# STRESS-STRAIN CURVES PROGRESS ANALYSE OF UFG Cu DURING DYNAMIC LOADING AND ITS FRACTURE AREAS INVESTIGATION

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# ANALÝZA PRIEBEHU NAPÄŤOVO-DEFORMAČNÝCH KRIVIEK UFG MEDI POČAS DYNAMICKÉHO ZAŤAŽOVANIA A SLEDOVANIE LOMOVÝCH PLÔCH

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**Abstrakt**

V predkladanom článku je popísané správanie sa ultrajemnozrnej (UFG) vysokočistej (OFHP) medi počas dynamického zaťažovania. Vstupná meď po zonálnej rafinácii bola spracovaná pomocou metódy založenej na intenzívnych plastických deformáciách (IPD) a to pomocou ECAP zariadenia (“equal channel angular pressing”). Počas ECAP procesu bolo realizovaných 5 prechodov spracovateľskou C cestou pri izbovej teplote, 5 ECAP prechodov je postačujúci počet na dosiahnutie stálosti mechanických vlastností a tiež veľkosti zrna pod 1 μm. Dynamické ťahové skúšky boli realizované pomocou vysoko-rýchlostného ťahového zariadenia pri izbovej teplote. Materiálové charakteristiky UFG medi boli skúmané pri rôznych obvodových rýchlostiach a to pri 2.0, 2.5, 3.0, 4.0 m/s. Dosiahnuté výsledky z merania počas dynamického zaťažovania ukazujú netypické priebehy napäťovo-deformačných kriviek. Na základe skúmania priebehu napäťovo-deformačných kriviek a na základe dostupnej literatúry [1,2] je zjavné, že v dynamicky zaťažovanej UFG medi sa vyskytuje dynamická horná medza kĺzu $R_{eH,d}$, dynamická dolná medza kĺzu $R_{eL,d}$ a tiež oscilácie, ktoré boli spozorované po ukončení zaťaženia. Prudký nárast medze kĺzu Re a jej prudký pokles sa v literatúre označuje ako tzv. „hrot” a predstavuje rozvoj plastických deformácií [1]. Vplyv rýchlosti zaťažovania na výskyt $R_{eH,d}$, $R_{eL,d}$ bol sledovaný a na základe výsledkov je možné predpokladať ich nárast s nárastom deformačnej rýchlosti. Fraktografická analýza lomových plôch ukázala typický tvárny lom v každom rýchlostnom režime, na základe stanovenia veľkosti jamiek je zjavné, že ich veľkosť klesá s nárastom rýchlosti deformácie. Veľkosť jamiek bola stanovená zo súboru 200 meraní pre každý skúmaný stav. Z dynamických ťahových skúšok bola vypočítaná kontrakcia, z výsledkov vyplýva jej nárast s nárastom veľkosti jamiek.

**Abstract**

In the present paper behavior of ultrafine-grained (UFG) oxygen free high purity (OFHP) copper prepared by severe plastic deformation (SPD) methods was investigated during

dynamic loading. The initial Cu after zonal purification was subjected by 5 passes of equal-channel angular pressing (ECAP) via C route at room temperature. The 5 ECAP passes are sufficient by reason of mechanical properties stable state achievement and grain size below 1 μm obtention. The dynamic tensile tests were conducted by high speed tensile machine at room temperature. The material characteristics of UFG Cu during tensile tests were investigated by various circumferential speeds namely 2.0, 2.5, 3.0, 4.0 m/s. Results, which were achieved during dynamic tests measuring clearly show atypical loading-elongation curves progress. The curves investigation and following available literature [1,2] it's clear, that dynamic upper yield stress $R_{eH,d}$, dynamic lower yield stress $R_{eL,d}$ (dynamic tensile properties) exist in dynamic loading UFG Cu and also oscillations were found in samples. The rapid yield stress $R_e$ increase and their rapid decrease it's named in literature "peak". The "peak" presents plastic deformation progress process [1]. The $R_{eH,d}$, $R_{eL,d}$ investigations in different deformation rates suppose their increase with deformation rate increasing. The deformed area observations of dynamically fractured surface show a typical ductile fracture mode in every circumferential speed regime. The dimple size measurements indicate decrease of dimple size with circumferential speed increasing. The dimple size was determined based on 200 measuring file for every regime. Following dynamic tests reduction of area shows its increase with dimple size increasing.

**Keywords:** ECAP, UFG copper, dynamic tensile tests, dynamic tensile properties, fracture analyse

## 1. Introduction

Ultrafine-grained materials represent a new generation of advanced materials exhibiting unique and technologically attractive properties due to the size of grains. Ultrafine-grained materials exhibit extremely high strength and good fatigue resistance and at the same time they are rather ductile [3]. There are many methods to achievement ultrafine-grained materials, nowdays. Equal-channel angular pressing is method, which was developed by Segal and his co-workers. The main goal is introducing severe plastic deformation (SPD) into materials without changing the cross section area of billets [4].

The dynamic tensile properties of ultrafine-grained samples are important since the dynamic behavior of material is different from quasi-static behavior. The most material data depend on the strain rate during plastic deformation process and it is much higher than the rate obtained in conventional tensile testing machines. Lately, several studies on quasi-static and dynamic deformation properties of ultrafine-grained or nanograined Fe, Cu and Ni have been conducted using a hydroservo system or a compressive Kolsky bar [5, 6, 7].

Deformation and fracture behaviors of UFG materials under dynamic loading are studied at the present time in limit area because the most of studies are related to phenomena occuring under quasi-static loading. The progress of dynamic deformation and fracture behavior is important to know owing to designing and applying ultrafine-grained materials to parts used under high-speed loading conditions.

## 2. Experimental methods and equipments

The material used in this study was a oxygen free high purity copper (OFHP-99, 99%), its initial mechanical properties and grain size are given in Table 1. Afterwards, the ECAP was carried out in order to achievement ultrafine-grained structure of copper. It was realized 5 passes by route C at room temperature, obtained subgrain diameter was below 1 μm.

Table 1 OFHP Cu properties before ECAP

| $R_{p0.2}$ [MPa] | $R_m$ [MPa] | $A_5$ [%] | Z [%] | HV | $d_z$ [μm] |
|---|---|---|---|---|---|
| 275 | 282 | 11,5 | 82 | 125 | 7 |

The next analyse was realized via dynamic tensile loading at the room temperature and fracture investigation. In dynamic tensile test a high speed tensile machine was used. The parameters of Cu samples with UFG structure which were used during dynamic tests are displayed in Fig.1. It was investigated dynamic behavior of UFG copper during four different circumferential speed conditions. Fracture surfaces were observed using a scanning electron microscope after the test.

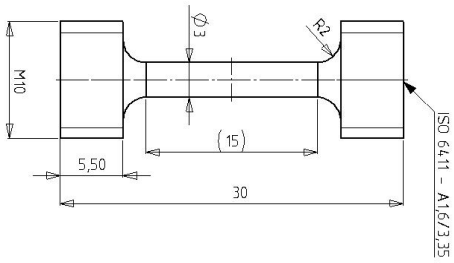



Fig.1 Shape and dimensions of the specimen for dynamic tensile test

## 3. Results and discussion

### *3.1 Dynamic tensile tests*

Following [1, 2] dynamic upper yield stress $R_{eH,d}$ and dynamic lower yield stress $R_{eL,d}$ were found in dynamic tested materials. Room-temperature dynamic tensile stress-strain curve of UFG copper is presented in Fig.2 with $R_{eH,d}$, $R_{eL,d}$ description.

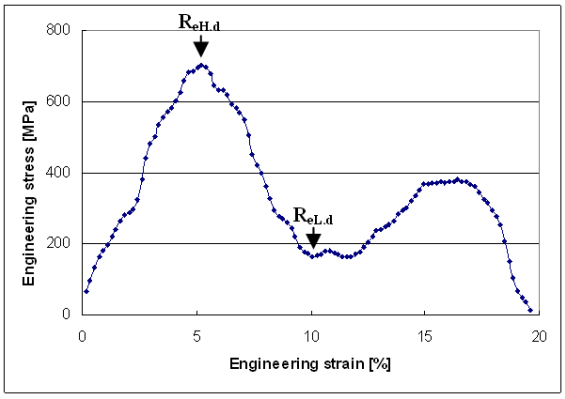



Fig.2 Stress-strain curve obtained from dynamic tensile test in circumferential speed 2.5 m/s

In the Table 2 $R_{eH,d}$, $R_{eL,d}$ values for every circumferential speed are determined and in Fig.3 engineering stress dependence on circumferential speed is plotted, where increase of $R_{eH,d}$ with deformation rate increasing is visible after 3.0 m/s by reason of strengthening.

Table 2 UFG copper dynamic tensile properties

| Circumferential speed [m/s] | $R_{eH,d}$ [MPa] | $R_{eL,d}$ [MPa] |
|---|---|---|
| 2.0 | 686 | 141 |
| 2.5 | 672 | 184 |
| 3.0 | 577 | 177 |
| 4.0 | 744 | 102 |

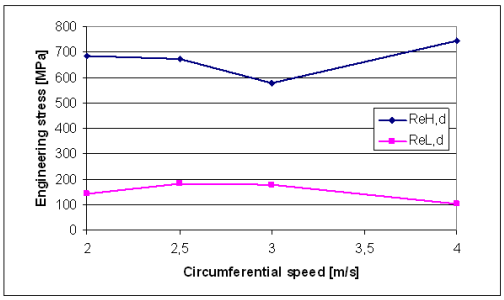
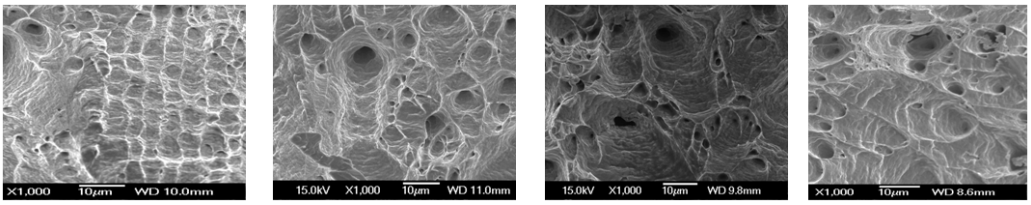



Fig.3 Engineering stress dependence on circumferential speed

### *3.2 Fracture observations*

Fracture characteristic observation using scanning electron microscopy was made. The SEM micrographs of dynamically fractured tensile UFG copper specimens clearly show a typical ductile fracture mode in every circumferential speed regime, Fig.4. The ductile fracture mode based on Gourland-Plateau theory suppose three stages dimple creation before the fracture: initiation, increase and coalescence of dimples. The Fig.5 clearly shows, that if circumferential speed increased dimple size would decrease in UFG copper after dynamic loading owing to high speed deformation, when progress of dimple increase and coalescence is not fully achieved. The mean dimple size was measured from around 200 dimples group, the results are illustrated in Table 3.

The reduction of area is very important plastic characteristic of material, following dynamic tensile tests it was determined and obtained results are also plotted in the Fig.5.




a) b) c) d)

Fig.4 SEM micrographs of UFG copper fractured area in a) 2.0 m/s b) 2.5 m/s c) 3.0 m/s d) 4.0 m/s

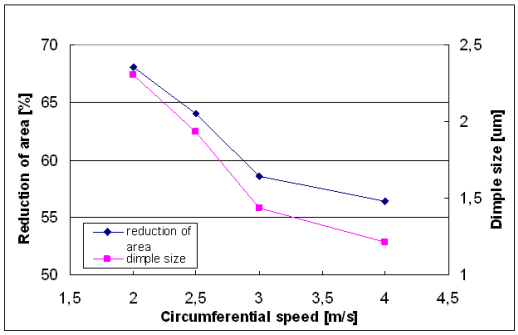



Fig.5 Reduction of area and dimple size dependences on deformation rate

Table 3 Mean dimple size in dependence on circumfer. speed

| Circumferential speed [m/s] | Mean dimple size [μm] |
|---|---|
| 2.0 | 2.3 |
| 2.5 | 1.9 |
| 3.0 | 1.4 |
| 4.0 | 1.2 |

The correlation between mean dimple size (d) and reduction of area (Z) was investigated by linear regression (MS Excel), it was obtained the following expression (1) and correlation coefficient. Following correlation coefficient it is clear, that linear dependence between dimple size and reduction of area is strong.

$$Z = 43{,}25652 + 10{,}74.d\,, \qquad r = 0,\ 9998 \tag{1}$$

## 4. Conclusion

In the present study, dynamic tensile tests were conducted on ultrafine-grained copper and its deformation and fracture behavior were analyzed.

1) According to the dynamic tensile test results, dynamic upper yield stress $R_{eH,d}$ and dynamic lower yield stress $R_{eL,d}$ were found in tested materials. In comparison with previous results, which were achieved from static test $R_{eH,d}$ from dynamic test is about 2 times higher as $R_{p0.2}$ from static test.
2) Following obtained results from dynamic tests, oscillations in dynamically loaded samples were also found.
3) Fracture characteristic observation dynamically fractured samples show a typical ductile mode in every deformation rate regime. The dimple size measurements indicate its decrease in dependence on deformation rate increasing.
4) The data obtained from dimple size and reduction of area determination were processed by linear mathematical. Following correlation coefficient it is clear, that linear dependence between dimple size and reduction of area is strong.

**Acknowledgement**

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