A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 59 2014 Issue 2
DOI: 10.2478/amm-2014-0089

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MECHANICAL AND STRUCTURAL BEHAVIOR OF COPPER SUBJECTED TO THE FLOW FORMING PROCESS

STRUKTURALNE PRZYCZYNY STABILIZACJI MIKROTWARDOŚCI MIEDZI PODDANEJ PROCESOWI ZGNIATANIA OBROTOWEGO

This work paper presents the results of HV 0.5 microhardness measurements and structural documentation of copper before and after the concurrent elongating flow forming process. No strain work hardening of products was noted. The cause of this behavior was recognized to be the location of strain strain localization in shear bands compounded by a change of the strain path imposed by the flow forming process. The dominance of this plastic flow mechanism makes it possible to conduct a technological process encompassing thinning of product walls with omission of expensive inter-operational softening heat treatment.
Keywords: flow forming, strain path, shear bands, localized plastic flow, copper

W pracy przedstawiono wyniki pomiarów mikrotwardości HV 0,5 i dokumentację strukturalną miedzi przed i po procesie zgniatania obrotowego wydłużającego współbieżnego. Stwierdzono brak umocnienia odkształceniowego wyrobów. Za przyczynę takiego zachowania, uznano lokalizację odkształcenia w pasmach ścinania spotęgowaną – narzuconą procesem zgniatania obrotowego – zmianą drogi odkształcenia. Dominacja tego mechanizmu plastycznego płynięcia, umożliwia prowadzenie procesu technologicznego obejmującego pocienianie ścianki wyrobu, z pominięciem kosztownej międzyoperacyjnej obróbki cieplnej zmiękczającej.

1. Introduction

It is generally known that strength properties of metallic materials are increased as a result of ”cold” metal forming. This increase, which is very intensive at first, is weaker as the process advances and may even be completely inhibited at very high plastic strains.

Various schemes of material deformation have been studied over the last dozen or so years decades, and they often generate a change of the strain path due to which leads to stabilization of the metal strength properties or even to strain softening may take place at practically at any stage of the deformation process [1-4]. Thanks to this, technological processes can often be conducted without expensive inter-operational softening heat treatment (e.g. recrystallization annealing).

From a physical perspective, the structure of consolidating dislocations that is responsible for strain hardening is mechanically unstable and may be destroyed (reconstructed) as a result of an autonomous self-induced or externally forced change of the strain path [5-8]. This leads to reduction of the work hardening index rate and to inhomogeneous plastic flow in the form of shear bands [9-14].

During plastic forming of metallic materials, limitation of their free flow in the zone of contact with working tools leads to strong structural effects. They are caused by the activation of secondary dislocation slip systems of an accommodating nature. For an advanced strain deformation process, the situation presented above is intensified to the point that despite the maintenance of an unchanging load scheme, an early, self-initiated -induced change of the strain path may occur in the metal, and localized plastic flow may take place in shear bands as a consequence of this. Generally speaking, the probability of shear band generation is dependent on both the initial state of the material (grain size, dislocation density) and on the degree strain value, strain rate, and temperature of deformation process.

Based on the results of experimental studies revealing the characteristic qualities features of actual real metallic materials, two groups of plastic strain flow mechanisms can be distinguished [2]:
– including instability of the crystal lattice and
– based on the instability of the dislocation structure.

Twinning, or the formation of twin kink bands, results from the global instability of a crystal lattice that is subjected to load, while dislocation slipping is only combined with the instability of the crystal lattice on the atomic scale. In turn, thick slip bands and shear bands that are derived from the destabilization of the dislocation structure are an intermedi-

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ate stage between global instability of the crystal lattice and instability on an atomic scale. It is significant that the spatial orientation of shear bands is exclusively dependent on the load scheme.

An important indicator of the activity of bands of localized strain that is revealed during tension is the clear mechanical instability that occurs (sudden oscillations of force) and a strong, although usually only instantaneous, reduction of the work hardening index rate θ or even strain softening of the material (θ <0). The localization of plastic flow in slip and shear bands replaces homogeneous plastic flow realized by multi-systemic small fine slipping because it requires a lower energy. In particular, therealization of strain in slip and shear bands is supported by internal stress and does not require the involvement of additional (secondary) slip systems that are necessary for maintaining cohesion of the material on the boundaries of subgrains and grains (internal bonds) in the case of homogeneous strain.

While the phenomenon of localized plastic flow only becomes the dominant mechanism of metal deformation in monotonically conducted deformations at advanced stages, an externally forced change of the strain path (load scheme) can lead to this phenomenon at any stage of the process. Very often, the geometry of the charge (ingot, input element) and of the product obtained from it imposes the application of complex load schemes, which promotes the localization of plastic flow at the same time. However, independently of the causes, a change of the strain path preceded by the formation of a clearly configured dislocation network always leads to localization of strain (a dynamic phenomenon!) and to specific structural effects in products.

Concurrent elongating flow forming (CEFF), which has undoubted technological advantages, also makes it possible to conduct empirical studies of the phenomenon of localized plastic flow. In particular, besides the diversified initial state of the deformed metal, the range of the drafts and number of operations (passes) applied in the process, and above all, the high strain rate that is possible to be achieved and the wide range of parameters of effecting a change of the strain path create unique conditions for shaping the micro/structure, and thus, the mechanical properties of metallic materials.

The experimental device that performs the CEFF process makes it possible to conduct purely scientific studies focused on specifying the role of relaxation of stresses generated during complex deformation, which is related to the dynamics of the process of shear band formation (activity) from a structural perspective. The time allotted for relaxation (the time between two successive acts of deformation performed by the rotating CEFF working tools) has a very important influence and is decisive to the reconstruction of the structure.

Relaxation of internal stresses is based on replacement of elastic strain with plastic strain. Diffusion processes that enable "unblocking" of dislocations as a result of climbing play a significant role here. Point defects are the carriers of diffusion, and their equilibrium concentration is strongly dependent on temperature. On the other hand, it can be expected that a consequence of a change of the strain path and the destabilization of the dislocation structure caused by this change (parting of the dislocation forest – a "foreign" distribution of dislocations) will be the creation of an enormous amount of dipoles, the "decay" of which will lead to instantaneous achievement of a significantly increased concentration of point defects and to acceleration (intensification) of stress relaxation.

In effect, depending on the dynamics of the phenomenon conditioned by the parameters of the CEFF process, annihilation of dislocations, intensive polygonization and/or formation of fine (nano) grains. It is significant that such reconstruction of the structure does not require increased temperature because room temperature is entirely sufficient for ensuring migration of point defects, particularly intrinsic interstitial atoms (Em ≈ 0.06eV).

Work [3] presents the results of experimental studies that indicate that the microhardness of copper is not changed during the concurrent elongating flow forming process (CEFF), despite the significantly increasing strain. In this work, an attempt has been made to identify the structural mechanism responsible for such behavior of metal based on structural observations.

2. Concurrent elongating flow forming

Concurrent elongating flow forming technology (Fig. 1) is an effective method for producing cylindrical products with a thick bottom and thinned side wall. In particular, the flow forming process may take place by means of one roller (unfavorable due to the large forces in the process, low rigidity, and strongly diversified system of forces in the process), two rollers (situated at every 180° relative to the input material), three rollers, and more. In the latter cases, the system of forces in the process is stable. The fundamental parameters of elon-

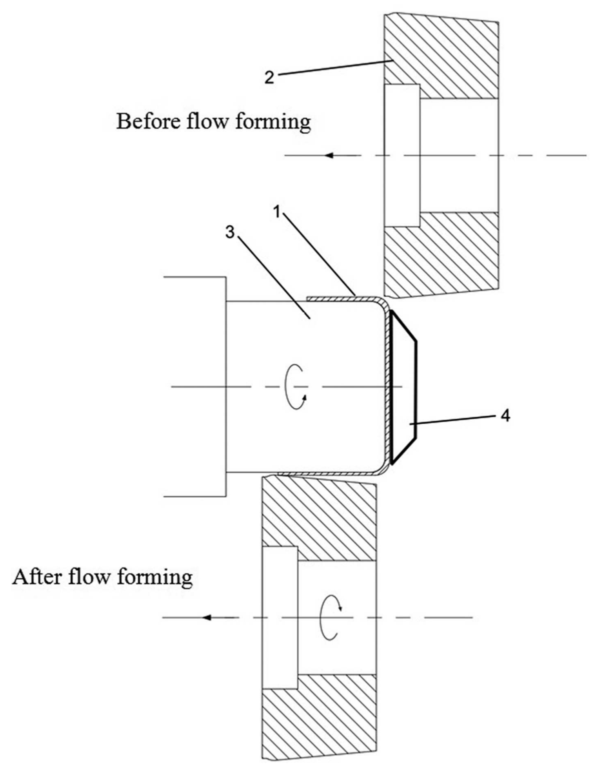


Fig. 1. Scheme of the concurrent elongating flow forming process of a cylindrical drawpiece, where: 1 – input material of a cylindrical shape, 2 – forming tool (roller), 3 – rotating templet causing rotation of roller, 4 – pressure pad [4]

gating flow forming are: spindle rotational speed (with mounted templet), and roller advance rates (tool slides with mounted rollers), which are decisive to the course of the process (magnitude and rate of strain), along with the amount of draft dependent on the initial wall thickness and on the distance between the roller and templet. In addition, other important factors are: the friction coefficient dependent on the type of lubricant applied between the deformed metal and forming tools, as well as the method of cooling during the process or lack thereof.

In the CEFF process, the input material is usually a cylindrical drawpiece obtained from a conventional drawing operation (with or without thinning of the side wall), and the forming surface of the templet (Fig. 1) corresponds to the forming surface of the drawing punch.

The technological process of concurrent elongating flow forming differs from the backward (Fig. 2) direction of material flow during forming.

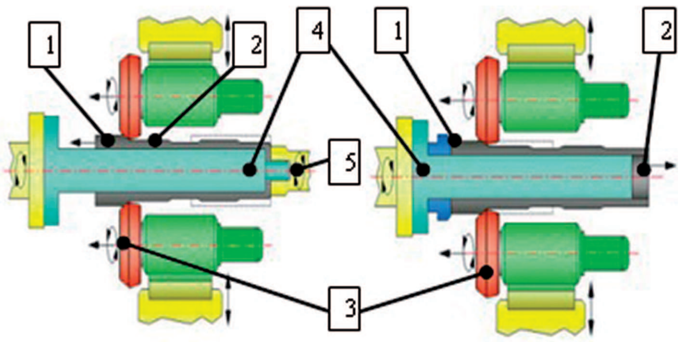


Fig. 2. Diagrams of the concurrent elongating flow forming (left) and backward flow forming (right) processes; 1 – input material, 2 – product, 3 – rollers (forming tools), 4 – templet, 5 – pressure pad [15]

While it is concurrent with the direction of the roller's (rollers') motion in the first method, it is contrary to it in the second method. Thus, concurrent elongating flow forming is applied for products with a bottom and backward flow forming is applied for pipe products.

3. Test methodology

The realization of the process of concurrent elongating flow forming of copper was preceded by cold drawing of cylinders with bottoms from disks of a diameter of 195 mm cut from a copper sheet with a thickness of 2.54 mm in a recrystallized state. Drawpieces with an interior diameter equal to 120.1-120.3 mm and a wall thickness of ~2.46 mm were subjected to the "cold" concurrent elongating flow forming process, that is, without preliminary heating, with a dextrorotary rotational speed equal to 500 rpm and a roller advance rate of 400 mm/min. Drawpieces and tools were continuously cooled with coolant (emulsion) in the form of an oil mixture of antol and water in the proportion of 1:10. The process was conducted in variants of one and two operations, and after the first operation, the reduction of drawpiece wall thickness was equal to about 41% and after the second, about 62%.

From a technological point of view, the fact that the wall thickness after the copper CEFF process is almost always different from the set size of the gap between the roller and templet is significant. It was experimentally proven [3-4] that if forming will take place at a slow roller advance rate, the wall will be thinned more than at a fast advance rate, despite the setting of an identical gap. Furthermore, the formation of thinned zones and increased of wall thicknesses on the drawpiece's side surface is observed, and these areas are arranged in a screw-like, almost spiral fashion, trailing after the forming roller and forming characteristic "waves". The phenomenon of material swelling also occurs and is made apparent by the increase of diameters after the forming process. This increase is the result of spring-back of the drawpiece, and this is largely dependent on the anisotropy of the input material, kinematic working parameters, and the presence of a material threshold (bulge) before the forming roller. In particular, the "bulge" zone of the material moves along the side surface over almost the entire course of the forming process, and its size is dependent on technological parameters - mainly kinematic parameters. No delamination of product walls was observed during the process of concurrent elongating flow forming of copper even after two forming operations, although this defect generally occurs for other materials [4].

Two drawpieces were subjected to one flow forming operation each, however the second drawpiece was not finished (the process was interrupted), which enabled the identification of 3 different strain zones: – the drawn zone, – transitory zone (zone of contact of the forming roller with the material of the drawpiece) and – after flow forming (Fig. 3). Two successive flow forming operations were carried out on a third drawpiece without inter-operational softening heat treatment (annealing).

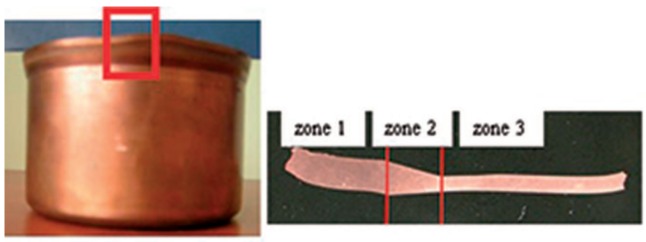


Fig. 3. Drawpiece (left) and its fragment with three strain zones (right): drawn zone – zone 1, transitory zone – zone 2, and after one flow forming operation – zone 3

Microhardness measurements were carried out on copper sheet disks, on drawpieces, and on the products obtained from the flow forming process. In particular, in the last two cases, test samples were collected from the side walls of drawpieces and products, and metallographic specimens were made on their side walls, cross-sections, and on the surface of the copper sheet. Hardness (microhardness) was tested using a Micromet 2104 – Buehler instrument with the application of a load of 0.5 N, indentation sizes remained within the range of 22-44 μm, their distance from the exterior surface was equal to 0.12 mm, and the distance between them was about 5.1 mm.

An Eclipse L150 (Nikon) optical microscope and Inspect S (FEI) scanning electron microscope (SEM) equipped with an EDS-Genesis 2 (EDAX) X-ray microanalyzer were used to observe the structure on the cross-sections of products. Metallographic specimens were etched with a reagent made up of: 100 cm^3 of water, 10 cm^3 HCl, 5 g $FeCl_3$.

For the sample from Fig. 3, additional structural observations carried out in the two remaining sections were to enable spatial identification of grain shape, and thus, to answer questions concerning the metal's mechanical state (hardening, recrystallization). This is justified because the large strain and strain rate resulting from the CEFF process may cause structural renewal or recrystallization processes despite intensive cooling of the metal.

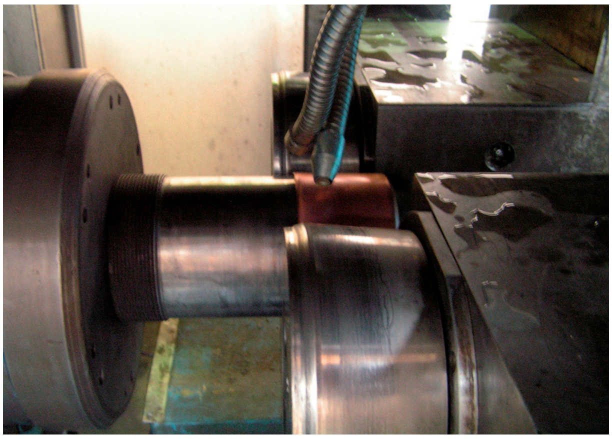


Fig. 4. General view of the forming tools of the MZH-400 roll former with a visible cylindrical drawpiece mounted on the templet after the second flow forming operation

4. Results and discussion

According to the test methodology presented earlier, structural observations and HV 0.5 microhardness measurements of the input material (sheet disk) were carried out – as documented in Fig. 5. In turn, Fig. 6 pertains to the drawpiece (Fig. 3) with the zones that were drawn, transitory, and after one flow forming operation, and Fig. 7 shows the drawpiece after two flow forming operations. Results are compiled in Fig. 8. The observations from Fig. 9-10 show that material grains were deformed in the other two directions.

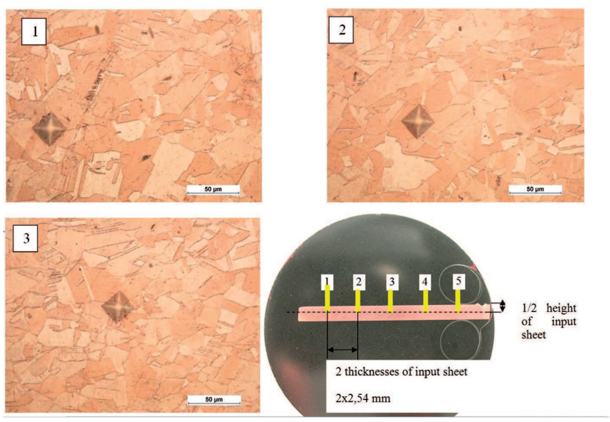
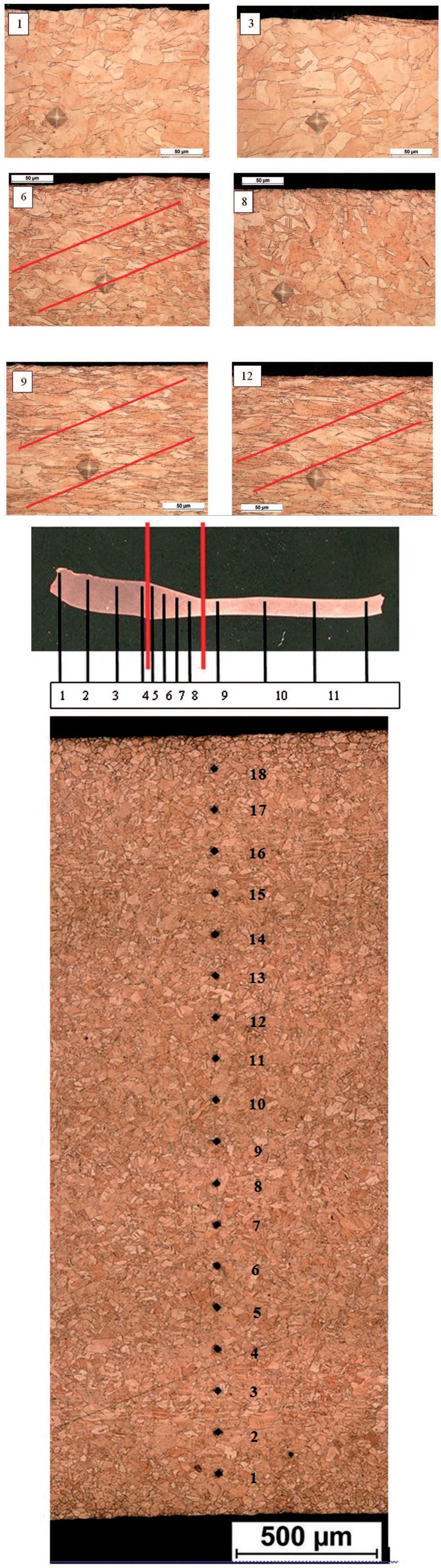


Fig. 5. Microstructure of the input sheet (copper) with locations of HV 0.5 microhardness indentations, where: 1, 2, 3 – successive microhardness indentations

Recrystallized, equiaxial copper grains and recrystallization twins are visible in Fig. 5. No traces of strain were observed in any of the studied samples.



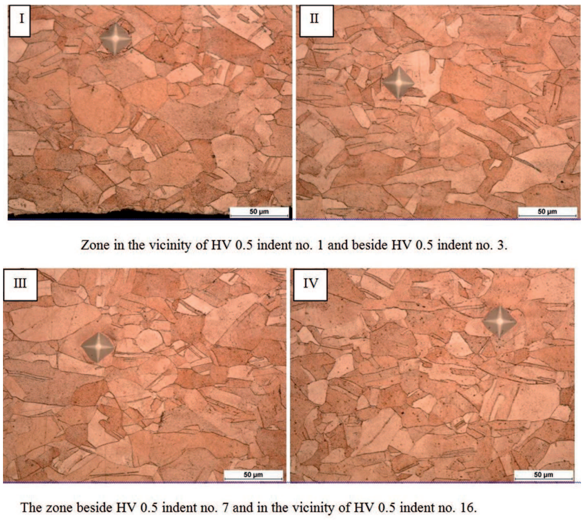


Fig. 6. Copper sample microstructure with locations of HV 0.5 microhardness indents; a) 1 – 12 – microhardness indents in 3 strain zones (division of sample into zones according to figure 3), b) microhardness path over the thickness of the drawn zone, c) indicative results of observations on the thickness (from the "center") of side wall d) I-IV corresponding to indents 1, 3, 7, 16 from Fig. 6 b

The results of observations are shown in Fig. 6, and results concerning the sample after drawing without thinning (indents 1 and 3) are similar to those shown in Fig. 5. This means that the microstructure shown there did not change during the drawing process. Equiaxial grains without visible traces of strain (e.g. elongation and thinning of grains) remain visible. Their shapes indicate a state after recrystallizing annealing.

Stretching of grains in the direction of side wall elongation is visible in the vicinity of indents 6 and 8 (see Fig. 2), and the localization of strain related to a change of the strain path is also observable. An even greater deformation of crystallites intensified by the localization of plastic flow is present beside indents 9 and 12.

The grain orientation indicates the presence of shear bands in the roll formed zone of the material. Two directions corresponding to two symmetrically situated families – shear bands – can be observed. The thickness of the drawpiece wall that was roll formed in one operation is equal to approximately 1.6 mm (and the degree of cold work on the side wall is nearly 40% relative to the initial 2.46 mm).

Figure 7 shows the intensified effect of strain localization and the more intensive presence of shear bands after two CEFF operations relative to zones that were roll formed in one operation (Fig. 6), as indicated by the grain orientation.

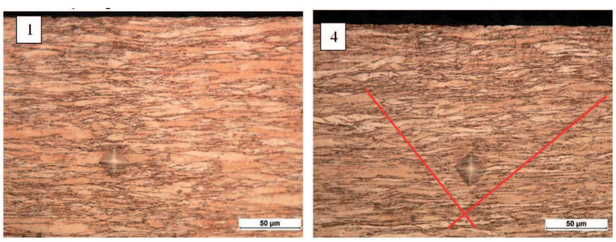


Fig. 7. Copper sample microstructure after two flow forming operations with penetrator indents created during HV 0.5 microhardness measurements

The thickness of the drawpiece wall after two flow forming operations is equal to about 1 mm (and the degree of cold working of the drawpiece side wall is nearly 60%, or over 20% more than after the first operation).

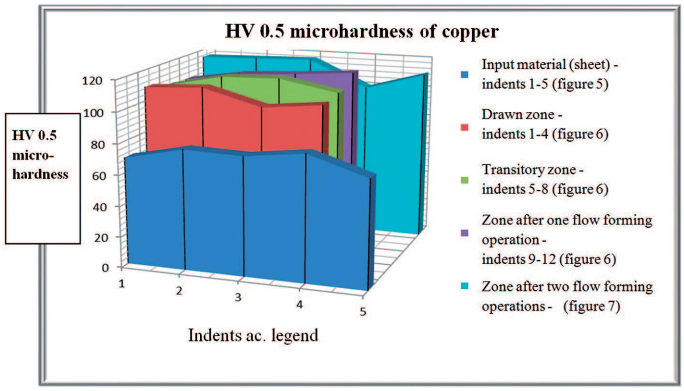


Fig. 8. HV 0.5 microhardness of copper in the form of a sheet, drawpiece, and after one and two operations in the CEFF proces

It can easily be observed (Fig. 8) that the microhardness practically remains at the level of the value after drawing despite the growth of strain during elongation and thinning the side wall during the CEFF process and despite the increasingly distinct formation of a fibrous structure. Also, the second flow forming operation does not cause a significant increase of microhardness. This state can be explained by strong strain localization in shear bands intensified by a change of the strain

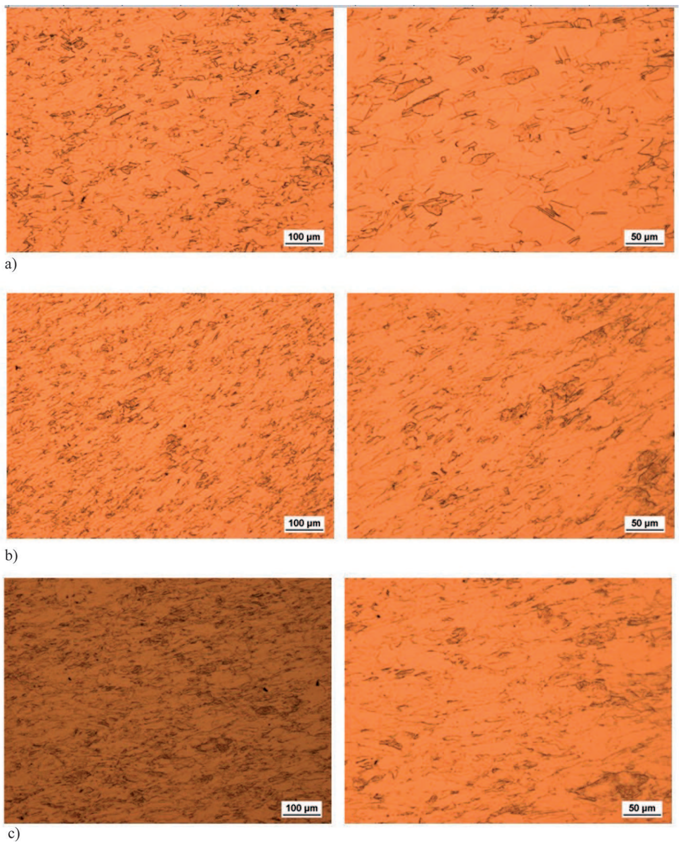


Fig. 9. Structural documentation of sample (as in Fig. 3 and 6 on cross-section) on the sheet surface at magnifications of 10 and 20x, where: a) zone 3 (drawn), b) zone 2 (transitory), c) zone 1 (flow formed)

path [3-4]. It is known that even without an externally forced change of the strain path, shear bands may be present in large numbers in material after significant plastic strain. On the other hand, the fact that a change of the strain path strengthens strain localization in shear bands is undisputable.

Analysis of the data presented in Fig. 8 shows that the significant increase of the material's microhardness can only be ascribed to the drawing operation (HV 0.5 microhardness increases from 69.6-81.6 for sheet in an annealed state to 101-111 for material subjected to plastic deformation). None of the subsequent flow forming operations cause any significant further increase of HV 0.5 microhardness.

Figures 9 and 10 do not make it possible to identify the cause of material microhardness stabilization. The effects of its recrystallization are not observed. Only the occurrence of the recovery of grain interiors (interior "cleaning") is observable, which may be decisive for mechanical properties.

Indicative results of observations of sample 2 using a scanning electron microscope are shown in Fig. 11. They confirm the opinions expressed on the basis of optical examinations.

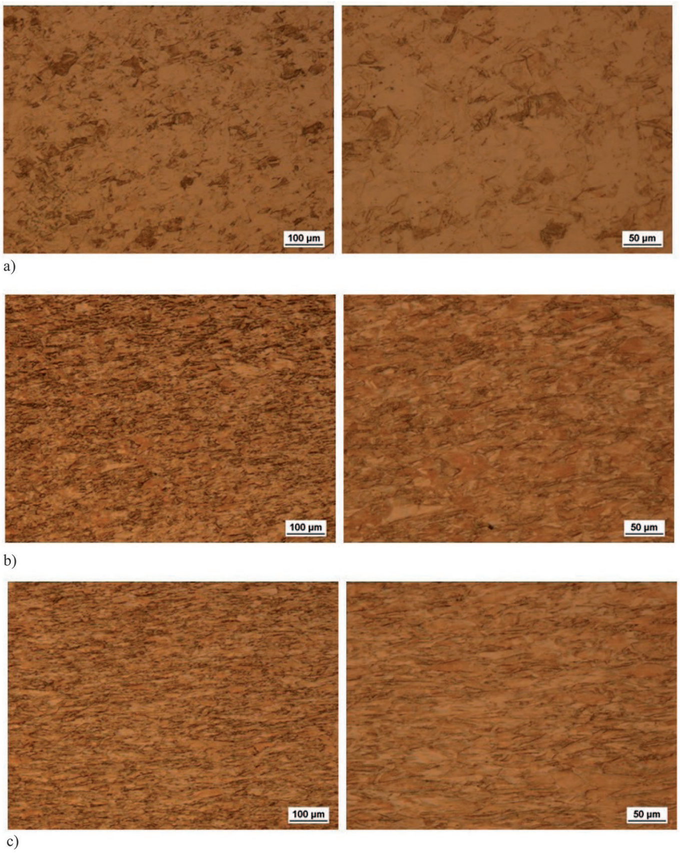


Fig. 10. Results of sample structure observations (as in Fig. 3 and 6) in the third sheet direction at magnifications of 10 and 20x, where: a) zone 3 (drawn), b) zone 2 (transitory), c) zone 1 (flow formed)

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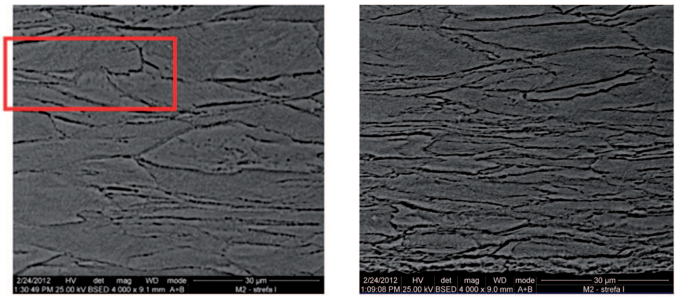

Fig. 11. Indicative images (SEM) of the copper sample collected from zone 1 of sample 2

However in this case, strain localization in shear bands leaves behind "traces" in the structure in the form of ragged grain boundaries resulting from reconstruction of the structure forced by stress relaxation (tendency towards minimization of internal energy). The shear bands themselves are not observed.

5. Conclusions

1. The concurrent elongating flow forming process destined for forming of cylindrical drawpieces causes strong strain localization in shear bands in the structure of copper thanks to the change of the strain path induced during the process.

2. The stabilization of the microhardness of copper is related to the process of grain recovery.

3. The lack of hardening of products made from copper in the CEFF method creates an opportunity for forming long drawpieces with the omission of expensive inter-operational softening heat treatment.

This article was written by the Statutory Research of Deep Drawing Department of Metal Forming Institute in Poznan in 2012.

Acknowledgements

The authors of this article give their sincere thanks to Paweł Ostachowski for his aid in the realization of microstructural observations.

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Received: 20 February 2014.