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Twist Channel Multi-Angular Pressing (TCMAP) as a method for increasing the efficiency of SPD

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Abstract. The paper proposes a new variation of the application of SPD methods. For the suggested TCMAP (twist channel multi angular pressing) technology a larger strain is imposed more effectively while homogeneity of material is increased. The number of passes needed to obtain the ultra-fine to nano-scale grains in bulk materials can be significantly reduced. Commercially pure Al (99.97%) was used for the experimental verification of the suggested process. The deformation parameters of the process were also described using a numerical simulation based on a FE analysis. The predicted value of imposed strain after a single pass reached approximately 2.7. Deformation homogeneity was confirmed by micro-hardness tests. Due to the designed shape of the channel both ends of the processed sample are defined by a higher imposed strain and vertical faces.

1. Introduction

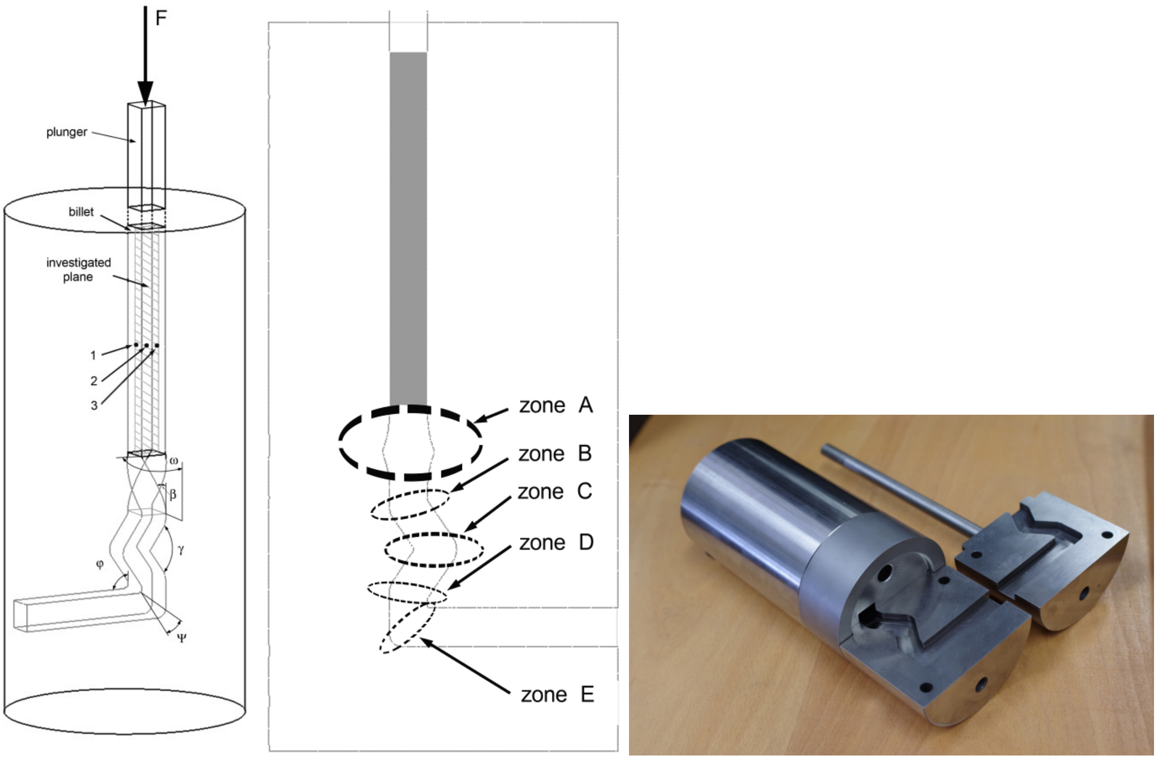
Increase of mechanical properties of metal materials due to increasing requirements is among the main objectives of contemporary research. One of the ways to achieve favourable mechanical properties while retaining acceptable costs are the severe plastic deformation (SPD) technologies, which are based on grain refinement and enable to decrease the grain size even to the nanoscale. Various SPD processes, such as the equal channel angular pressing (ECAP) [1,2] method and its modifications (TCAP [3,4], NECAP [5]), the torsion extrusion (TE) [6], the accumulative roll bonding (ARB) [7] or the high pressure torsion (HPT) [8,9], which is the most effective from the grain refinement point of view, have already been quite extensively investigated.

The ECAP technology belongs to the firstly developed SPD processes and is still one of the most frequently used ones. Its relatively effortless applicability for various purposes, such as bulk materials mechanical properties increase [10], consolidation of powder materials [11] or "recycling" of waste material in the form of chips [12], are among the reasons. Several deformation paths the efficiency is strongly dependent on have been proposed, the influence of the paths was investigated in several previously published studies [13, 14]. The attention has been focused on possibilities of increasing the efficiency of the process as well. A higher strain can be imposed into a material by increasing the number of passes [15] or by implementation of a (partial) back pressure [16,17], but it would be advantageous to achieve a high strain value during a single (continuous) pass extrusion in order to increase the efficiency of the process while decreasing the costs. As was already mentioned, various modifications of the method, such as the torsion extrusion, or the twist channel angular pressing (TCAP) have been already designed. When compared to the ECAP, imposing a considerably higher strain into a sample during a single pass is enabled by the TCAP process. Moreover, the equivalent strain (ES) distribution through the cross-section of the extruded sample is more homogenous, therefore efficiency can be increased with lower costs by decreasing the total number of passes. Detailed information on the TCAP process can be found elsewhere [3,4].

With the objective of further increasing the TCAP process efficiency, the twist channel multi-angular pressing (TCMAP) technology has been designed. For this purpose the TCAP conception was modified by implementation of another deformation zone. The aim of this paper was to observe the influence of the die channel geometry on the equivalent strain value and its homogeneity throughout the sample, the material plastic flow stability and the punch load. The process was analysed using the finite element method.

2. Experimental

An analysis was carried out in order to characterize the TCMAP process with regard to the influence of the die channel geometry on the final ES value and deformation homogeneity throughout the cross-section of the sample, punch load and plastic flow of the material. The TCMAP die is schematically depicted in Fig. 1a.



(a) (b) (d)

Fig. 1 (a) scheme of the TCMAP process; (b) TCMAP – longitudinal section through the centre of the die with depicted individual deformation zones (c); the TCMAP die used for the experiment

The first part of the paper was focused on numerical analysis of the TCMAP process. The TCAP method was simulated as well in order to compare the efficiency of the TCMAP process; for both the processes the defined conditions were the same.

For investigation of the deformation behaviour of the material $\upsilon = 3\ mm\ s^{-1}$ extrusion velocity and $\mu = 0.02$ Coulomb friction were defined. The friction coefficient value was chosen on the basis of several previously published studies, in which comparisons of values predicted by numerical simulations and obtained experimentally with the help of punch loading measurement had been in accordance. Influence of the die geometry defined by the ω angle (the twist rotation angle), β angle (the twist slope angle), γ angle (the angle between the individual parts of the embedded deformation zone), φ angle (the angle between the individual parts of the channel) and ψ angle (the outer corner angle) (Fig. 1a) on the above mentioned parameters was investigated. The study was also aimed on characterization of the influence of the individual deformation zones sequence on the extruded material deformation behaviour. The TCMAP process was defined with *A-B-C-D-E* deformation zones sequence (Fig. 1b).

The second part of the paper dealt with an experimental realization of the TCMAP technology. The focus of this part was on verification of the used FE model. The extruded samples were the same as in the numerical simulations, i.e. from the commercially pure Al (99.97%) with chemical composition of 0.125Fe; 0.10 Si; 0.020Zn; 0.020 Cu; 0.015Mn; 0.015Mg; 0.015Ti (in wt.%) and of a square cross-section with dimensions 12 mm x 12 mm x 130 mm. Before the practical experiment the Al samples were subjected to annealing at 400°C for 1 hour. To objectively compare the predicted and experimentally obtained results both the dies were defined by 40° β angle, 90° ω angle, 110° γ angle, 90° φ angle and 20° ψ angle (Figs. 1a and 1c). Extrusion was carried out on a hydraulic press at 3 $mm\ s^{-1}$ extrusion velocity at room temperature (20°C); as a lubricant MoS_2 was used. During the experiment punch load values were observed and subsequently used for verification of the predicted results. To confirm the predicted results micro-hardness at the cross-section of the sample was measured as well.

3. FE modelling

The analysis was performed using the Forge 2009 software; all the components of the assembly were created using the ProEngineer software. An elastic-plastic material model was used to predict the deformation behaviour of the material after a single pass. During the simulations the Newton-Raphson convergent algorithm and automatic re-meshing were activated due to the supposition of a large shear deformation occurrence. The die and the punch were defined as rigid bodies, whereas the billet was considered to be a deformable body. The billet mesh consisted of 48,675 nodes and was created using tetrahedral elements. The stress-strain curves used for the investigated material (Fig. 2) had been determined using a torsion test performed on a SETARAM servo-hydraulic torsion plastometer at three different strain rates (0.1 s^{-1} and 1 s^{-1}) at room temperature. The geometric dimensions and mechanical properties for the analysis and for the subsequent experiment were defined in the same way; thereby a direct comparison of the predicted and experimental results was enabled.

The data obtained from the torsion test were inserted into the material flow stress database of the software and to describe the material behaviour during the extrusion the Haensel – Spittel equation (1) was used.

$$\sigma_f = A e^{m_1 T} T^{m_9} \varepsilon^{m_2} e^{m_4 / \varepsilon} (1+\varepsilon)^{m_5 T} e^{m_7 \varepsilon} \dot{\varepsilon}^{m_3} \dot{\varepsilon}^{m_8 T} \tag{1}$$

Where ε is equivalent strain, $\dot{\varepsilon}$ is equivalent strain rate, T is temperature and $A, m_1, m_2, m_3, m_4, m_5, m_6, m_7, m_8, m_9$ are regression coefficients, the values of which were 151.32 MPa, -0.00253, 0.21142, 0.03177, -0.00654, m_5-m_9 were 0.

The boundary conditions defined in the simulations were the parameters describing temperature behaviour of the aluminium sample and the die, the ambient temperature (20°C) and the number of passes (single pass in this case). Young's modulus, Poisson's ratio, thermal expansion, thermal conductivity, specific heat, emissivity and density were defined as the follows: 72 (GPa), 0.3, 2.4 × 10^{-5} (K^{-1}), 228 (W/m K), 894 (J/kg K), 0.03 and 2700 (kg/m^3).

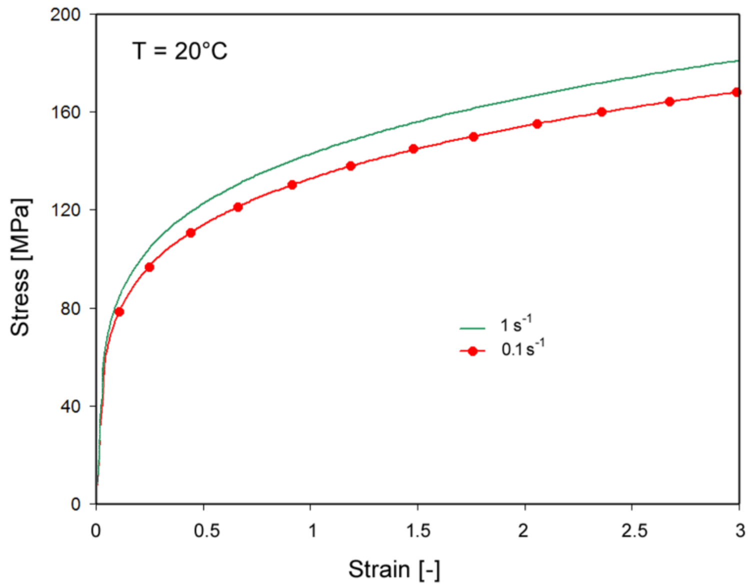


Fig. 2 stress-strain curves used for the simulations

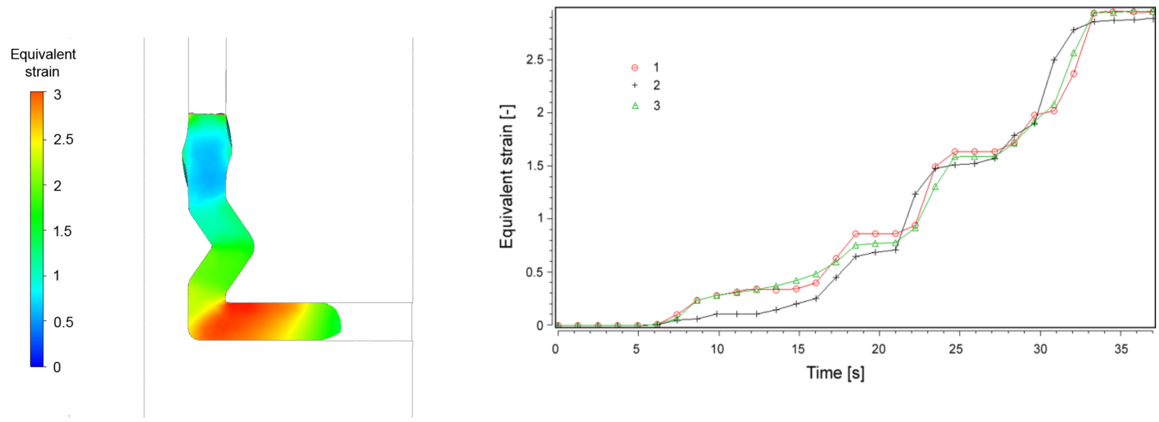
Three separate areas (points 1, 2, 3) positioned on a plane passing through the centre of the sample parallel to its longitudinal axis (Fig. 1a) were selected to better characterize the individual observed parameters of the extruded sample. The analysis was focused on investigation of the influence of the die geometry on the ES value and its homogeneity throughout the cross-section of the sample and the punch load needed for the extrusion.

4. Results and Discussion

4. 1. Equivalent Strain

The average ES value after a single TCMAP pass was ~2.76 (Fig. 3a). Each of the deformation zones was of a different influence on the final strain value, the influence of the deformation zones sequence is characterized by the ES value gradual increase; non-equivalent strain increments are evident in the graphical dependence in Fig. 3b. The deformation influence of the twist (*A* zone) in the primary extrusion period is obvious especially in the surface regions of the sample, whereas the central region of the sample is delayed. On the other hand, the central region of the sample is deformed the most in the following *B* and *C* zones. Due to a change in the material flow vector in the *B* and *C* zones the ES distribution throughout the cross-section of the sample gets more homogenous, therefore deformation gradient throughout the cross-section decreases. A relatively lower deformation can be noticed in the central region of the sample after passing through the *D* zone. In this extrusion phase the peripheral regions are deformed more intensively and the ES homogeneity throughout the cross-section of the sample decreases again. In the following channel bending shear deformation zone, i.e. the *E* zone defined by the φ angle, homogeneity throughout the cross-section of the sample increases, moreover the ES value increases once again due to the imposed shear strain in the main deformation zone (MDZ) of the die. Influence of the MDZ shape and localisation on the imposed strain had already been proven by several ECAP and TCAP analyses carried out before [3, 18, 19].

Following this deformation zones sequence, the ES homogeneity throughout the cross-section of the sample after one pass is very high; this finding is in accordance with the TCAP process. A difference from the ECAP process is in the ES value and distribution in the end of the sample. A relatively high ES value (~1.7), significantly higher than for the TCAP or the ECAP processes, is imposed in end part of the sample. Only a small change in the shape of the outgoing end of the extruded sample occurred for the TCMAP method, which is similar to the TCAP process.



(a) (b)

Fig. 3 (a) 2D section and equivalent strain (ES) contours in the sample after TCMAP; (b) time dependence of ES homogeneity

The ES time dependences of the extruded sample central areas for the TCMAP and the TCAP processes were compared (Fig. 4), from the Figure differences in the values of individual increments, as well as in the total ES values, can be seen. For the TCMAP the ES increase, especially in the primary extrusion stage, is gradual, whereas for the TCAP process the curve is smoother. Therefore, the difference in the strain homogeneity between the TCMAP and the TCAP processes is not only in the number of deformation zones, but also in their sequence.

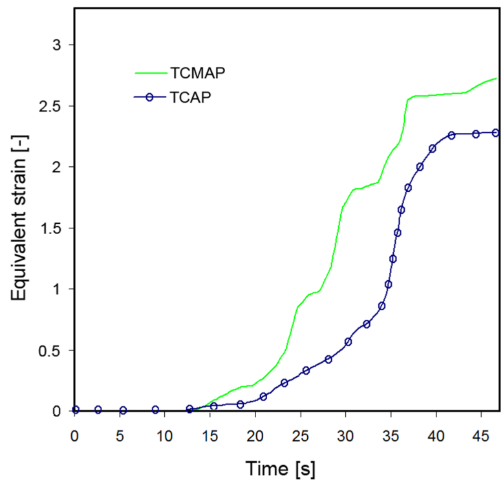


Fig. 4 ES time dependence during TCAP and TCMAP

4.2. Plastic flow

A grid was superimposed in the plane passing through the centre of the sample to evaluate the plastic flow of the material during the TCMAP process, the grid was modelled very fine with individual cells' dimensions 0.5 x 0.5 mm.

The dead zone angle is one of the often discussed factors. In most of the works carried out before a presupposition of a negative influence of the dead zone on the ES value and homogeneity was introduced [20-22]. It is obvious that no dead zone occurred during the

TCMAP process in any of the deformation zones. During the TCMAP extrusion, the left and right halves of the extruded material accelerated alternatively (Fig. 5). In front of the last shear deformation zone (*E* zone), the flow in the left half of the material was faster than in the right one. This was caused by the geometry of the vertical part of the channel. The material flow in the left half of the channel was faster due to a shorter trajectory; the flow changed when the material was passing through the intersection of the horizontal and vertical section of the channel, therefore in the MDZ the upper (former right) region of the material was accelerated when compared to the bottom (former left) region. Following this trend, the shape of the end of the extruded sample was influenced favourably. The material flow development is obvious from the deformation (slope) of the superimposed grid individual cells. From the oscillations of the superimposed grid horizontal lines the cell deformations are evident especially in the bottom half of the sample and locally in the upper one. The oscillations are not localized on the surfaces, but in under-surface layers.
After the TCMAP extrusion the shape of the end of the sample was completely different when compared to the TCAP extrusion. Moreover, during the TCAP process occurrence of relatively small oscillations in the whole cross-section of the sample are obvious.

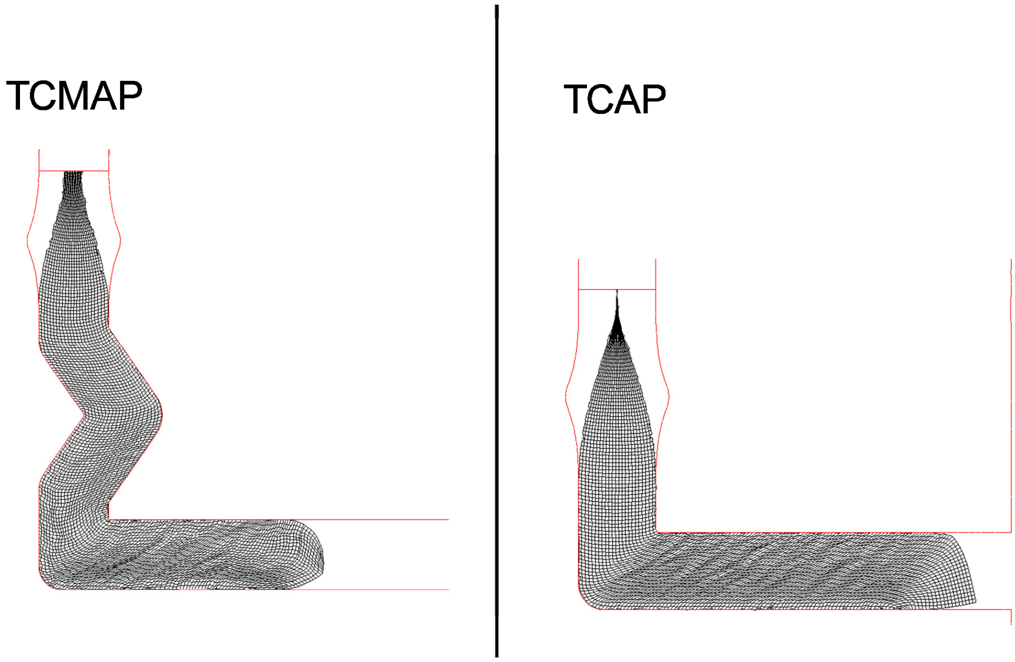


Fig. 5 plastic flow pattern for the modelled variants

4.3. Punch load
Punch load is among the important factors influencing the TCMAP process application, therefore the punch load during the extrusion was observed. In the time dependence in Fig. 6, higher punch load values for the TCMAP than for the TCAP process can be seen. The punch load increased of 58% for the TCMAP when compared to the TCAP, the highest punch load was observed during the sample deformation in the *E* zone. On the other hand, a short-time punch load decrease occurred in the area between the deformation zones *D* and *E*. The most probable reason for the decrease was filling of the *E* zone with material; the contact surface area between the extruded material and channel walls locally decreased due to the unfilled channel deformation zone.

As was proven by the experiment, the predicted punch load values correlated with the experimentally obtained data. Compared to the analysis, during the experiment a lower punch load increase was observed during sample passing through the *A, B, C* zones, whereas the punch load was higher during sample passing through the *E* zone; after reaching the peak load value the load decreased relatively fast during the following extrusion stage. Differences between the predicted and experimentally obtained values can be caused by several factors, such as sensors accuracy, material properties, friction variability, or the used mathematical model and possible simplifications.
The punch load for the TCMAP process was relatively higher than for the TCAP, but it can be influenced e.g. by reduction of the outlet channels length. By such a modification friction and thus deformation resistance of the extruded material can be influenced.

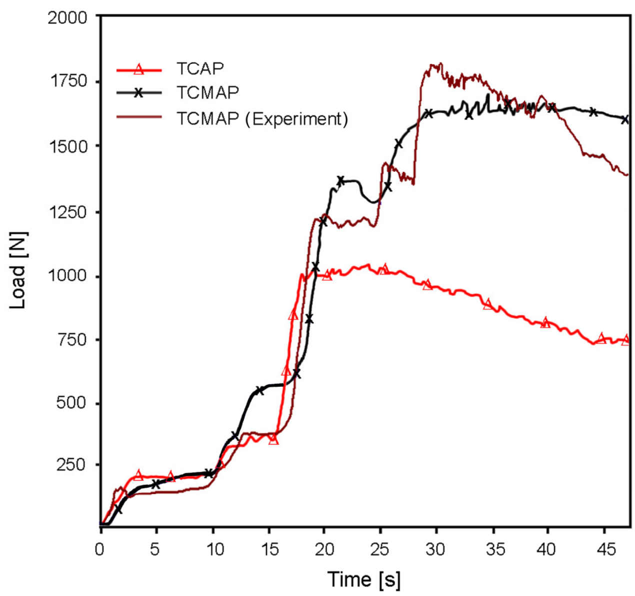


Fig. 6 dependence of punch load for the individual variants

4.4. Micro-hardness
After a single pass, micro-hardness on a cross-section of the sample was measured; measurements were performed in both the diagonals for a more precise evaluation (Fig. 7). In the graphical dependence in Fig. 7 the highest values are obvious in the upper region of the sample, nevertheless only a slight difference was observed between the maximal and the minimal measured micro-hardness values when compared to the central area. On the other hand, a possible influence of the surface cross-section areas, where the indentations were localized very near to the diagonals ends, must be taken into account. Despite this, only a little decrease in micro-hardness was observed. This conclusion refers to a relatively good correlation between the micro-hardness and the predicted ES distribution in the extruded sample. After the deformation the micro-hardness increased to the average value of 90 HV, which is a 97 % increase when compared to the state before deformation.
On the basis of the obtained data the TCMAP process can be considered as a suitable SPD process from the point of view of achievement of a high ES value and its homogenous distribution. Among the main factors influencing processed material deformation behaviour is the die geometry. The results can be significantly influenced by a suitable selection of the deformation zones sequence.

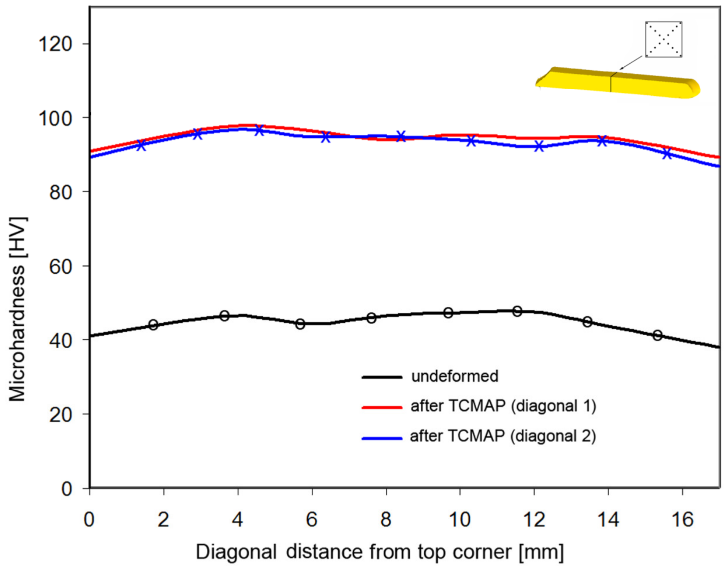


Fig. 7 micro-hardness measurements

5. Conclusions

The paper deals with numerical simulation of a newly designed TCMAP SPD process. The main focus is on evaluation of efficiency of the process considering the value of imposed strain, stress state or material flow. The objective of the subsequent experiment was to verify the predicted results, which can be defined as follows:

- The distribution of the deformation imposed into a sample during the TCMAP process is of a high homogeneity, the strain maximal values are about ~ 3.
- During the TCMAP process no dead zone occurs, which enables to obtain a more homogenous strain distribution.
- By a suitable design of the TCMAP die channel tensile stresses in the extruded material can be eliminated, therefore a danger of material cracking is decreased.
- The TCMAP die geometry enables to impose a high value of strain into a sample without significant changes of the shape of the cross-section and the end of the extruded material.
- A higher value of the strain imposed during the TCMAP extrusion is compensated with a higher punch load.
- The experimental micro-hardness values throughout the cross section of the deformed sample correlated relatively well with the predicted strain values.

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Corrigendum: Twist Channel Multi-Angular Pressing (TCMAP) as a method for increasing the efficiency of SPD

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