of 7075 Al alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.12	0.37	1.76	0.06	2.66	0.23	5.66	0.02	balance

2. Table 2 shows the chemical composition of 6082 Al alloy. The initial material was received as hard extruded rod 20 mm in diameter, because the industries usually use the material as it received, therefore the preparation for next process includes just cutting to 100 mm in length.

Table 2 Chemical composition of 6082 Al alloy

Mg	Si	Mn	Fe	Ti	Cu	Zn	Ni	Sn	Cr	Al
1.016	0.88	0.9	0.21	0.003	0.029	0.026	0.003	0.003	0.002	balance

Material tests

The materials those conducted to the mechanical tests has different designations, IS for initial state, MF for multiple forged and MF-RS for multiple forged rolled sheet. Table 3.3 is shown the investigated test and the alloys.

Table 3 Conducted material tests and the alloys

Tests \ material	7075 Al alloy			6082 Al alloy	
	IS	MF	MF-RS	IS	MF
Tensile test	X	X	X	X	X
Cold compression test	X	X		X	X
Hot compression test	X	X			
Bending test	X	X	X	X	X
Hardness measurement	X	X	X	X	X
Optical metallographic	X	X		X	X
Fractographic picture	X	X	X	X	X

Theses

1. Open die forging for 7075 Al alloy [II]

The 7075 Al alloy subjected to open die forging at 250 ºC is gaining unusual increase in ductility. The yield stress, maximum elongation and hardness were increased after three MF passes as it is shown in the Table 4.

Table 4 Tensile results and hardness for 7075 Al alloy

Material	Hardness	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)
IS material	65.7	95	195	11
MF(third pass)	72	105	201	14.2

The maximum accumulative strain after three passes of MF was calculated, the results obtained using finite element program was 2.6. At this level of accumulative strain the microstructure was refined.

2. Producing sheet from multiple forged 7075 Al alloy [II]

Producing sheet form from multiple forged material using cold rolling is aimed in my work, as it is expressed in the work title. Based on the result of rolling process that was conducted to the Multiple forged 7075 Al, I can state that multiple forged 7075 Al alloy at 250 °C – total plastic strain 2.6 – followed by cold rolling up to a thickness reduction of 58% in ten steps behaves as ductile material without any sign of brittle failure mode or undesirable flow defects, moreover the ductility of rolled sheet was proved using fractographic pictures of the tensile fracture surface, where only ductile dimples are observed and no sign of cleavage-like features exist.

Table 5 Tensile results and hardness for cold rolled MF material

Material	Hardness	Rp0.2 (MPa)	Rm (MPa)	A (%)
MF-RS	112.2	290	319	6.8

3. Correction method [III]

New method has been established to eliminate the forming equipment elasticity effects in the measured force–height data. For cold deformation such problem can be solved easily using multi-step test, however during hot deformation the multi-step test it is not applicable. The method is illustrated on the figure below. The point *c* height was measured by the machine and point *b* height was measured by micrometer caliper. The line *ae* and *bd* are extended up to crossing each other at point *f* (it is high up). The angle *efd* is divided to several smaller equal angles by straight lines, each lines are crossing the data curve and *H* axis using a straight line from point *f*, thus for each curve point the corrected one H_{n*} can be determined, For instant the line *1* is crossing the data curve at F_1 and H_{1*}, where this point (H_{1*}, F_1) is the new pair of force–height curve instead of (H_1, F_1).

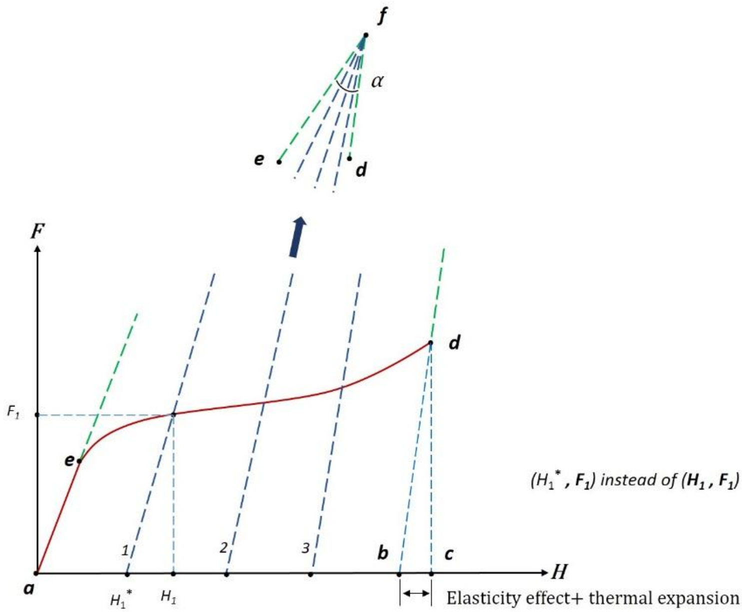

Figure 3 The method of force-height data correction

4. Constitutive equations [III, V]

A set of constitutive equations were obtained for 7075 Al alloy (IS and MF material) based on two models equations (3 and 4). These constitutive equations were found to predict the flow stress precisely over wide range of temperature and strain rate, the deformation temperature were between 250 and 450°C, and strain rate between 0.002 and 2 s^{-1}. Although both models gave good average absolute relative error AARE, but the model using sin hyperbolic function gives better results than the other using exponential function.

$$\sigma = \frac{ln\,\dot{\varepsilon}}{\beta} + \frac{Q}{\beta RT} - \frac{lnA}{\beta} \tag{3}$$

$$\sigma = \frac{arcsinh\left(exp\left(\frac{(RT(ln(\dot{\varepsilon}) - ln(A)) + Q)}{RTn}\right)\right)}{\alpha} \tag{4}$$

All material parameters in the equations are considered as function of equivalent strain, these functions are described by using fourth order polynomials.

Table 6 Verification parameter values for IS and MF material and all used functions

Material	Used function	AARE	R^2
IS material	exponential function	6.195	0.99862
IS material	sin hyperbolic	4.559	0.99854
MF material	exponential function	5.124	0.99869
MF material	sin hyperbolic	4.270	0.99847

The average absolute relative error (AARE) and correlation coefficient (R) were calculated for all data using Eq. (4, 5):

$$AARE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\sigma_m - \sigma_c}{\sigma_m}\right|100 = 6.42\% \tag{4}$$

$$R = \frac{\sum_{i=1}^{n}\left(\sigma_m - \bar{\sigma}_m\right)\left(\sigma_c - \bar{\sigma}_c\right)}{\sqrt{\sum_{i=1}^{n}\left(\sigma_m - \bar{\sigma}_m\right)^2\left(\sigma_c - \bar{\sigma}_c\right)^2}} = 0.998 \tag{5}$$

5. Anisotropy behavior [V]

Multi step compression test results were used to investigate the deformation anisotropy of multiple forged 7075 Al alloy after the third passes. The test were carried out at room temperature and elevated temperature as well. The two perpendicular diameters of the specimen's cross section were measured during the test steps, Table 7 shows the value of maximum logarithmic strain in the direction of a and b at cold and hot forming, and the Lankford value (R).In the isotropic case the R equal to one, It is very clear that the anisotropic deformation has notable effect at cold deformation(R=2.08), while it is negligible at hot forming (R=1.1).

Table 7 Logarithmic strain for Cold and hot forming

	MF 7075 Al alloy cold forming	MF 7075 Al alloy hot forming
ε_{a-max}	0.26	0.30
ε_{b-max}	0.54	0.33
R	2.08	1.1

6. 6082 Al alloy after closed die MF [IV, VI]

The 6082 Al alloy was subjected to tensile and compression test after every pass of MF. Both tests results show similar material behavior, the yield strength increases notably on the second pass, further MF passes don't change the strength remarkably. This conclusion is supported by hardness measurements as well. On the second MF pass the material lost a part of its ductility, but some of it is restored gradually up to the fourth pass, the tensile and compression results are shown in Table 6.4, the material shows ductile fracture even after the fifth pass.
The grains shape is elongated and the size is decreasing after MF passes, this conclusion is proved using optical microscopic pictures Figure 4.29.

Table 8 Tensile and hardness results for 6082 Al alloy

Material	Hardness	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)
IS	206	206	300	27.8
MF pass 1	303	303	332	14.45
MF pass 2	329	329	352	10.5
MF pass 3	316	316	347	14
MF pass 4	332	332	354	17.9
MF pass 5	312	312	341	16.6

Publications

[I.] Tareg S. Ben Naser, Andras Ree. The workability of bulk nanostructure material. Material forum, 2010 Trans Tech publication, vol. 659, p.p. 221-227.

[II.] Tareg S. Ben Naser, Krállics György. The effect of multiple forging and cold rolling on bending and tensile behavior of Al 7075 alloy. Material forum, 2012 Trans Tech publication, vol. 729, p.p. 464-469.

[III.] Tareg S. Ben Naser, Krállics György. The constitutive behavior of Al 7075 aluminium alloy under hot compression test. Material forum, 2012 Trans Tech publication, vol. 752, p.p. 69-74.

[IV.] Bobor Kristof, György Krállics, Tareg S. Ben Naser. Modeling of severe plastic deformation processes. Tools and Technologies for Processing Ultra High Strength Materials conference 2013, Verlag der Technischen University Graz, p.p. 435-446.

[V.] Tareg S. Ben Naser, Krállics György. Mechanical behavior of multiple forged Al 7075 aluminium alloy. Acta Polytechnica Hungarica.

[VI.] Tareg S. Ben Naser, Bobor Kristof, György Krállics. Tensile behavior of multiple forged 6082 Al alloy, Periodica Polytechnica Mechanical Engineering 2014.