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FABRICATION OF FINE-GRAINED FLAT PRODUCTS BY CONTINUOUS KoBo METHODS

WYTWARZANIE DROBNOKRYSTALICZNYCH WYROBÓW PŁASKICH CIĄGŁYMI METODAMI KoBo

Fine-grained metallic materials posses several functionally attractive properties making them irreplaceable in aviation, automotive industry, electronics, medicine or sports. Besides very high strength, one of the specific features of fine-grained materials is their possibility to superplastic forming at relatively high strain rates and within the range of medium temperatures, what is exceptionally advantageous for the process of deep pressing. As far as the fabrication of fine-grained metallic products with small overall dimensions has already been quite well developed, some significant problems accompanying of massive products still wait be solve. It also applies to the methods based on SPD (severe plastic deformation), generally found to be the only economically justified.

The paper presents a few new technological solutions based on KoBo method that could be used for refinement of strips and sheets structure, bringing attention to the most important positive and negative aspects that might occur during their implementation. There were also presented the results of mechanical and structural tests of strips made of 7075 aluminum alloy that were rolled with shearing realized through a cyclic change of their insert angle between the rolls.
Keywords: Diagnostics, Recognition, Sound, Nearest Mean, Synchronous motor

Drobnokrystaliczne materiały metaliczne posiadają szereg atrakcyjnych właściwości czyniących je niezastąpionymi w lotnictwie, motoryzacji, elektronice, medycynie czy w sporcie. Obok bardzo wysokich własności wytrzymałościowych, jedną ze szczególnych cech materiałów drobnokrystalicznych jest możliwość ich nadplastycznego kształtowania ze stosunkowo dużymi prędkościami i w zakresie niezbyt wysokich temperatur, co jest wyjątkowo korzystne w operacjach głębokiego tłoczenia. O ile jednak produkcja drobnokrystalicznych wyrobów z metali i stopów o małych gabarytach została już dość dobrze opanowana, istotne problemy napotyka wytwarzanie wyrobów masywnych. Dotyczy to również metod opartych na dużych odkształceniach plastycznych SPD (severe plastic deformation), powszechnie uznawanych za jedyne znajdujące ekonomiczne uzasadnienie.

W pracy przedstawiono kilka nowych rozwiązań konstrukcyjno-technologicznych opartych na metodzie KoBo, mogących służyć rozdrabnianiu struktury taśm i blach, zwracając uwagę na ich pozytywne i negatywne uwarunkowania mogące wystąpić podczas praktycznej eksploatacji. Zaprezentowano również wyniki badań wytrzymałościowych i strukturalnych taśm ze stopu aluminium 7075 walcowanych ze ścinaniem, realizowanym poprzez cykliczne zmiany kąta ich wprowadzania pomiędzy walce walcarki.

1. Introduction

Fine-grained metallic materials, particularly nanomaterials, have not only very attractive mechanical properties such as high strength at ambient temperature and superplasticity under appropriate deformation conditions, but also a very beneficial chemical (corrosion resistance), electrical or magnetic properties. These characteristics make them to be preferred for use in aviation, automotive, electronics and medicine (biomaterials) or sports (devices) [1].

Until recently, the superplasticity has been treated as a unique phenomenon, referring to case of only just a few materials. Currently, it is known that superplasticity has a universal character and applies not only to a wide range of metals and alloys but also to "intermetallics" and "ceramics" [2,3], and the mechanism of superplastic flow of materials is associated with the presence of fine structure (nano- or ultrafine-grain size of less than 10 μm [4-6]). In this context, the sustainability of fine-grained structure of alloys, that is often deformed at elevated temperatures, is a prerequisite and necessary for the practical use of superplastic flow. Dispersed particles in alloys inhibit the mobility of borders and thus limits the growth of grain and allows the superplastic formation of materials at elevated and often at high temperatures.

Despite the fact that the fabrication of fine-grained elements of small dimensions (powders, nano-wires,

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nano-layers) is fairly well controlled, the problem of production of massive fine-grained materials, particularly of large dimensions, has still not been satisfactorily resolved. Moreover, the results of research on the means of manufacturing of fine-grained materials from the solid, liquid or even gaseous state prove, beyond all doubt, that only one group of methods satisfies the requirements for technical and economic grounds justifying the industrial use. It is based on a severe plastic deformation (SPD), which implementation is usually very difficult for conventional low-temperature processing because of reduced plasticity of the material. On the other hand, a high temperature of deformation, although essentially improves the elongation and significantly reduces the flow stress, it creates favorable conditions for the occurence of recrystallization process (dynamic recrystallization), leading to the formation of large grains. Hence, in order to ensure the fine-grained structure, it uses special SPD methods, in particular: high-pressure torsion (HPT) [7-10] and equal-channel angular pressing (ECAP) [11-16] or their modifications [17,18].

However, it should be noted that the ECAP and HPT methods not only require unusual processing equipment and huge pressures but also are characterized by low efficiency mainly due to limited size of the material being deformed in single operation and relatively high rate of scrap production. For this reason, more and more hopes are tied to the use of SPD methods in continuous processes [19]. The problem becomes particularly important when it comes to the production of fine (nano-) grained flat products, such as sheets and strips for deep pressing. However, even within this area there are proposed at least three significantly different solutions namely: i) an accumulative roll-bonding (ARB) [20,21] (Fig.1a), ii) the process of rolling with equal channel angular pressing (C2S2) [22,23] (Figs 1b and c), iii) the continuous method of repetitive corrugation and straightening (cRCS) [24] (Fig.1d).

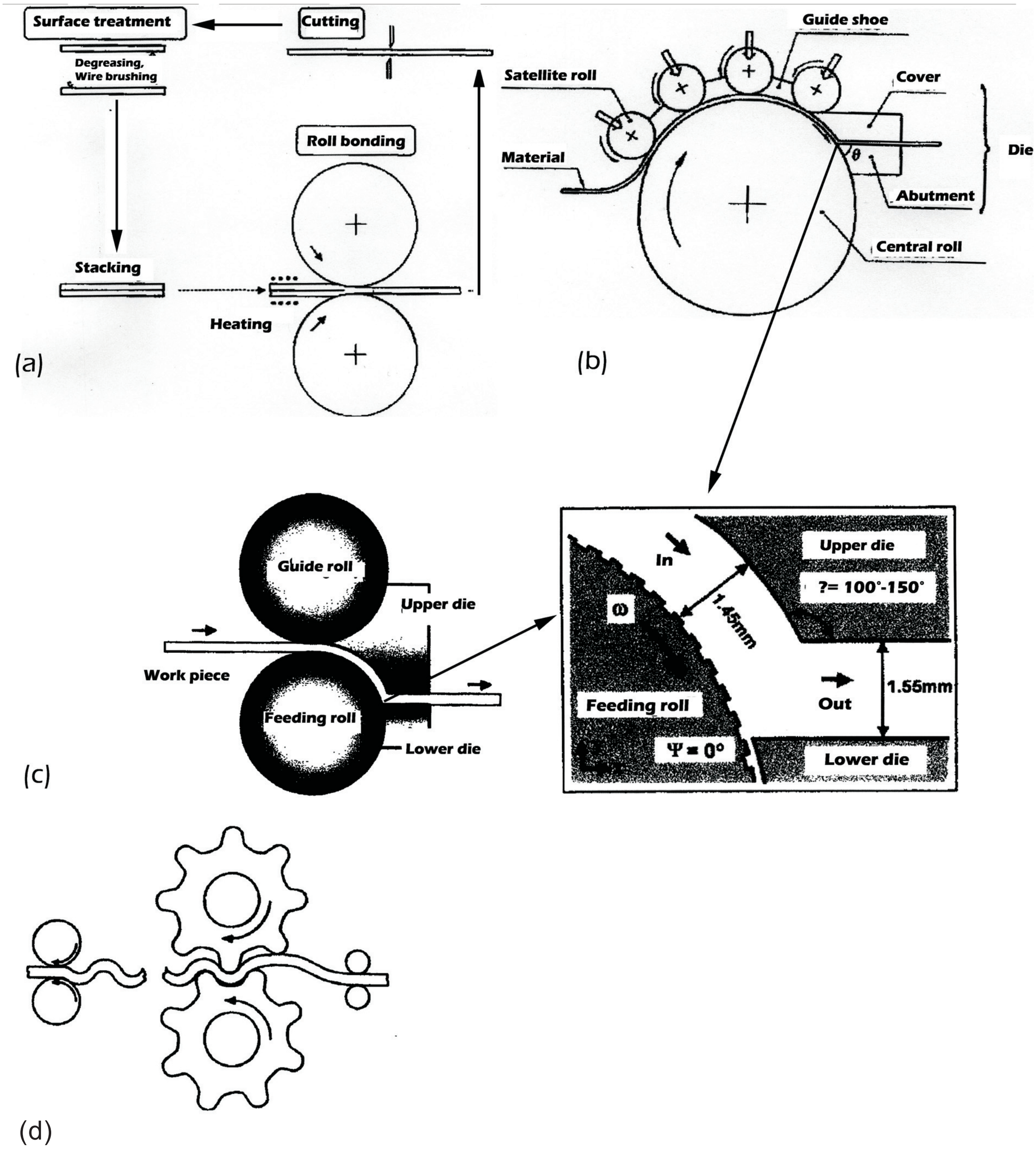
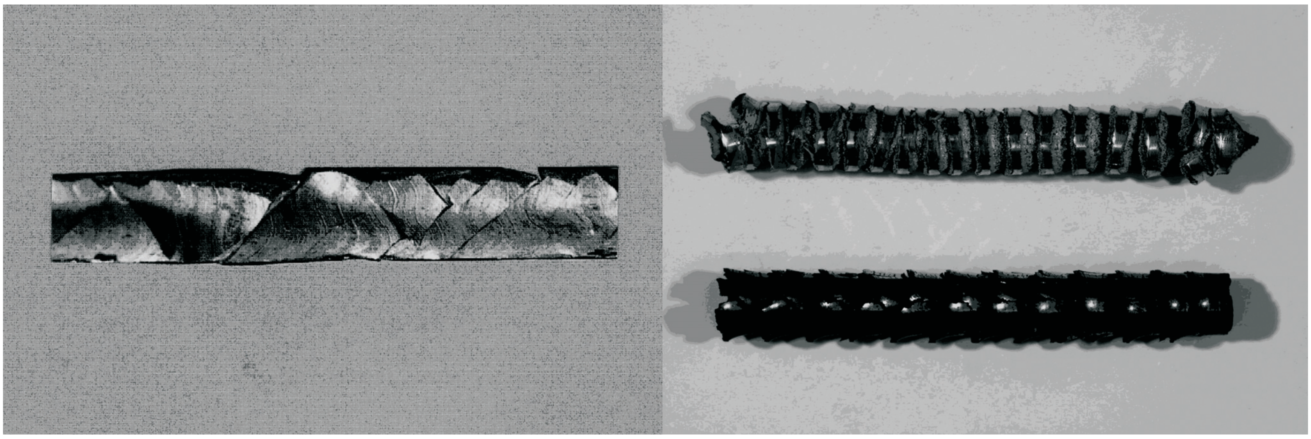


Fig. 1. Methods of continuous rolling: a) ARB [20], b) and c) C2S2 [22,23], d) cRCS [24]

Despite the progressive improvement of SPD continuous methods, there are still many problems associated with their implementation. In particular, the ARB method is not useful for hardly-deformable materials, because of inability to use large strains, in individual passes, guaranteeing sufficient connection of particular layers at low temperature [25]. In addition, after a few passes, the quality of the surface of rolled material could significantly worsen and the sides be cracked. The fundamental problem encountered in the method of C2S2 is the durability of the tools working under tremendous loads and assurance of tightness of the working device, i.e. to prevent uncontrolled flow of metal through a gap between the moving and stationary elements. Also, the execution of cRCS method may run into a significant problems related to assurance of the same strain on the entire length of the strip or sheet (according to schedule of corrugation and straightening), even at precise synchronizing of many passes. On the other hand, the strength and geometry of "teeth" of the roll stand makes the cRCS method suitable only for certain materials and they also must be of low thickness.

From a structural point of view, the deformation of materials using SPD methods is accompanied by change of the deformation path leading to localized plastic flow in shear bands and consequently to the refinement of grains [26]. In the ARB method, it is obtained on the way of suitably large strain, while in the method of C2S2, during the forced pass of the material through the channel bend (a generation of large local shear stress). The cRCS method is directly based on the externally forced changes in deformation path (load scheme).

However, too intense localization of plastic flow is not a desirable phenomenon, since it can lead to decohesion of deformed material and ultimately to its destruction [27, 28]. These negative effects occur not only during the final stage of tension, when a generation of split fracture is very obvious, but also during the rolling (Fig. 2a) or extrusion (Fig. 2b), despite the triaxial compressional stress state present in the latter process.



(a) (b)

Fig. 2. Results of intense localization of deformation visible in the defective products received in the plastic deformation processes: a) side surface of the rolled CuZn37 brass tape, b) a view of conventionally extruded 7075 aluminium alloy (upper sample) and a mixtured of Cu+ 5% Al_2O_3 powders.

In the view of the fact that for the SPD processes it is not possible to avoid the formation of shear bands, such conditions of deformation were desired that would prevent too high strain concentration in an individual band and in a consequence fracture of material, while the total magnitude of material deformation would be achieved on the way of larger number of "weaker" bands engaged. Such a chance is offered in KoBo method (e.g. [29]) applied in the processes of extrusion, forging, rolling or drawing. Using the effect of changes in the deformation path through the additional cyclic movement of the working tools, initiates and quantitatively increases the phenomenon of localized plastic flow in shear bands. Furthermore, as the result of intersection of shear bands, it allows the bands to "cut" the material into blocks (sub/grains), which under appropriate conditions of the process can achieve nanometric dimensions.

The KoBo method has larger, than in conventional processes, number of parameters controlling the deformation process and thus allows to strictly control the accompanying structural phenomena.

2. Rolling with KoBo method

In 1992 the first solution for the rolling of materials utilizing the KoBo method was patented [30] and was implemented on roll stand with additional reciprocal shifting of one of the turning rolls - along its axis (Fig. 3).

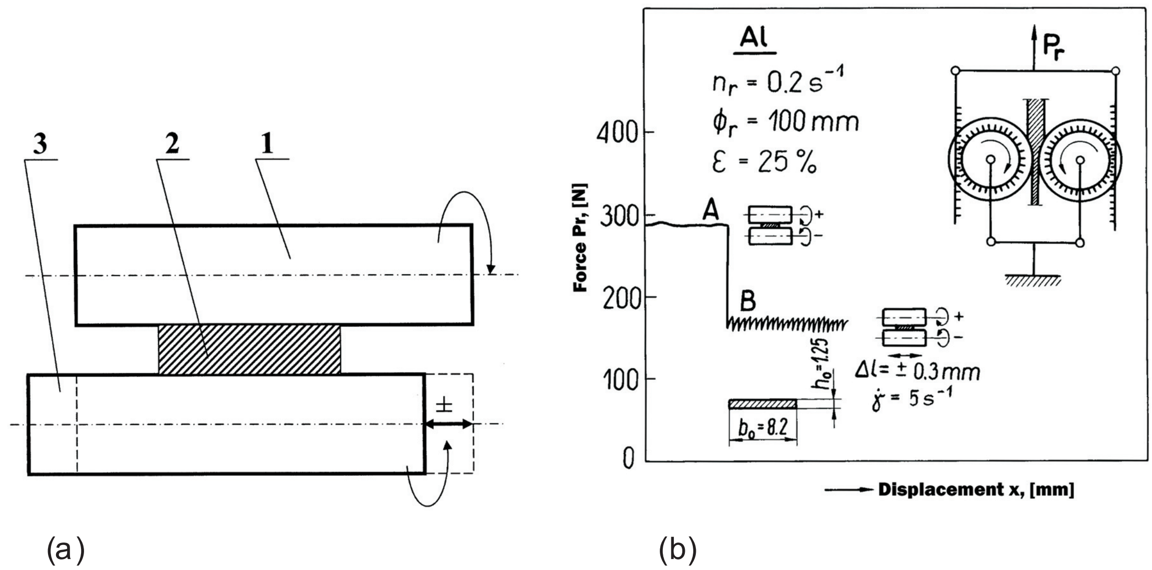


Fig. 3. Scheme of rolling with the KoBo method: 1) upper working roll, 2) rolled material (strip), 3) lower working roll cyclically-moving along its axis (a) and comparison of deformation force Pr in a model of aluminum rolling using conventional "A" and KoBo "B" method (b)

This method, as one of the SPD solutions, causes a change of deformation path, and hence the reduction of pressing force of metal on rolls and results in structural effect in form of refinement of grains [31,32].

A variation of this method is based on the usage of the roll stand with one spherical roll (spherical sector) and the second with variable diameter that matches the first roll (Fig. 4) [33]. Forcing of cyclic changes of the deformation path in this case is easier because it eliminates the undesirable transverse sliding of rolled material between rotating rolls, especially if it is of a large width, as it is possible to occur in case of roll movement along the axis (previous method). Unfortunately, presented methods require not only a specially designed roll stands but also the movement of significant masses of the rolls and it is at high frequency, what is not easy to implement in practice, in particular the industrial one.

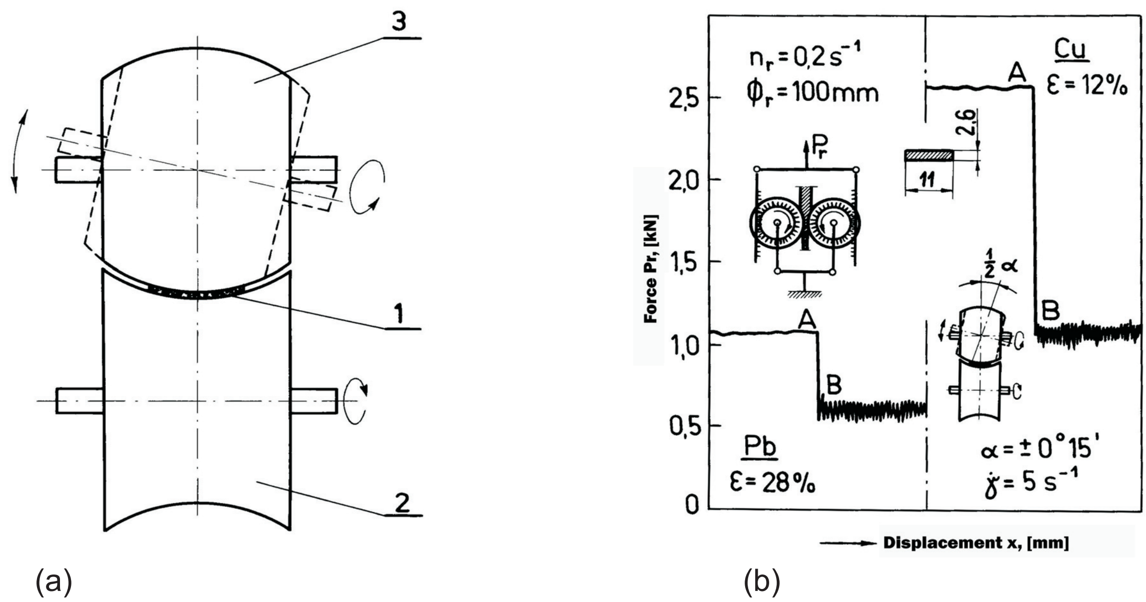
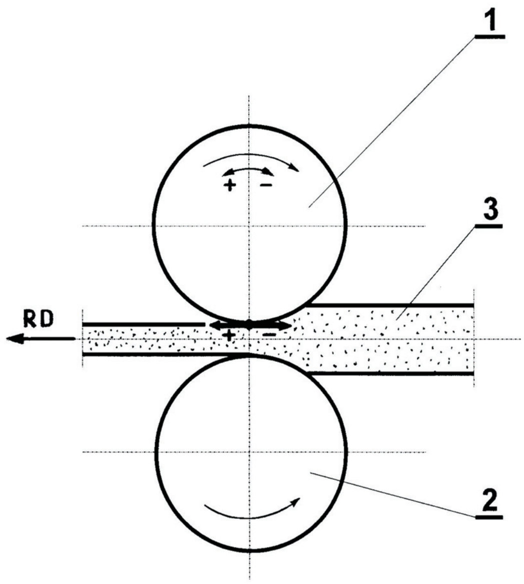
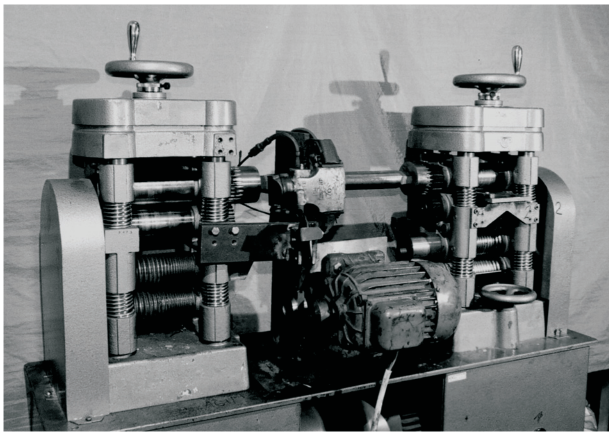


Fig. 4. Scheme of rolling with upgraded KoBo method: 1) rolled material, 2) "reel" roll, 3) swinging spherical roll (a) and the comparison of deformation force Pr in a model of rolling of lead and copper strips using conventional method "A" and KoBo one "B" (b)

Therefore, another proposal to resolve the process of rolling the material in SPD conditions called Cyclicform, does not interfere in the design of roll stand (it is to be carried out on conventional machines), but only requires a modernization of driving systems in such a way, that one of the rolls would accelerate and delay its rotation at the high rate, while the average speed of both rolls remains the same (Fig. 5) [34].





(a) (b)

Fig. 5. Scheme of Cyclicform rolling – one of the solution of KoBo method: 1) cyclically accelerated and delayed upper working roll, 2) lower working roll, 3) rolled strip (a) and a device for this purpose using the drives of two roll stands and a driving system cyclically coupling/uncoupling the upper working roll (b)

The results related to the rolling of copper with Cyclicform method using roll stand with roll diameter of 60 mm and operating at an average speed of 0.5 rev/s and the change of speed of one of the rolls at the frequency of 18 Hz, are shown in Fig. 6.

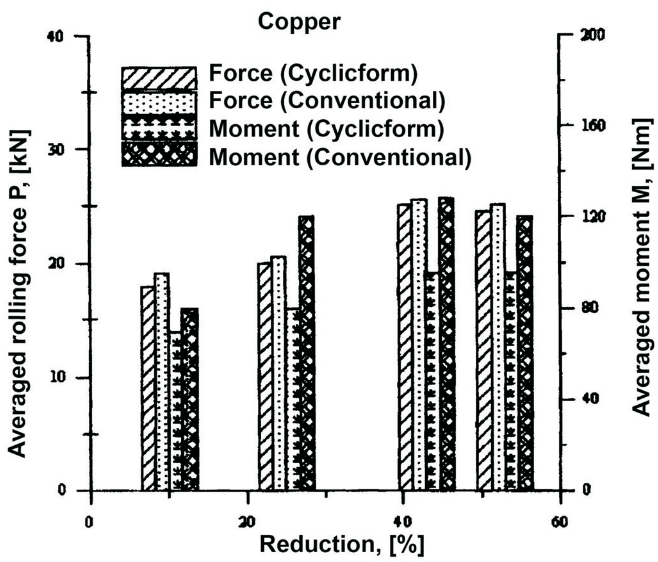
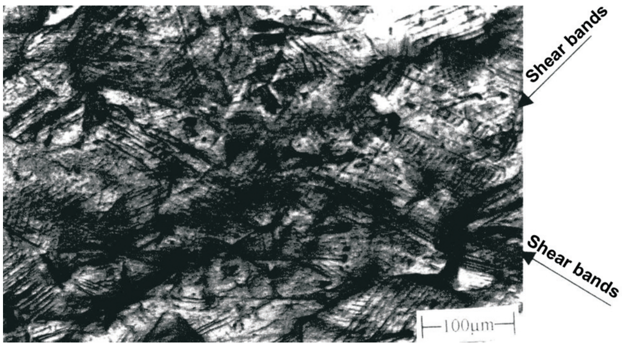


Fig. 6. Comparison of the average values of rolling force P and the average torsional moments M, occurring during the rolling with Cyclicform method and conventional rolling, for strain of 10 – 53% [35]

It is evident in Fig. 6 that initially for strains (10 – 20%), the rolling force and torsional moment increase with the increase of strain to achieve a relative stability in the later stage of the process, both for conventional as well as Cyclicform rolling methods. Significant differences existing between the two methods concern the torsional moment. Its lower value is achieved in case of the Cyclicform method, suggesting its energy-saving character.

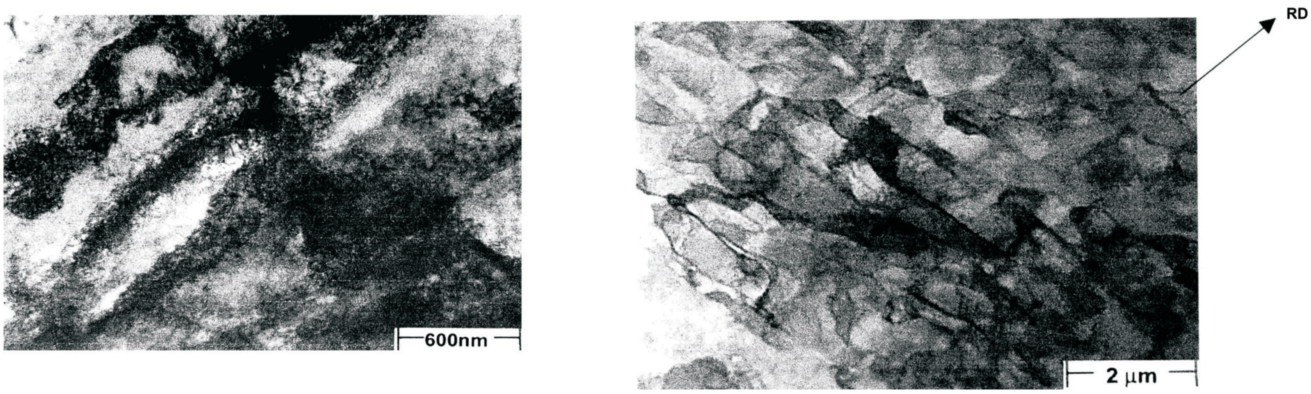
Figs 7 and 8 present the results of structural and microstructural (TEM) observations of rolled samples.



(a) (b)

Fig. 7. Side surface topography with traces of shear bands in copper sample rolled with Cyclicform method with 6% strain (a) and the results of identical observation of copper sample rolled conventionally with 10% strain (b)

A structure of copper rolled with Cyclicform method with 6% strain is decorated with intersecting shear bands, which are not present in copper even after 10% strain obtained on the way of conventional rolling (Fig. 7). On the other hand the microstructural observations (TEM) of copper rolled with 83% strain, in both cases reveal the effects of severe plastic deformation (Fig. 8). However, after conventional rolling dominates cellular structure formed of high density dislocation tangles, while after the rolling with Cyclicform method, the shear bands filling the material contain recovered sub/grains.



(a) (b)

Fig. 8. Microstructure (TEM) of copper rolled with 83% strain: conventionally (a) and with Cyclicform method (b)

Other solutions of KoBo rolling method were based on the assumption of running the process on typical rolling devices and with their original drives. In this case, in order to generate the cyclic changes of deformation path, a rolling adapter was used (e.g. consisting of two rolls of small diameter) which was placed just before the roll stand, giving the rolled material a introductory reverse movement (Fig. 9) [36]

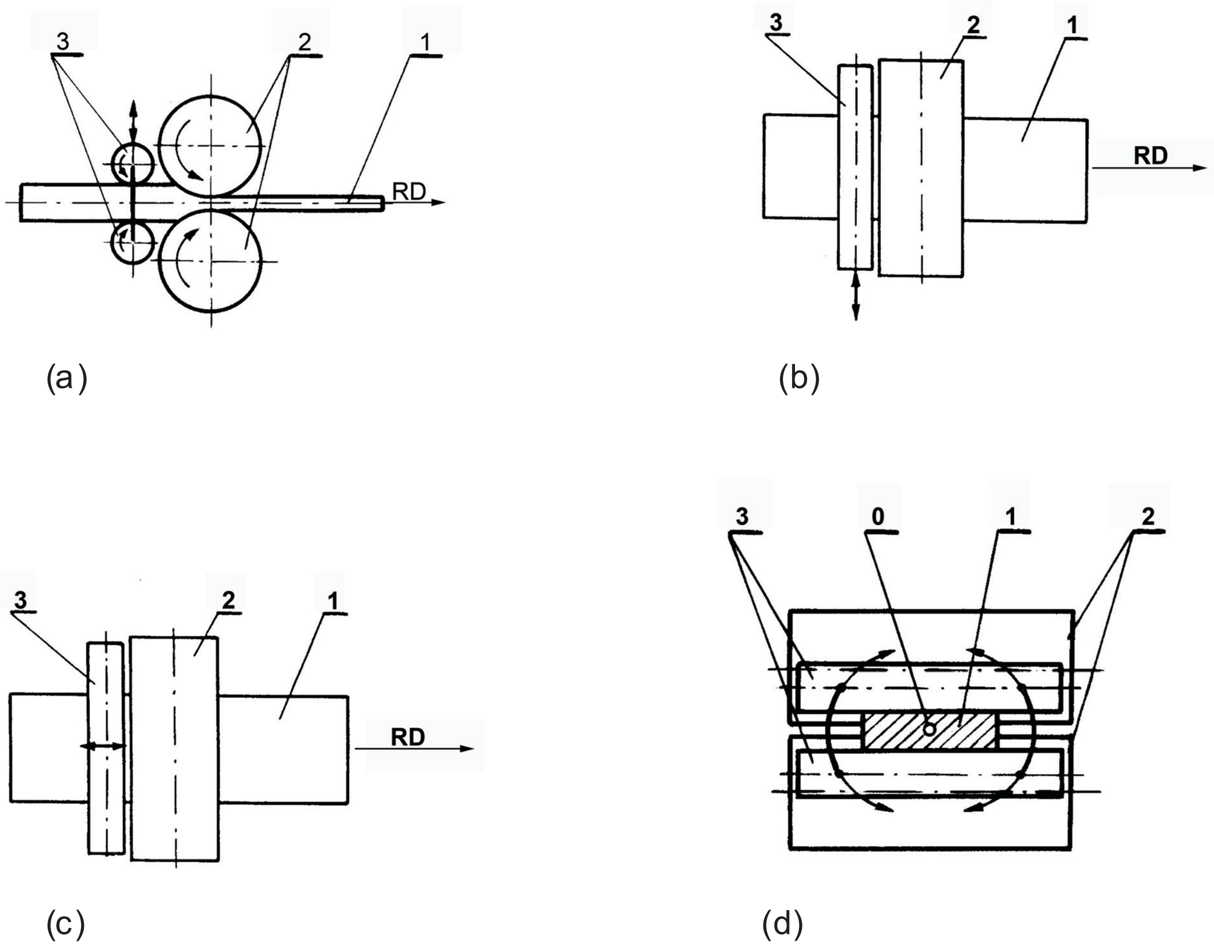
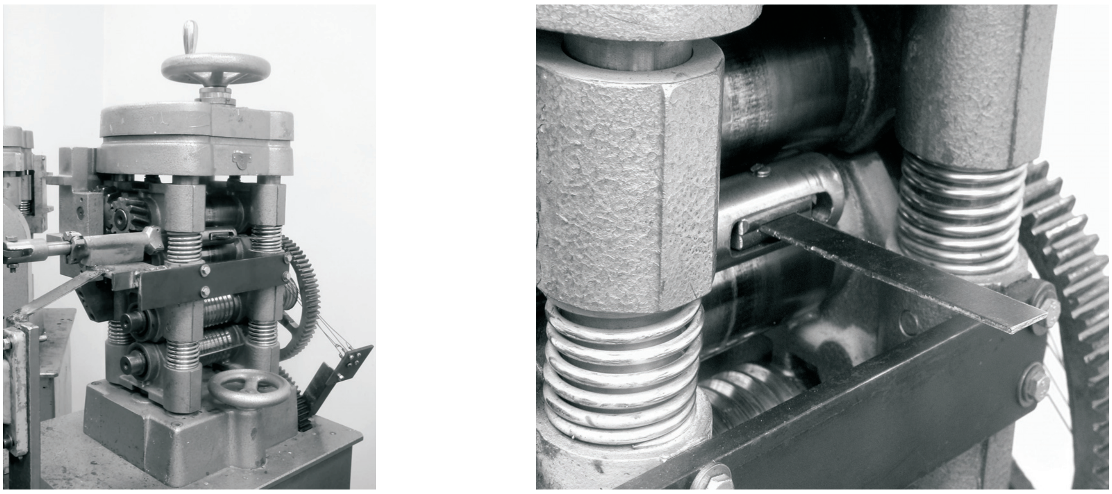


Fig. 9. Examples of rolling carried out under conditions of cyclic change of deformation path (KoBo method) exploit with adapters using different methods of inserting the material between the working rolls: a) two-side flexure (1 – rolled strip, 2 – working rolls, 3 – rolling adapter consisting of two rolls cyclically moving in the plane perpendicular to rolling direction (RD) together with the rolled tape passing between them, b) inserting at variable angle (3 – rolling adapter cyclically moving in the direction parallel to working rolls axis, c) cyclically variable tension (3 – rolling adapter cyclically moving in the direction perpendicular to working rolls axis), d) two-side torsion (3 – rolling adapter cyclically turn around the axis "0")

3. Mechanical properties and the structure of 7075 aluminum alloy rolled by modified KoBo method

The method of rolling with cyclic change of inserting angle of the material between the rolls was used for deformation of the strips made of 7075 aluminum alloy. The research stand working in this scheme is presented in Fig. 10.



(a) (b)

Fig. 10. Research stand designed for rolling of materials (strips) with cyclic change of inserting angle of the material between the rolls (as in Fig. 9b): a) general view, b) view of the rolling adapter (cyclic shifted frame with swinging element)

Samples of strips of 7075 aluminum alloy with composition presented in table 1 and of dimensions 20x2,7x300 mm were submitted to experiments

TABLE 1

Chemical composition of 7075 aluminum alloy used for research

Material	Cu [%]	Fe [%]	Mn [%]	Zn [%]	Mg [%]	Si [%]	Ni [%]	Ti [%]	Cr [%]	Zr [%]
AA7075	1,714	0,367	0,251	5,452	2,339	0,181	0,002	0,2	0,185	0,06

Part of the samples assigned for rolling was at commercial-state (variant I), part was after solution heat treatment from the temperature of 475 °C after 1h of annealing (variant II).

Four rolling schemes (designed A-D) were applied, each time in order to obtain by the samples a total strain of 20%:

- A) rolling with cyclic change of insert angle of the strip (in 1 pass),
- B) conventional rolling (in 1 pass),
- C) mixed rolling (1st pass with 10% – conventionally, 2nd pass – with cyclic change of insert angle of the strip),
- D) conventional rolling in two passes (each pass of 10%).

Rolls diameter was 60 mm, and their speed was 0.5 rev/s (variant 0.5) or 0.7 rev/s (variant 0.7). Insertion angle of the strip between the rolls was changing within the range of ± 12° at the frequency of 22 Hz.

After rolling, part of the samples were aged at the temperature of 150°C for 2h (variant S), while other part was subjected to natural aging (variant N).

The research of so prepared material consisted in measurements of microhardness (μHV_{500}) and first of all in tensile tests carried out at the rate of $1.33 \cdot 10^{-2} s^{-1}$ at the temperature of 20°C, 425°°C and 450°C and structural observations (TEM). The most interesting results are presented below.

The strips after rolling with cyclic change of insert angle (in particular the variant A) had a characteristic appearance, as shown in Fig. 11.

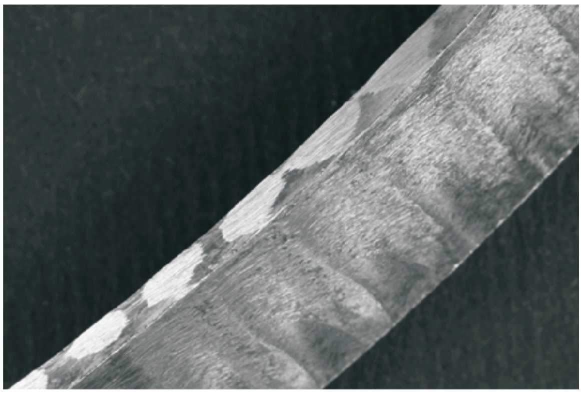
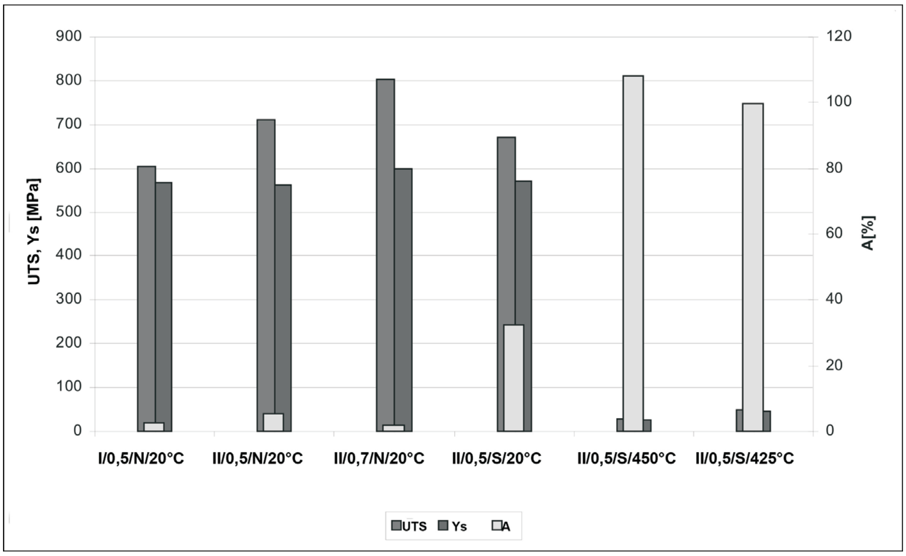


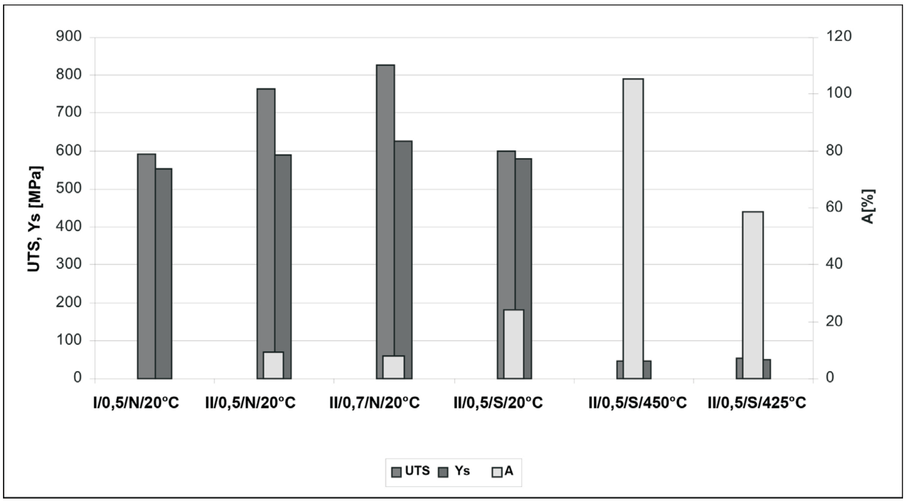
Fig. 11. View of 7075 aluminum alloy strip after rolling in accordance with variant A, using the research stand presented in Fig. 9b

Although the diversification of particular fragments of the sample is visible in macro-scale, the results of microhardness measurements made along its sides (176-181μHV) reveal a significant degree of homogeneity. Also the observations of etched metallographic sections by means of an optical microscope confirm the lack of internal signs of structural diversification.

As it follows from the figures 12a and b relating to mechanical properties of different variants of samples made of 7075 aluminum alloy, the influence of rolling method variant is significantly revealed only in case of samples subjected to tensile test at the temperature 425°C (material marked as II/0.5/S/425°C) and concerns the elongation, which after rolling with cyclic change of insert angle exceeds the value of 99% and is higher by 40% than the one obtained after conventional rolling. This parameter is extremely important in case of further mechanical processing of the alloy in deep pressing. For this reason the mechanical properties of the alloy should not be too high to avoid making difficult the processing, especially if they can be subjected to age hardening after obtaining the final shape of the product.



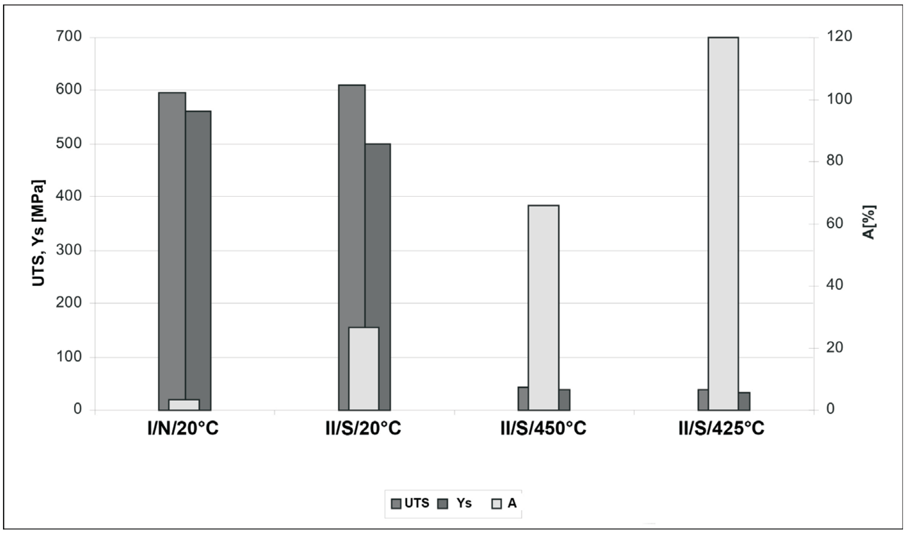
a)



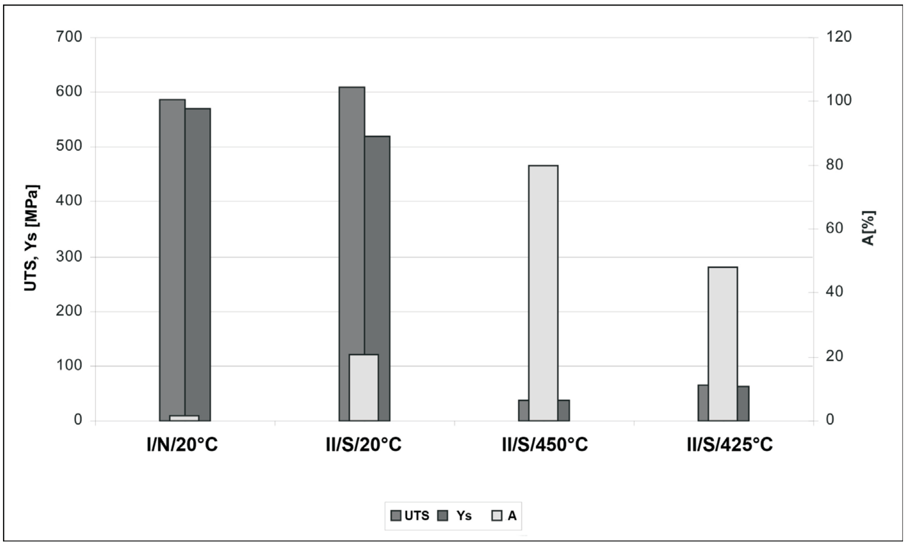
b)

Fig. 12. Mechanical properties of 7075 aluminum alloy strips subjected to different heat treatment and rolled up to 20% strain with KoBo method, according to variant A (a) and conventionally rolling, according to variant B (b)

Even greater diversification, also at the tensile temperature of 425°C, applies to the samples rolled in two passes according to variant marked as II/S/425°C (Figs 13a and b)



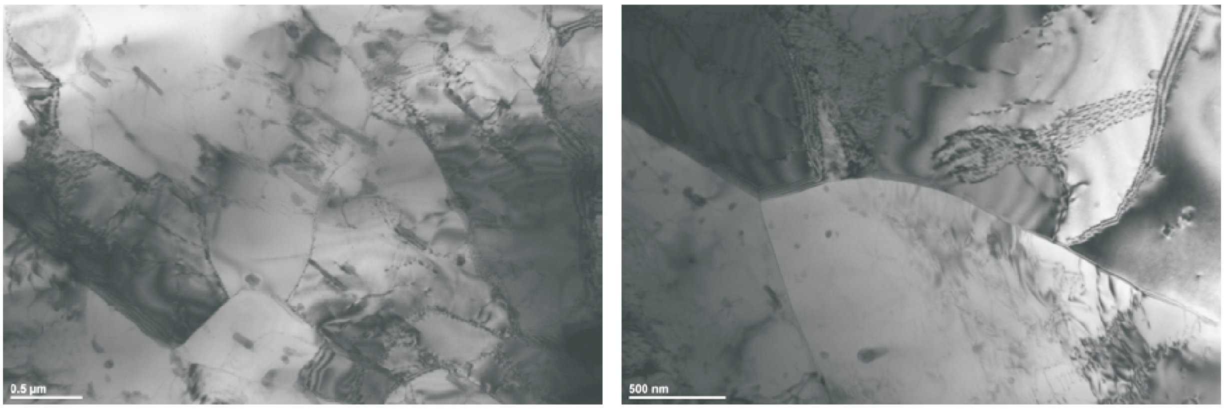
a)



b)

Fig. 13. Mechanical properties of 7075 aluminum alloy strips subjected to different heat treatment and rolled up to 20% strain at the rate of 0.5 rev/s in two passes of mixed method according to variant C (a) and conventionally according to variant D (b)

As far as the conventional rolling realized in two passes allows to obtain the elongation of about 48%, the mixed rolling increases this value up to 120%. The reasons for such behaviour of the alloy, considering also the strength properties, shall be a matter of further research and analysis in structural aspect, which is limited in this work only to samples marked as variant II/0,5/N/20°C in figures 12a and b. Typical microstructures of samples rolled with cyclic change of insert angle and conventionally rolled are presented in Figs 14a and b, respectively.



(a) (b)

Fig. 14. Microstructures (TEM) of 7075 aluminum alloy strips supersaturated from the temperature 475° after 1h of annealing, rolled with 20% strain and naturally aged: a) rolling with KoBo method (variant marked II/A/0.5/N), b) conventional rolling (II/B/0.5/N)

In the first case the alloy consists of refined sub/grains with the size close to 1 µm. However the dominant is the structure made of subgrains with various misorientation angles (Fig. 14a). The alloy rolled in conventional way is characterized by lower degree of refinement (grains of the order of a few micrometers) and significantly higer fraction of large angle grains (Fig. 14b).

4. Summary

Present study documents the progress in practical realization of rolling methods with cyclic change of deformation path (KoBo methods). Basing on it one may assume the existence of real chances of discovering of even more advantageous solutions allowing to fabrication of fine- grained products.

The study also presents the possibility to affect the structure and mechanical properties of 7075 aluminum alloy by its rolling realized with cyclic change of insertion angle of materials between the rolls.

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