NUMERICKÉ SIMULÁCIE HLINÍKOVEJ ZLIATINY EN AW 2014 V ECAP PROCESE

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NUMERICAL SIMULATIONS OF EN AW 2014 ALUMINIUM ALLOY IN ECAP PROCESS

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Abstrakt

Metóda konečných prvkov (MKP) je odskúšaná a vhodná technológia pre analýzu rôznych procesov tvárnenia zahŕňajúcich aj progresívnu technológiu Equal Channel Angular Pressing (ECAP). ECAP (pretlačovanie cez kanál rovnakého prierezu) je pomerne jednoduchá IPD (intenzívna plastická deformácia) metóda na získavanie ultra jemnej štruktúry (UFG – ultrafine-grained). Materiály sú charakterizované zvýšenými hodnotami vlastností a procesných premenných. Pomocou programu DEFORM 2D (pracujúceho na báze MKP) sa simuloval priebeh plastickej deformácie hliníkovej zliatiny EN AW 2014 počas ECAP procesu pri sklone kanálov 90°. Predmetom príspevku je porovnanie výsledkov matematických simulácii ECAP procesu materiálu EN AW 2014, ktorého krivky spevnenia boli do programu Deform 2D implementované pomocou výberu napäťovo-deformačnej krivky z programovej databázy a experimentálne stanovenej závislosti napätie-deformácia. Hlavným cieľom príspevku je poskytnúť informáciu o distribúcii deformácie, deformačnej rýchlosti a teploty v skúmanej hliníkovej zliatine EN AW 2014. Detailný rozbor výsledkov simulácie ECAP procesu hliníkovej zliatiny EN AW 2014 pomocou simulačného programu DEFORM 2D ukázal, že z hľadiska predikcie jednotlivých premenných počas tvárnenia materiálu bol v niektorých prípadoch (intenzita rýchlosti plastickej deformácie a teploty) značný rozdiel, ak boli údaje použité zo softvérovej databázy, alebo definované na základe experimentálne stanovenej napäťovo-deformačnej krivky. Spôsobené zmeny sa môžu vysvetliť lepším poznaním materiálových charakteristík zo skúšky ťahom, pretože materiál v sebe nesie všetky stopy predchádzajúcich technologických operácií a použitie údajov z programu DEFORM 2D nemusí v plnej miere zodpovedať experimentálnemu materiálu. Z tohto dôvodu je nevyhnutné pri simulácií procesu vychádzať z poznania materiálových charakteristík, ktoré sa získajú pomocou laboratórnych skúšok.

Abstract

The finite element method (FEM) is a proven and reliable technique for analyzing various forming processes, including a progressive technique like Equal Channel Angular Pressing (ECAP). ECAP is one of the severe plastic deformation (SPD) techniques, which is rather effective for producing ultrafine-grained (UFG) metals with enhanced mechanical and processing properties inherent in various ultrafine-grained materials. The plastic deformation behaviour of the materials during the ECAP process with a round die corner angle (90°) and a frictionless condition was investigated using a program DEFORM 2D (it is a FEM based process simulation system). The aluminium alloy EN AW 2014 was used as the workpiece material; the stress-strain relationship were derived both from experimental investigation and from DEFORM 2D database. The main aim of the present work was provided information concerning the distribution of effective strain, strain rates and temperatures in the aluminium alloy EN AW 2014. The simulation analyses of ECAP process of aluminium alloy EN AW 2014 by means of the DEFORM 2D shows that in term of prediction individual parameters during forming processing was in the some case (strain rate intensity and temperature) sensible different, providing that material characteristic were given by database or on the basis experimentally determined stress-strain curve. In this regard, is necessary to consider in the simulation process to appear from knowledge of material characteristic obtained by laboratory test of formability.

Keyword: aluminium alloy, SPD, ECAP, FEM, DEFORM

1. Introduction

ECAP is one of the SPD techniques, which is rather effective for producing UFG metals with enhanced mechanical and processing properties inherent in various ultrafine-grained materials [1-3]. The ECAP process is a promising method that involves large shear plastic deformation in a deforming layer of a workpiece.

The unique mechanical properties of the ECAPed material are directly affected by plastic deformation. Hence, the understanding the development of strain during processing [4-6] has a key role for a successful ECAP process. In order to understand various processes like as the workpiece, die design, the friction conditions, etc.; it is essential to combine experimental research with a theoretical analysis of inhomogeneous deformation behaviour in the workpiece during the process.

The FEM is a proven and reliable technique for analyzing various forming processes [7-11], including progressive technique like ECAP, in order to analyze the global and local deformation response of the workpiece with nonlinear conditions of boundary, loading and material properties, to compare the effects of various parameters, and to search for optimum process conditions for a given material [12].

In addition to the aforementioned properties, the most important factor affecting the mathematical simulation of material is the stress-strain curve (stress-strain curve influences the calculation precision). These data can be derived either from database program or from experimental achieved stress-strain curve. Experimental stress-strain can easily be determined by laboratory tests of formability. The most frequently used formability tests are torsion and tension [13-16].

The main aim of the present work was provided information concerning the distribution of effective strain, strain rates, stresses and temperatures in the EN AW 2014 material.

2. Material and experimental methods

The experimental material was aluminium alloy EN AW 2014. The experimental ways of preparing the investigated material are shown in **Fig. 1**.

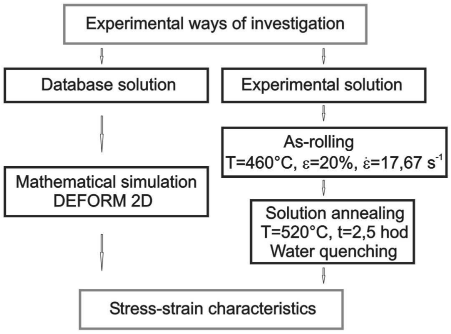

Fig.1 Experimental schemes of preparing investigated materials

Die geometries were directly built in the software Deform2D. The parameters were: circle canal of die with diameter d_0 =10 mm, die with channels angle Φ = 90°, outer radius R = 5 mm and inner radius r = 0 mm. The workpiece dimensions were: diameter d_0 =10 mm and length l_0 = 60 mm. The length of plunger was $l_{plunger}$ = 105 mm, and their processing rate was constant v = 1 mm/s^{-1}. Friction was superposed to follow Coulomb’s law with friction coefficient μ = 0,12. The processing temperature was 20°C. The theory at the base of FEM implies that at first, the problem has to be divided into little sub problems that are easily to be formulated. There over, its all must be carefully combined and then solved. The manner in which a problem is divided constituents the so called meshing process. Mesh density refers to the size of elements that will be generated within an object boundary. The mesh density is primarily based on the specified total number of elements. Mesh density according to [17, 18] is defined by the number of nodes per unit length, generally along the edge of the object. The mesh density values specify a mesh density ratio between two regions in the object. A higher mesh density offers increased accuracy and resolution of geometry, on the other hand in general, the time required for the computer to solve the problem increases as number of nodes increases. An optimal meshing density has to be chosen according to the geometry and size of object according in [7-9] specimen with diameter d_0 = 10 mm has been decided using 20 elements along the width. Hence, the specimen with diameter d_0 = 10 mm and length l_0 = 60 mm was meshed with 3000 elements, that’s to say 28 elements on the specimen diameter, as shown in **Fig. 2**.

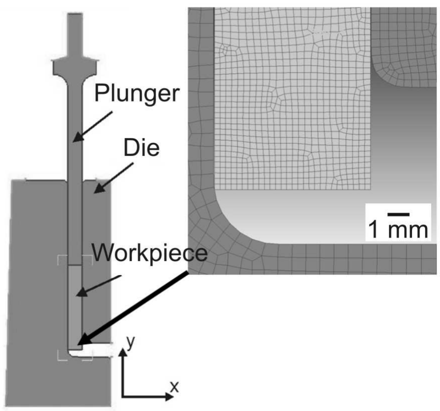

Fig.2 The geometry of ECAP die with detail of mesh density

The finer meshes were built close to the surface in order to better match the geometry of the process, for example in channel areas. Previous mathematical simulations [19, 20] showed that the influence of channel angles of ECAP equipment was influencing the development of effective strain. Thus the highest effective strain is achieved if the angle between channels is 90°.

The tools of ECAP equipment (the die and plunger) were assumed to be elastic materials and they were assigned of tool steel material characteristic, them being much higher than those of deformed material. The specimen was assumed as elasto-plastic object with their material characteristics characterized by stress-strain curve (**Table 1**) Young's modulus and thermal properties.

Table 1 Stress-strain data of aluminium alloy EN AW 2014 for both conditions

Strain [-]	0	0,1	0,2	0,3	1
Database data / stress [MPa]	0	200	233	250	312
Experimental data / stress [MPa]	0	68	144	174	324

Materials characteristics for both conditions are presented in **Table 2**.

Table 2 Material characteristics for both investigated specimen

Workpiece		**Database**	**Experimental**
Plastic		Flow stress (Table 1)	
Elastic	Young's modulus [MPa]	68900	70000
	Poisson's ratio [-]	0,33	
	thermal expansion [K^{-1}]	$2{,}2 \cdot 10^{-5}$	
Thermal	thermal conductivity [kW/m·K]	180,2	
	heat capacity [$kJ \cdot kg^{-1} \cdot K^{-1}$]	2,433	
Damage model (Fracture data)		Cockcroft-Latham	

Hence, mathematical simulations of ECAP process of aluminium alloy EN AW 2014 were realized on the basis of two approaches for stress-strain curve selection: from DEFORM material database and from experimental result. The DEFORM material database contains flow stress data for aluminium alloy EN AW 2014 (**Table 1**). The flow stress data provided by the material database has a limited range in terms of temperature range and effective strain. Certainly, the simulation conditions of investigated materials were considered so that the bounds of the deformation strain, strain rate and deformation temperature cannot lead to loss of accuracy.

3. Experimental results and discussion

Distribution of equivalent plastic deformation after one ECAP step for both conditions presented in the **Fig. 3**.

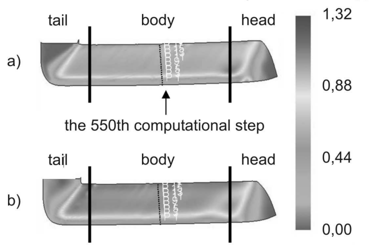

Fig.3 Distribution of equivalent strain after one ECAP pass at the same forming condition: a) for database data, b) for experimental data

Plastic deformation is non-uniformly distributed along the cross-section and also the length of specimen (see **Fig. 3**). Along the workpiece length is possible to divide the plastic deformation into three deformation areas:

head – non-uniformity of plastic deformation is caused by non-uniformly material flow during junction from vertical to horizontal canal,

body – steady state of plastic deformation,

tail – non-uniformity of plastic deformation is related to the uncompleted pressing of specimen during the exit channel.

Non-uniformity of plastic deformation the most be concentrated to the bottom part of the workpiece, in accordance with literature [7-10]. Due to this fact, the material properties after ECAP are carried out only from body of specimen.

The distribution of equivalent plastic deformation in cross-section part of specimen for the 550th computational step (steady state area of plastic deformation) was illustrated in the **Fig. 4** for both conditions.

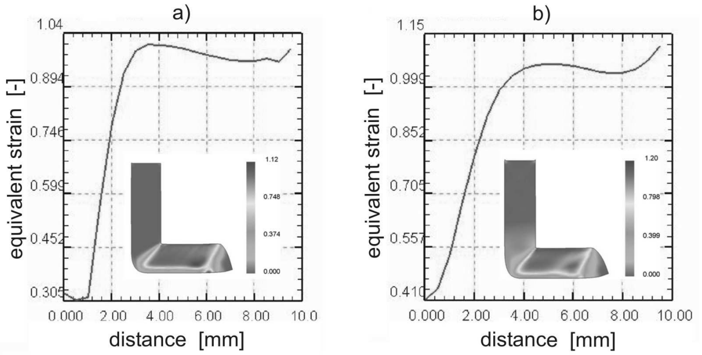

Fig.4 Distribution of equivalent strain in cross-section part of workpiece in 550th computational step: a) for database data, b) for experimental data

Local changes were observed in maximum of curve, where the simulation analysis with database characteristic achieved effective strain value of 1,12 while in simulation analysis with experimental characteristic attained 1,2. The difference represented 7 %. That means the entry data from stress-strain curves did not affect the distribution of plastic deformation intensity in cross-section area of workpiece.

The distribution of strain rate intensity for both conditions was illustrated in the **Fig. 5**.

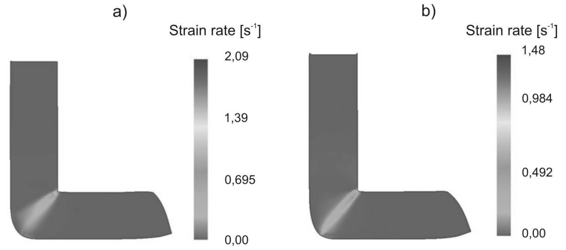

Fig.5 Distribution of strain rate intensity along to cross-section in 550th computational step: a) for database data, b) for experimental data

Strain rate determined the plastic deformation area and/or the plastic deformation zone (PDZ). It can be seen that strain rate is concentrated in the narrow zone – PDZ. In all cases, the plastic deformation zone varies both along the workpiece axis and along the transverse direction from top to bottom as it is confirmed in [7, 8]. It is needed to keep in mind that ECAP deformation is generally non-homogeneous, especially when the die is rounded or if conditions lead to a free surface corner gap [9, 20]. However, a disadvantage of the FEM studies is that various different combinations like the workpiece, die design, the friction conditions, etc. are applied. All mentioned factors can deeply influence the simulation results and therefore make it difficult to compare results from different studies. Hence, studies for understanding PDZ during the forming process and interpreting the real forming conditions in ECAP process are still lacking.

It can be found from the distribution of strain rate intensity (the 550^{th} computational step in the **Fig. 5**) that the strain rates are clearly different in case of the database and experimental material; in the inner side of the channel achieved an increase in strain rate about 29 % for experimental material characteristics.

A temperature development during the ECAP process was shown in the **Fig. 6**.

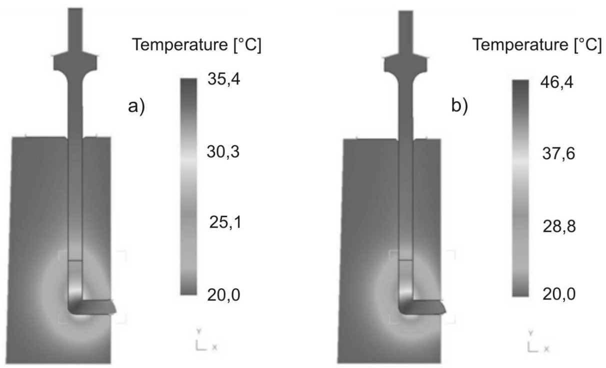

Fig.6 Temperature development during ECAP process and heating of forming tools: a) for database data, b) for experimental data

Results from **Fig. 6** that an increase in temperature during the process, from initial ambient temperature to 35,5°C for database data and to 46°C for experimental data. An increase in temperature is connected to heat transformation of plastic deformation part. In simulation to take heat transfer into consideration, for that reason during the ECAP process can to observe a heating of forming tools too. It is important point that temperature of forming tool not allowed to reach a tempering grade. It results from [7] that the significant recovery process can be recognized for temperatures over 300°C.

4. Conclusion

The simulation analyses of ECAP process of aluminium alloy EN AW 2014 by means of the FEM based DEFORM 2D process simulation system shows that in term of prediction individual parameters during forming processing was in the some case (strain rate intensity and temperature) sensible different, providing that material characteristic were given by database or on the basis experimentally determined stress-strain curve. The recorded changes in simulation can be explained to better knowledge of material characteristics from tensile test, by reason that material in them carries the all history of previous technological operations and using a data from program database it needn't exactly to correspond of material selection. In this regard, is necessary to consider in the simulation process to appear from information from material characteristic obtained by laboratory test of formability.

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Literature

[1] Kvačkaj T., Zemko M., Kuskulič T., Kočiško R., Besterci M., Dobatkin S.V., Molnarová M.: High Temperature Materials and Processes, 26, 2007, 2, 147-150.
[2] Bidulská J., Kvačkaj T., Bidulský R., Actis Grande M.: High Temperature Materials and Processes, in print.
[3] Bidulská J., Kvačkaj T., Bidulský R., Actis Grande M.: Kovové materiály, 46, 2008, 6, 339-344.
[4] Ceniga L.: Acta Mechanica Sinica, 24, 2008, 2, 189-206.
[5] Ceniga L.: Journal of Thermal Stresses, 31, 2008, 8, 728-758.
[6] Ceniga L.: Journal of Thermal Stresses, 31, 2008, 9, 862-891.
[7] Kvačkaj T., Zemko M., Kočiško R., Kuskulič T., Pokorný I., Besterci M., Sülleiová K., Molnárová M., Kováčová A. : Kovové materiály, 45, 2007, 5, 249-254.
[8] Kočiško R., Zemko M., Kuskulič T., Kvačkaj T., Kováčová A.: Acta Metallurgica Slovaca, 13, 2007, SI. 1, 397-404.
[9] Li S., Bourke M.A.M., Beyerlein I.J., Alexander D.J., Clausen B.: Materials Science and Engineering, 382 A, 2004, 1-2, 217-236.
[10] Leo P., Cerri E., De Marco P.P., Roven H.J.: Journal of Materials Processing Technology, 182, 2007, 207-214.
[11] Zemko M., Nový Z., Kvačkaj T.: Acta Metallurgica Slovaca, 10, 2004, 2, 94-101.
[12] Kim H.S.: Materials Science and Engineering, 315 A, 2001, 1-2, 122-128.
[13] Pernis R., Bořuta J., Bořuta A.: Vplyv dĺžky skúšobnej tyčky na rýchlosť deformácie krutovej skúšky nábojnicovej mosadze. In.: TRANSFER 2008, ed. E. Podmaková, R. Ďuďáková, Trenčín, 27.-28. 11. 2008, DIGITAL GRAPHIC Trenčín, CD-ROM, ISBN 978-80-8075-356-6.
[14] Vlado M.: Výroba a vlastnosti neorientovaných plechov pre elektrotechniku so zreteľom na oblasť valcovania za tepla. Habilitačná práca. HF TU Košice, 2000.
[15] Nový F., Palček P., Chalupová M.: Kovové materiály, 43, 2005, 6, 447-456.
[16] Pernis R.: Teória tvárnenia kovov. Trenčín: FŠT TnUAD v Trenčíne, 2007.
[17] Kobayashi S., Oh S.I., Altan T.: Metal Forming and the Finite-Element Method, 1 ed., Oxford University Press, New York, 1989.
[18] Deform Manual, version 8.0, Scientific Forming Technologies Corporation, Columbus, 2003.
[19] Semiatin S.L., DeLo D.P., Shell E.B.: Acta Materialia, 48, 2000, 8, 1841-1851.
[20] Kvačkaj T., Zemko M., Kočiško R., Kuskulič T., Pokorný I., Besterci M., Sülleiová K., Molnárová M., Kováčová A. : Acta Metallurgica Slovaca, 13, 2007, 3, 311-319.