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PHYSICAL AND MECHANICAL MODELLING OF PROCESSING ULTRA-FINE- AND NANOGRAINED BULK METALLIC ALLOYS BY MULTIPLE FORGING

PHD THESES

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Theses critiques and minutes recorded on the defence can be viewed later in the Dean's Office of Faculty of Mechanical Engineering of Budapest University of Technology and Economics.

1. INTRODUCTION TO THE RESEARCH TOPIC AND THE OBJECTIVES

My research work is part of the wide and complex scientific discipline of nanostructured materials. The properties of these materials, which consist of building blocks with the maximum size of 100nm in any direction, are significantly different from the traditional materials with same composition. The main driving force of the researches is the application of these materials in various areas. Recently, the nanotubes, the nanocomposites, the nanocatalysts with large specific surface, the thin-layers and the nanosized functional devices are widely used. The nanomaterials are applied in microelectronics, optics, sensors, medical devices, fuel cells and coatings.

Concerning the potential mechanical engineering applications, the bulk nanograined and ultra-finegrained materials are very important. Over the past decades, many technologies and experimental techniques were developed to produce these materials. These processes can be classified into two groups, the „bottom-up" and the „top-down" methods. In the first case, the materials are built up from nanoparticles by different processes, such as powder metallurgy. In the other case, the microstructure of the coarse grained metallic materials are transformed to ultra-fine- or nanograined microstructure. My research activity concerns the production and investigation of ultra-fine- and nanograined metals and alloys as presented in the dissertation.

The processes for producing bulk ultra-fine- and nanograined metallic alloys can be divided into two groups. One of them is the group of advanced thermomechanical processes which contribute to decrease the grain size by activating or intensifying different metallurgical processes in metals. The other group of these processes is the severe plastic deformation techniques. Over the past decades, a lot of technological arrangement was evolved and one of these is the multiple forging. To produce ultra-fine- and nanograined microstructure, I used one of the multiple forging processes which was carried out by using the Gleeble simulator with the MaxStrain device. The multiple forging process in Gleeble simulator and the results of the most important related research works are presented in the next chapter.

In the following, I introduce the aims of my research related to the ultra-fine- and nanograined bulk metallic alloys. As it can be seen from the technical overview in the next chapter, the main motivation of my research work was that just a few studies have dealt with the investigation of the stress-strain state under multiple forging with cyclic repetitive loading. Concerning the multiple forging on MaxStrain device, it can be stated that our knowledge on the relation between the flow stress and plastic strain under cyclic repetitive loading, induced by large plastic deformation, is incomplete.

Based on the afore-mentioned considerations, the aims of my research work were the followings:

- To model the mechanical response of materials under multiple forging, the commercial simulation program of the MaxStrain device had to be improved. The basic goal was to develop a simulation process and a control program for multiple forging which are proper to control the amount and the rate of deformation in each forging pass.
- The following aim was to calculate the equivalent plastic strain and equivalent stress for multiple forging directly from the measured data, i.e. to develop a suitable mechanical model for determining the flow curves which describe the change of flow stress. To achieve these goals, it was necessary to continuously measure the dimensions of the deformed volume, which also required the improvement of the simulation program.
- The flow curves, which were determined by applying the mechanical model and using the measured data from the multiple forging simulations, showed the cyclic evolution of the flow stress. Based on these flow stress data, to describe the evolution of the flow stress, I aimed to develop a mathematical approach which is proper to express the cyclic flow stress in one formula and to determine its limiting curves. An additional aim was to evolve a formula which gives the expected range of the cyclic flow stress in terms of the applied strain per forging pass (i.e. strain amplitude).
- • Another intention of my research activity was to investigate the evolution of some mechanical properties in the deformed volume in terms of the accumulated plastic strain. I aimed to study the evolution of hardness as well as the mechanical and formability properties from the tensile tests of forged specimens. These were subjected to multiple forging with the same simulation parameters, but the number of applied forging pass increased by one in the consecutive specimens.

The next important direction of my research activity was the quantitative and qualitative characterization of the multiple forged specimens. One of the goals was the analysis of the microstructure after multiple forging in terms of the grain size, the orientation of the grains and some properties of the deformation induced grain boundaries as well as the comparison of these properties with the initial microstructure. The other important aspect was to study the evolution of the grain refinement mechanism during the forging process, and the investigation of the affect of the forging processes, having different strain amplitudes, on the resultant grain size.

2. BACKGROUND AND METHODS OF RESEARCH

It is necessary to introduce the severe plastic deformation processes and the most important properties of the resulted ultra-fine- and nanograined microstructure because these are in close connection with my research work.

Regarding the bulk metallic materials, the nanograined structure means that the basic matrix is built up by crystallites with the maximum size of 100nm. These small grains can be separated by equilibrium or non-equilibrium grain boundaries. The domains, which are bounded by non-equilibrium, i.e. geometrically necessary grain boundaries, are called cells or dislocation cells. Their characteristic property is that they are induced in polycrystalline metals by large shear deformation, for instance by severe plastic deformation processes. One of the common properties of the severe plastic deformation techniques is that the achievable plastic deformation during the process is much larger than that of the traditional forming technologies, it can reach the order of hundred. To avoid the degradation of the structure in the materials, compressive, close to hydrostatic stress, even in the range of GPa's, is applied. Due to the intensive shear strain during severe plastic deformation, the lattice dislocations accumulates at the original boundaries of crystallites, and create thickened cell walls with high dislocation density. The cell structure is usually formed if the equivalent plastic strain reaches the range of 0,8-1. If the accumulated plastic strain further increases the dislocation density reaches a critical level in the cell walls, then through the partial annihilation of dislocations, the ultra-finegrained microstructure develops. These materials consist of grains having sizes from 100nm to 1μm, which are bounded by equilibrium or close to equilibrium, high angle grain boundaries.

The physical, thermal, electrical, magnetic, corrosive and other properties of the ultra-fine- and nanograined metallic materials indicate significant change or improvement compared to their coarse grained state. Regarding the mechanical engineering applications, the evolution of the mechanical properties is very important. If the grain size decreases, the yield stress of the metals increases. Besides the increasing in strength, comparing with the traditional cold forming technologies, the materials have better formability after processed by severe plastic deformation. This fact can be originated in the mentioned properties of the ultra-finegrained microstructure. Moreover, their toughness properties can improve, for instance through decreasing in the ductile-brittle transient temperature by body-centred cubic metals. Such an improvement in the properties of metals is the main driving force of the development and application of ultra-fine- and nanograined metallic alloys.

Over the past decades, plenty of severe plastic deformation processes were developed to transform the microstructure of the bulk metallic materials to ultra-fine- or nanograined structure. The large plastic deformation, which takes place in this processes, besides their shearing character, is typically non-monotonic.

A widely accepted interpretation of the non-monotonity is that the eigenvectors of the rate of deformation tensor are not parallel to the same material lines during the whole deformation process, in contrast to the tensile or compressive straining in uniaxial stress state which are perfectly monotonic. The higher degree of non-monotonity contributes to increase the grain refinement. Besides the intensive shear strain, which is provided by the geometry of the tool, the degree of non-monotonity is increased by turning the specimens between each pass according to different deformation routes.

One of the severe deformation processes is the multiple forging, which can be performed between plain dies as hammer forging or in closed dies as a series of upsetting. Between each pass, the specimen is rotated around its two or three axes respect to the cyclic repetition of the forming direction. Among the different technical solutions of multiple forging, the Gleeble simulator with the MaxStrain device exceeds the possibility of other equipments in controlling the parameters of the process. Using the MaxStrain device, the centre cubic part of the specimen can be subjected to multiple forging by rotating the specimen back and forth around its longitudinal axis by 90° (Figure 1(*a*)). During the simulations, the movement of the hard metal anvils and the temperature of the specimen, heated by a resistance heating system, can be controlled in a program with high accuracy. Concerning the application of the MaxStrain device, a significant part of the researchers investigated the joint affect of the controlled temperature profile and the severe plastic deformation on the grain refinement process in different metals and alloys. Other researchers studied the mechanism of grain refinement and the evolution of mechanical properties on aluminum alloys, titanium and red copper. Among the studies about modelling, there are analytic models for describing the evolution of some properties of the microstructure, and finite element models for investigating the stress-strain state. The model of the working chamber of MaxStrain device with the specimen (4), which is fixed in the rotator (3), is shown in Figure 1(*a*).

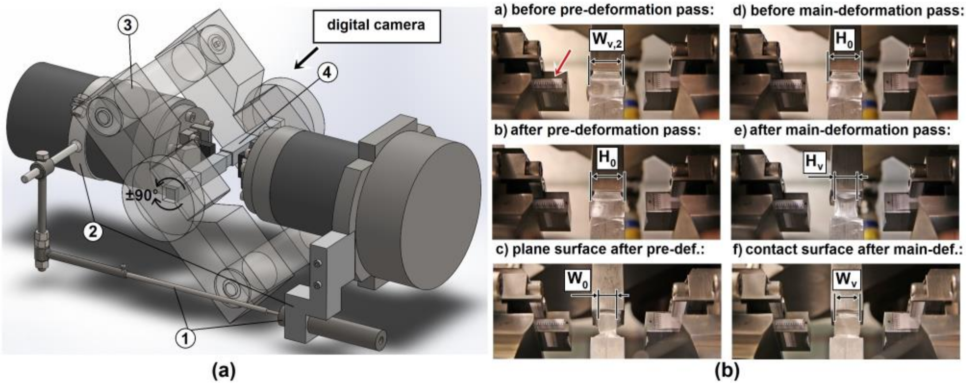

Figure 1 *(a) The 3D model of the functional parts of the MaxStrain device*
(b) The characteristic steps of a forging pass

My primary aim to determine the flow stress-plastic strain relation under cyclic, non monotonic plastic deformation is a new research area concerning the multiple forging on MaxStrain device. To create the mechanical model and calculate the flow curves, I developed a simulation method for controlling the equivalent logarithmic strain and strain rate in the direction of the anvil's movement in each forging pass. Moreover, the height (Figure 1(*b*) – H_o and H_v) and the thickness (Figure 1(*b*) – W_o and W_v) dimensions of the deformed volume as well as the thickness of the contact surface (Figure 1(*b*) – $W_{v,2}$) between the anvil and the specimen can be measured. The height dimensions are parallel, while the thickness dimensions are perpendicular to the direction of the deformation. To improve the control of the simulations and increase the accuracy of the measurement, an inductive displacement transducer (1) was mounted (2) onto the hydraulic pistons, as shown in Figure 1(*a*). The thickness of the contact surfaces were calculated from a picture, taken in the position of „b" in Figure 1(*b*), using the scale in millimetres marked by the red arrow. The mentioned dimensions of the deformed volume were measured before (dimensions with index „o") and after (dimensions with index „v") each forging pass which was the basic requirement by the determination of the velocity field and the development of the model. The forming force was also measured during the simulations.

The multiple forging experiments were carried out on metals and alloys with different crystalline structures, with various strain amplitudes and at different strain rates, as well as at room and elevated temperature. The face-centred cubic EN AW-6082 aluminum alloy, the body-centred cubic DD11 unalloyed mild steel and the Grade2 titanium with hexagonal lattice were used to perform the experiments. The chemical composition of these materials are given in Table 1.

Table 1 *The chemical composition of the materials used in the forging experiments*

	Alloying elements (m/m %)							
	C	Mn	Si	Al	P	S	Cu	Ni
EN AW-6082		0,51	0,87	rest				
DD11	0,05	0,22	0,013	0,025	0,006	0,008	0,02	0,01
Grade2 Ti								
	Cr	Ti	V	Mo	Nb	Mg	Zn	Fe
EN AW-6082						0,60	0,02	0,21
DD11	0,01	<0,001	<0,001	<0,001	<0,001			rest
Grade2 Ti		>99,90						

The raw material of the aluminum specimens was an extruded rod with a square cross section of 25×25mm which was used in annealed condition. The forging simulations were performed on the mild steel and on the titanium in the as received hot rolled state. The fundamental aim of the forging experiments with these materials was to study the suitability of the mechanical model. In addition, samples in different deformation state were produced to execute the aimed evaluation and investigation activities.

In the following, the most relevant parameters of the forging experiments are detailed which are connected to the theses. The forging experiments at room temperature were performed to study the evolution of the mechanical and microstructural properties. These experiments were carried out on aluminum and mild steel with the same strain amplitude ($\Delta\varphi = 0,4$) and equivalent logarithmic strain rate ($\bar{\xi} = 0,1s^{-1}$) at each applied forging pass ($n = 1 \ldots 10$) and each specimen. The affect of the strain amplitude on the evolution of flow stress was investigated by forging simulations on the aluminum alloy at room temperature and at the same equivalent logarithmic strain rate ($\bar{\xi} = 0,1s^{-1}$) but applying different strain amplitudes ($\Delta\varphi = 0,2;\ 0,285;\ 0,4$). The evolution of the flow stress in the range of large plastic deformation was studied by executing a forming experiment with 40 forging passes. Besides the experiments on aluminum and mild steel, the 10-passes forging simulation on titanium at 400°C with the strain amplitude of $\Delta\varphi = 0,4$ was carried out as a basic experiment to study the suitability of the mechanical model.

A hardness map on the cross section of the aluminum specimens, subjected to different forging passes, was performed by Vickers microhardness measurements, while the tensile tests were carried out on a universal tensile testing machine with extensometer after the longitudinal flat tensile specimens were manufactured. The microstructure of the deformed aluminum specimens was studied by a Philips CM20 transmission electron microscope, while the evolution of the microstructure in mild steel specimens was investigated by a JSM 6500 F scanning electron microscope, equipped with a HKL type EBSD detector.

3. THE SUMMARY OF THE RESEARCH WORK AND THE THESES

The components of the kinematically admissible velocity fields, the equivalent strain rate ($\bar{\xi}$) and the equivalent strain ($\bar{\varepsilon}$), according to the H-M-H theory, were determined using the measured dimensions of the deformed volume and the constant width of it, which coincides with the longitudinal axis of the specimen and equal to the width of the anvils. The relations between the components of the rate of deformation tensor were defined using the variational parameter a_o. The energetic functional of plasticity for multiple forging was expressed using the kinematically admissible strain rate fields. In this form, the functional is a variational function of the power which requires to execute the plastic deformation in a forging pass. The real velocity field, which minimize this functional, can be determined using the variational parameter. The value of a_0 was calculated by considering and applying the measured dimensions as geometrical boundary conditions. Using these considerations, the unknown compressive force, which acts in the axis of the specimen, can be expressed in terms of the flow stress.

Executing this calculation in each time steps of the forging passes and considering that the required power is equal to the externally supplied power which can be calculated from the instantaneous force, the value of flow stress can be determined in each time step. In the model, the material is assumed to be isotropic and incompressible, and the flow stress is assumed to be constant overall the deformed volume in each moment of time.

Plotting the flow stress values as a function of equivalent plastic strain, the generated flow curves describe the evolution of the flow stress. The flow curves, calculated for the forging experiments on aluminum alloy with different strain amplitudes, are shown in Figure 2(*a*). The monotonic flow curves of the first forging passes are plotted in Figure 2(*b*). These flow curves and the reference flow curve from the Watts-Ford test are giving approximately the same flow stresses at the common range of the equivalent strain. To verify the mechanical model, the flow curves under monotonic deformation condition were also measured for the two other materials. These curves also show similar correspondence with the flow curves of the first forging passes.

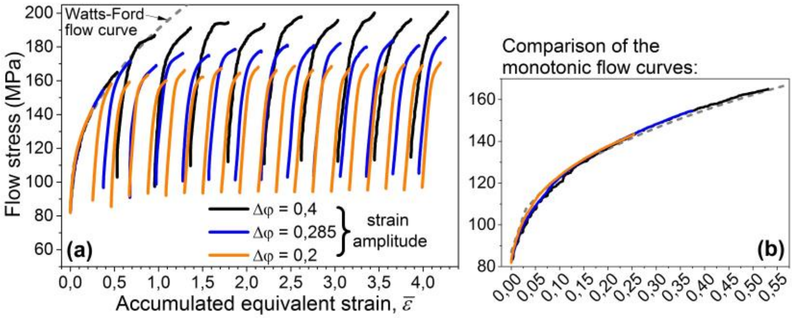

Figure 2 *(a) The flow curves of the multiple forging simulations with different strain amplitudes and (b) the enlarged flow curves for the first pass*

The flow curves of the cyclic, non-monotonic plastic deformation are running under the flow curve of the monotonic deformation path. The flow curves of each strain amplitude show the cyclic evolution of the flow stress which is indicated by the large decline in the flow stress at the change in the direction of deformation. This effect can be observed at the two other materials as well. In the following evaluation process, a mathematical approach and connecting calculation algorithm were developed to express the cyclic flow stress for multiple forging in one formula. Based on the generalized Masing equation for small cyclic plastic deformation and using the flow curve of the monotonic deformation path as well as the three parameters (α, β and γ), a transformation of the monotonic flow curve can be generated which can describe the evolution of the cyclic flow stress. Moreover, the parameter β quantifies the Baushinger-like effect at the change in the direction of deformation. Analysing its values, I ascertained that respect to the multiple forging of the tested aluminum alloy at room temperature, the degree of this effect is independent from the strain amplitude in the used range of $\Delta\varphi = [0,2 \ldots 0,4]$. The fitted flow curves, which were generated by these functions to describe the evolution of the flow stress at different strain amplitudes, are shown in Figure 3(*a*).

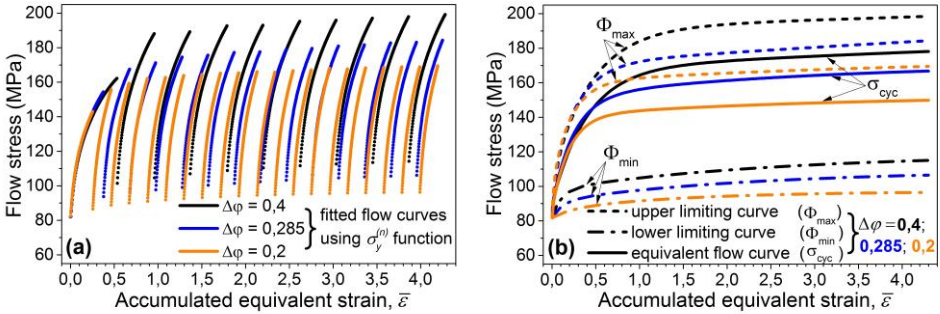

***Figure 3** (a) The fitted flow curves which describes the evolution of flow stress under multiple forging with different strain amplitudes and (b) the limiting as well as the equivalent flow curves of the flow stress*

The fitted flow curves are valid in the range of the used plastic deformation. In the previous calculation process, using the initial and the final points of the calculated flow curves from the mechanical model, the lower Φ_{min} and the upper Φ_{max} limiting curves of the range of flow stress were also determined by fitting. Moreover, the equivalent flow curve σ_{cyc}, which characterise this cyclic forming process, was defined and determined. This curve was generated by the proportional transformation of the upper limiting curve. The principle of its definition was that it covers the same amount of plastic work as occurred during the complete forging process. As it can be seen in Figure 3(*b*), the limiting curves are growing with increasing strain amplitude, consequently the plastic deformation starts at higher stress level at the beginning of the loading cycles, and the maximum value of the flow stress also increases. In terms of the strain amplitude, the coefficients of the functions of limiting curves also change monotonically. Using this feature, the formula which gives the expected range of the flow stress in terms of the strain amplitude in the range of $\Delta\varphi = [0,2\ldots0,4]$, was determined.

The evolution of the mechanical properties under severe plastic deformation was investigated on forged aluminum specimens deformed with the same strain amplitude at the same temperature and strain rate, but the applied forging passes were different. Vickers microhardness tests were performed in gridded layout on the same centre cross section of the deformed samples and on one specimen in initial state. These cross sections were perpendicular to the longitudinal axis of the specimens. The 120-150 hardness measurements per specimen were statistically evaluated. Using the continuous Weibull probability-distribution with three parameters, the median, the modus and the standard deviation of each data set were determined. The characteristic hardness values of the specimens after subjected to different forging passes, as well as the mean of the hardness values, measured in the regions with different thicknesses of the Watts-Ford specimen, were plotted on a common graph in Figure 4(*a*) in terms of the accumulated equivalent plastic strain. Using another series of forged specimens, which were processed by the same simulation programs, longitudinal flat tensile specimens were manufactured, while a cylindrical specimen was also fabricated from the raw material.

The mechanical properties, which were determined from the tensile tests at room temperature, are also plotted in terms of the accumulated equivalent plastic strain in Figure 4(*b*). The values at the equivalent plastic strain $\bar{\varepsilon} = 0$ refer to the raw material on each of the graphs.

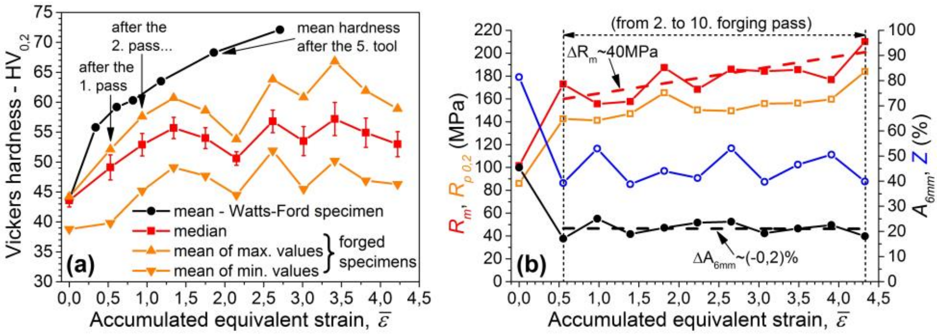

Figure 4 *The evolution of (a) the hardness and (b) the mechanical properties of EN AW-6082 aluminum alloy during multiaxial forging*

The hardness, which is almost the same in the initial state, indicates a greater increasing rate under monotonic deformation than by non-monotonic strain path. Under monotonic deformation, the hardness increases continuously, while the monotonic growing in hardness can be observed only between the first and third forging pass. After the third pass, the evolution of the hardness is inordinately. Concerning its character, the tensile strength and the yield stress of the deformed specimens increase continuously, while the elongation to fracture, which characterizes the formability, stabilizes at a nearly constant level after the first forging pass.

Using other aluminum specimens, the evolution of the microstructure under multiple forging was studied by transmission electron microscopy. Both of the cell structure arranged in blocks with thickened dislocation walls and the ultra-finegrained domains bounded by relaxed, close to equilibrium grain boundaries can be found in the microstructure. The average grain size of those specimens, which were forged with different strain amplitudes up to the same level of accumulated plastic strain, decreases with increasing strain amplitude, and reach the average size of 0,45 μm.

The evolution of the microstructure in the mild steel specimens was studied by EBSD imaging technique. Specimens were taken after each forging pass, which were deformed with the same strain amplitude at the same temperature and strain rate. With increasing of forging passes, the mean grain size is exponentially decreasing, reaching the range of 0,8...1,1μm. The raw material contained mainly high angle grain boundaries, it changed after the second forging pass and the fraction of the low angle boundaries increased significantly. After that, this fraction was continuously decreasing with the increasing number of forging passes, while the fraction of the high angle grain boundaries was increasing monotonically. This kind of evolution in the microstructure, similarly to the aluminum, indicates the formation of ultra-finegrained microstructure.

4. THESES

Using the MaxStrain device of the Gleeble thermomechanical simulator, the physical simulation of multiple forging can be performed with cyclic repetitive loading schedule in two, mutually orthogonal directions. To model the cyclic, non-monotonic plastic deformation under the forging process, a control program and an experimental setup were developed which enable to control the equivalent logarithmic strain and strain rate in each forging pass, as well as it is suitable to measure the characteristic dimensions of the deformed volume. The evolution of the flow stress and the characteristic properties of the microstructure under cyclic loading path were studied through forging experiments on metals and alloys with different crystalline structures, such as face-centred and body-centred cubic as well as hexagonal lattice structure. Analysing the results, the following scientific statements were drawn:

1. **Based on the application of the principle of virtual velocities in the energetic functional of plasticity and using the forming force as well as the dimensions of the deformed volume, the developed rigid-plastic mechanical model to describe the material response gives the flow curves, i.e. the relation between the equivalent plastic strain and the equivalent stress under monotonic deformation path, which is characteristic for each loading cycle [S1], [S4], [S6], [S7].**

2. **I have extended the generalized Masing equation, valid for small cyclic plastic deformation, for large plastic deformation and developed a calculation method to describe the relation between the cyclic flow stress and the accumulated equivalent plastic strain under multiple forging. Three parameters and the monotonic flow curve of the tested material were used for that. The β parameter was defined to quantify the decrease in flow stress at the change in the direction of deformation. Regarding the forging experiments on EN AW-6082 aluminum alloy at room temperature with different strain amplitudes and at the equivalent strain rate of $\bar{\xi} = 0{,}1s^{-1}$, the value of β stabilizes in the range of [0,55…0,6] during the progression of the forging process. The Baushinger-like effect, which follows the whole cyclic plastic deformation process, was found independent from the strain amplitude in the range of $\Delta\varphi = [0{,}2 \ldots 0{,}4]$ [S2], [S8].**

$$\beta\left(\bar{\varepsilon}_{\max}^{(n\text{-}1)}\right) = \frac{\sigma_{y_0}^{(n)}}{\sigma_{y_{\max}}^{(n\text{-}1)}}, \quad n > 1$$

where:	$\bar{\varepsilon}_{\max}^{(n-1)}$	**the accumulated equivalent plastic strain in the deformed volume at the end of the *(n-1)*th loading cycle;**
	$\sigma_{y_0}^{(n)}$	**the initial flow stress which is necessary to the start of plastic deformation in the *n*th loading cycle (MPa);**
	$\sigma_{y_{\max}}^{(n-1)}$	**the flow stress at the end of the *(n-1)*th loading cycle (MPa);**
	n	**the number of loading cycles.**

3. **The flow curves, obtained by forging experiments on EN AW-6082 aluminum alloy at room temperature with different strain amplitudes and at the equivalent strain rate of $\bar{\xi} = 0,1s^{-1}$, show that the yield stress, the equivalent flow stress – based on the equivalence of the plastic work – and the flow stress at the end of the loading cycles increase continuously with the increasing strain amplitude. The calculation method developed to describe the relation between the extrema of the flow stress in the loading cycles and the accumulated equivalent plastic strain gives the lower $\Phi_{\min}(\Delta\varphi)$ and the upper $\Phi_{\max}(\Delta\varphi)$ limiting curve of the cyclic flow stress for any strain amplitude in the range of $\Delta\varphi = [0,2\ldots0,4]$, i.e. it gives the range of the flow stress $\Delta\sigma_y(\Delta\varphi)$ according to the following formula [S2], [S5], [S8].**

$$\Delta\sigma_y(\Delta\varphi) = \Phi_{\max}(\Delta\varphi) - \Phi_{\min}(\Delta\varphi) =$$
$$= \left[f_r^{(0)}(\Delta\varphi) - f_p^{(0)}(\Delta\varphi) \right] + \sum_{k=1}^{3} \left[f_r^{(2k-1)}(\Delta\varphi) - f_p^{(2k-1)}(\Delta\varphi) \right] -$$
$$- \sum_{k=1}^{3} \left[f_r^{(2k-1)}(\Delta\varphi) \cdot e^{-\bar{\varepsilon} f_r^{(2k)}(\Delta\varphi)} - f_p^{(2k-1)}(\Delta\varphi) \cdot e^{-\bar{\varepsilon} f_p^{(2k)}(\Delta\varphi)} \right]$$

where:	$f_{p/r}^{(i)}(\Delta\varphi)$	**the exponential functions to describe the relation between the coefficients of the Lademo functions and the strain amplitude, where the Lademo function is applied as fitting function to the lower (index *p*) and the upper (index *r*) limiting curves of the flow stress;**
	$\Delta\varphi$	**strain amplitude;**
	k	**the auxiliary index to separate the coefficients of the Lademo functions having odd and even i indexes.**

4. **Considering the results of the microhardness measurements and the tensile tests, executed on samples from the same loading direction, obtained from the forging experiments at room temperature with the strain amplitude of $\Delta\varphi = 0,4$, at the equivalent strain rate of $\bar{\xi} = 0,1s^{-1}$ and in the common range of the accumulated equivalent plastic strain, the hardness of EN AW-6082 aluminum alloy is smaller than the hardness under monotonic deformation path and it changes in non-monotonic way with the increasing plastic strain. The tensile strength of the material continuously increases from 101MPa to 210MPa, while its elongation to fracture, which characterizes the formability of the material, stabilizes around 21±4% in the range of the severe plastic deformation, i.e. from the second to the tenth forging pass.**
According to the experimental results, under the cyclic, non-monotonic plastic deformation of multiple forging, the increasing in strength is not followed by the continuous growth of hardness, in contrast to the general experience concerning the monotonic plastic deformation at room temperature [S5].

5 **Through the multiple forging experiments at room temperature with different strain amplitudes and at the equivalent strain rate of $\bar{\xi} = 0,1s^{-1}$, the coarse grained microstructure of EN AW-6082 aluminum alloy and DD11 mild steel develops to ultra-finegrained structure by reaching the accumulated equivalent plastic strain of $\bar{\varepsilon} \cong 4$. The average grain size of the ultra-finegrained microstructure is in the range of [0,5...1,1] µm independently from the crystalline structure of the two materials. The following properties are characteristic for the developed ultra-finegrained microstructure and its formation process [S2], [S3], [S5], [S9]:**

- **Regarding the DD11 mild steel specimens, which were forged with the strain amplitude of $\Delta\varphi = 0,4$ and subjected to 2, 4, 6 and 10 passes then studied by EBSD technique, the size of the crystallites, bounded by high angle grain boundaries over 5° and 15° in misorientation, continuously decreases during the progression of the forging process, and reaches the average grain size of 0,8 and 1,1µm at the accumulated equivalent plastic strain of $\bar{\varepsilon} \cong 4$. With the increasing number of loading cycles, the fraction of the low angle grain boundaries below 5° in misorientation decreases from 28,5% to 11,2%, while the fraction of the high angle grain boundaries over 5° in misorientation increases from 71,5% to 88,8%.**
- **The microstructure of EN AW-6082 aluminum specimens, which were forged with different strain amplitudes up to the same accumulated plastic strain of $\bar{\varepsilon} \cong 4$ then studied by TEM method, indicates ultra-finegrained structure. However, with the increasing strain amplitude, the average grain size decreases from 1,05µm to 0,45µm, while the deviation of the grain size distribution also reduces, i.e. the inhomogeneity of the microstructure gets smaller.**

5. PUBLICATIONS RELATED TO THE THESES

[S1] P. Bereczki, V. Szombathelyi, G. Krállics, *Determination of flow curve at large cyclic plastic strain by multiaxial forging on MaxStrain System*, International Journal of Mechanical Sciences Vol. 84 (2014) pp. 182-188

[S2] P. Bereczki, G. Krallics, *Flow Curve Evolution during Cyclic Processing of Ultrafine Grained Aluminum Alloy by Multiaxial Forging*, Advanced Engineering Materials, DOI: 10.1002/adem 201400588 (published online)

[S3] P. J. Szabó, P. Bereczki, B. Verő, *The Effect of Multiaxial Forging on the Grain Refinement of Low Alloyed Steel*, Periodica Polytechnica, Mechanical Engineering Vol. 55/1 (2011) pp. 63-69

[S4] P. Bereczki, B. Fekete, V. Szombathelyi and F. Misjak, *Different Applications of the Gleeble® Thermal-Mechanical Simulator in Material Testing, Technology Optimization and Process Modelling*, ASTM International Journal on Materials Performance and Characterization, DOI: 10.1520/MPC20150006 (published online)

[S5] P Bereczki, V Szombathelyi and G Krallics, *Production of ultrafine grained aluminum by cyclic severe plastic deformation at ambient temperature*, IOP Conf. Series: Materials Science and Engineering Vol. 63 (2014) 012140

[S6] P. Bereczki, B. Verő, Zs. Csepeli, B. Fekete, *Thermomechanical process simulations with Gleeble 3800 physical simulator at College of Dunaújváros*, XXXIII. Verformungskundliches Kolloquium, Zauchensee, Austria, 15.3-18.3.2014, pp. 18-23., ISBN 978-3-902078-19-3

[S7] Bereczki P., Verő B., Janó V., *Többtengelyű hidegalakítási kísérletek*, Bányászati és Kohászati Lapok, 146. évf. (2013/2) pp. 31-37 (in Hungarian)

[S8] Bereczki P., Krállics Gy., *Ciklikus folyási feszültség meghatározása alumínium többtengelyű kovácsolásakor*, Bányászati és Kohászati Lapok, 147. évf. (2014/5-6) pp. 6-10 (in Hungarian)

[S9] Szabó P. J., Bereczki P., *Intenzív alakítási és hőkezelési folyamatok mikroszerkezetre gyakorolt hatásának értelmezése visszaszórtelektron-diffrakcióval*, Bányászati és Kohászati Lapok, 146. évf. (2013/3) pp. 42-47 (in Hungarian)