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On the Tool Stress Analysis in Twin Parallel Channel Angular Extrusion

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Abstract

Twin Parallel Channel Angular Extrusion (TPCAE) is a newly presented Severe Plastic Deformation (SPD) technique in which two specimens can be processed simultaneously. This method is capable of processing more volumes of materials in addition to less energy consumption. In the present work, stress analysis of tools in this method was conducted using DEFORM 2D finite element software package. Moreover, in order to compare the results with the stress configuration in the conventional Equal Channel Angular Extrusion (ECAE) process in parallel channels, named Single Parallel Channel Angular Extrusion (SPCAE), stress analysis was also conducted with the same processing condition as TPCAE simulation. The results illustrate that TPCAE is a method with lower magnitudes of stress concentrations in the die and lower overall stress magnitudes in the punch with respect to the SPCAE. In addition, it was found that on the contrary to SPCAE, there is a symmetrical stress distribution in the punch and die in TPCAE, bringing about more lifetime for this method.

Nomenclature

$2D$	Two dimensional	σ	Effective stress
ε	Effective strain	σ_y	Stress along Y axis
X, Y	Cartesian coordinates	dx	Linear increment along X axis
x	Distance of any increment from the origin	b	Thickness of the punch
M	Moment		

Abbreviations

UFG	Ultra-fine grained	SPD	Severe plastic deformation
ECAE	Equal channel angular extrusion	HPT	High pressure torsion
TE	Twist extrusion	ARB	Accumulative roll bonding
SPCAE	Single parallel channel angular extrusion	SSE	Simple shear extrusion
TPCAE	Twin parallel channel angular extrusion	FEM	Finite element method

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1. Introduction

Nowadays, ultra-fine grained (UFG, 100-1000nm) structures [1] have attracted great interest because of the unique combination of mechanical properties due to the role of grain boundaries based on the Hall-Petch relation [2]. Severe Plastic Deformation (SPD) techniques are the well-known top-down approach to fabricate UFG bulk structures [3]. In these techniques, intense plastic strains are imposed during particular metal forming processes without any cross-sectional changes in the dimensions of specimens [4]. To date, several SPD methods [5] have been introduced, among them are Equal Channel Angular Extrusion (ECAE) [6, 7], High Pressure Torsion (HPT) [8], Twist Extrusion (TE) [9, 10], accumulative roll bonding (ARB) [11, 12], and simple shear extrusion (SSE) [13], and multi-directional forging [14]. ECAE is one of the most popular ones in which the material is pressed through a facility containing two channels intersecting at a certain angle [6]. Several modifications have been carried out in order to eliminate the limitations of this method, such as rotary die ECAE [15], the side-extrusion process [6], and using a die having multiple passes [6]. ECAE in parallel channels is another development in which a die facility has parallel inlet and outlet channels bringing about two shearing events through a single pass [16].

Some work was conducted to investigate the flow behavior in this technique and determine the optimal geometry in the die design, including the intersection angle of the channels and displacement between two parallel channels [17, 18]. In a recently published work by Abdi and Ebrahimi [19], a new development of ECAE in parallel channels was introduced, named Twin Parallel Channel Angular Extrusion (TPCAE), which is capable of processing more volume of materials and bringing about more tools stability. In that work, the flow pattern and strain state were investigated experimentally and numerically using Finite Element Method (FEM) analysis. In addition, comparison with the conventional ECAE in parallel channels, named Single Parallel Channel Angular Extrusion (SPCAE), from the viewpoint of load needed to accomplish the processes was conducted [19, 20]. Moreover, the feasibility of producing UFG bulk structure by TPCAE processing of aluminum samples was studied in another work using X-ray analysis [21]. In the present paper, tool stress analysis during deformation in the TPCAE process is studied and compared to the SPCAE process. According to the comparison of die and punch stresses between two methods, stability of the tools in TPCAE method is illustrated more with respect to the SPCAE method.

2. Materials and Methods

The commercial FEM package, DEFORM 11, was considered to simulate and study the stress state in the process. Considering that the material flow was constrained laterally in the die and the materials can just flow longitudinally, the simulation can be considered in the plane strain state. Therefore, the simulations were conducted making 2D models. The die details for both SPCAE and TPCAE methods, as can be seen in Fig. 1, are considered according to the previous work [19]. Aluminum specimens with a width of 10mm and a height of 60mm were considered in the inlet channels, as shown in Fig. 1. D2 steel was considered as the material of die and punch with the elastic behavior definition for both methods. The friction factor and stress-strain relationship for the aluminum samples were defined as 0.1 and $\sigma = 106\varepsilon^{0.347}$(MPa), respectively. 4-node linear 2D elements were used to mesh the billets, punch, and die. Smaller meshes are generated at the punch outer edges and sharp corners of die deformation zones. The simulations were conducted at room temperature without considering heat transfer. The lagrangian approach with the Newton-Raphson iteration method was used in the finite element simulations. The dies were fixed in any rotation and displacements along X and Y directions. The punch was kept moving in the inlet channel for 55mm with a velocity of 0.2mm/s.

3. Results and Discussion

Firstly, two steps of deformation were chosen in order to investigate the stress analysis of dies and punches during deformation. The first step, which is illustrated in Fig. 2, is related to the die displacement of 35mm when the occurrence of two shear events by their passage through rotations of each channel reaches the steady state. The second step, which is shown in Fig. 3, is related to the die displacement of 53mm, which equals the final steps of simulation. Both Fig. 2 and Fig. 3 compare the distribution of effective stresses imposed on the dies and punches through the processing of the samples in SPCAE and TPCAE methods. This paper is concentrated on the stress analysis of the tools; therefore, it is tried not to focus on the stress distribution in the samples. However, this point can be mentioned that the maximum stresses in the samples are made at the shear events in both methods, which align with the maximum strain magnitudes at both shear events in any channels. Shear events coincide on the theoretical shear planes which are considered theoretical shear lines in the present work due to the 2D simulation. The deformed specimens, theoretical shear planes, and strain distribution in the specimens can be found in the previous work [19].

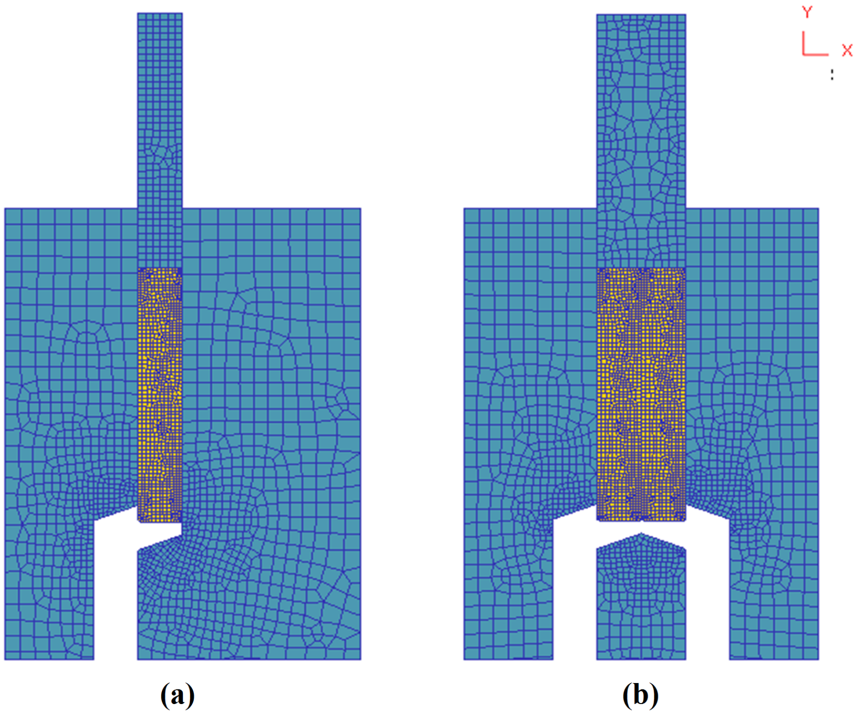

Fig. 1. Processing details and mesh generations of tools and specimens, a) SPACE method, b) TPCAE method.

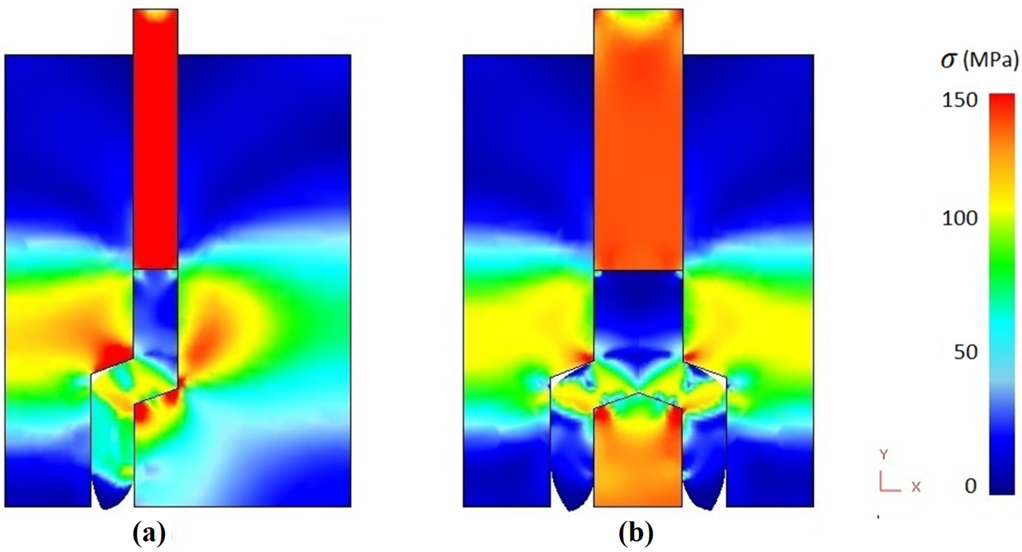

Fig. 2. Effective stress distribution at the first step (35mm die displacement), a) SPACE method, b) TPCAE method.

At the first step, the stress imposed on the die in the SPCAE method (Fig. 2a) is generally higher in comparison to the TPCAE one (Fig. 2b). In addition, there is a symmetrical stress distribution in the latter method concerning the asymmetric distribution in the former one. Stress distributions at the second step are limited to the die regions around the deformation zones (Fig. 3a and 3b). At this step in the SPCAE method, there is a milder asymmetrical pattern of stress with respect to the first step. Additionally, there is a nose in TPCAE in which stress is made due to the movement of the specimens in the inlet channel, which is obvious at both steps.

There are some die corners in contact with the samples at which absolute maximum stresses are made at both steps and both methods. For further investigations, some paths are defined from these corners at the die surface to the depth of the die and stress distributions are determined along these paths. The paths were placed with 55° deviation from the Y axis. Fig. 4 and Fig. 5 show these paths and related stress distributions for both methods at the first and second step, respectively. For both methods, path 3 is located parallel to the inlet and outlet channels in order to better investigate the stresses imposed to the die. Approximately, there are similar trends of stress distribution in all paths. The maximum stress is made at the surfaces of the dies with sudden reductions occurring in the 5-8mm distance from the surfaces, except in path 3 in TPCAE method due to the different design of this method.

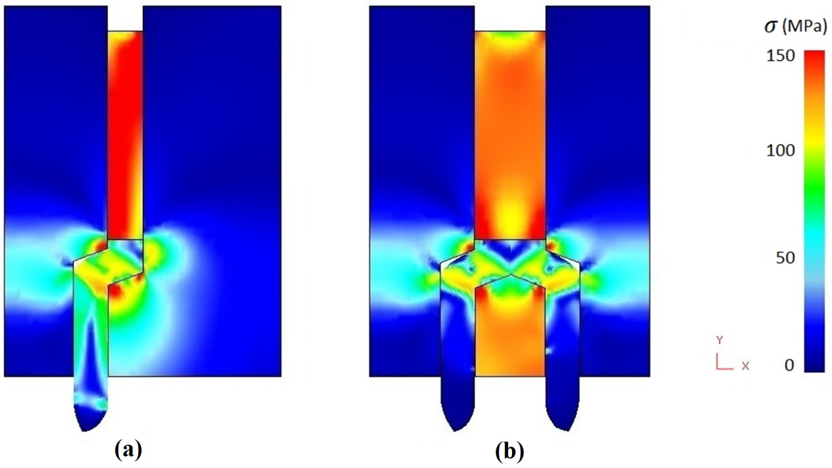

Fig. 3. Effective stress distribution at the second step (53mm die displacement), a) SPACE method, b) TPCAE method.

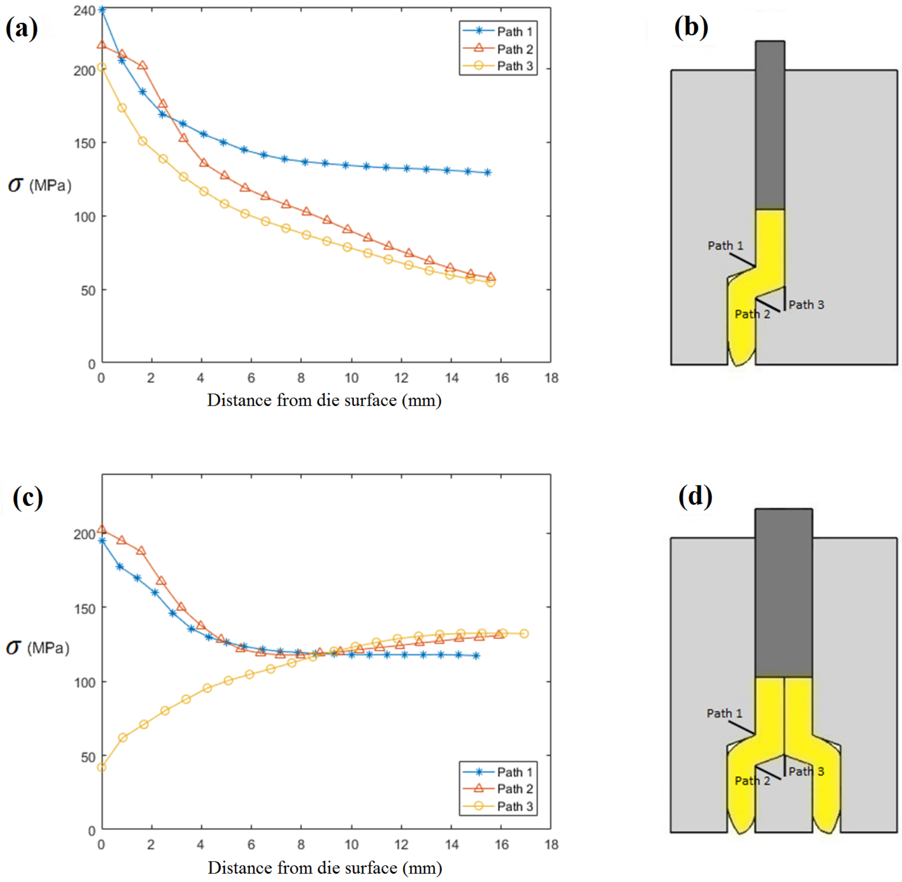

Fig. 4. Effective stress profiles at the first step at different paths, a) SPACE method, b) SPACE method, c) TPCAE method, and position states of the specimens in the processes and definition of paths for both methods, d) TPACE method.

In TPCAE, the samples move in a way that they are not in contact with a rigid fixed sidewall but with another sample that moves itself with the other sample. The samples can have the role of the side wall for each other since there is not any sliding between them, leading to the elimination of stress concentration at the nose tip of the die. Therefore, the stress distribution at path 3 for the TPCAE method includes very low stress of 40MPa at the die surface and constant stress of 120MPa at the nose body (Fig. 4c and Fig. 5c). The stress magnitudes do not change from the first to the second step, meaning that the stress state of the nose tip is stable through the whole stages of deformation in TPCAE method.

In the first step, the maximum magnitude of stress belongs to the path 1 in SPCAE method which is around 240MPa and minimum stress concentration is not lower than 200MPa (Fig. 4a). On the other hand in TPCAE method, the maximum stress does not exceed 200MPa (Fig. 4c). Hence, it can be said that the maximum stress in TPCAE method is approximately 40MPa lower than the one in SPCAE method at the first step. This difference reduces to 20MPa at the second step, where the maximum stress is near 200MPa in the SPCAE method (Fig. 5a), while the one in the TPCAE method is near 180MPa (Fig. 5c). Hence, it can be concluded that the maximum stress concentrations at the die corners in SPCAE method are higher than the ones in TPCAE method.

The next point which should be considered is that there are sudden reductions of stress in SPCAE at the first step, except for path 1 due to the effect of lateral pressure imposed by the specimen in the inlet channel, as illustrated in Fig. 4a. On the other hand, there are no sudden stress changes along all paths in the first step of the TPCAE method, as shown in Fig. 4b. The reason for path 1 is the same effect of lateral pressures, as well as path 1 in SPCAE. The reason for path 2 and 3 is the existence of the nose beneath the inlet channel, to which the vertical and lateral pressures of deforming specimens are imposed. At the second step, the lateral pressures beside the inlet channels are approximately eliminated owing to the fact that deficient amounts of deforming materials have remained in these channels; therefore, there are sudden stress reductions at all paths in the SPCAE method (Fig. 5a) and path 1 in TPCAE method (Fig. 5b).

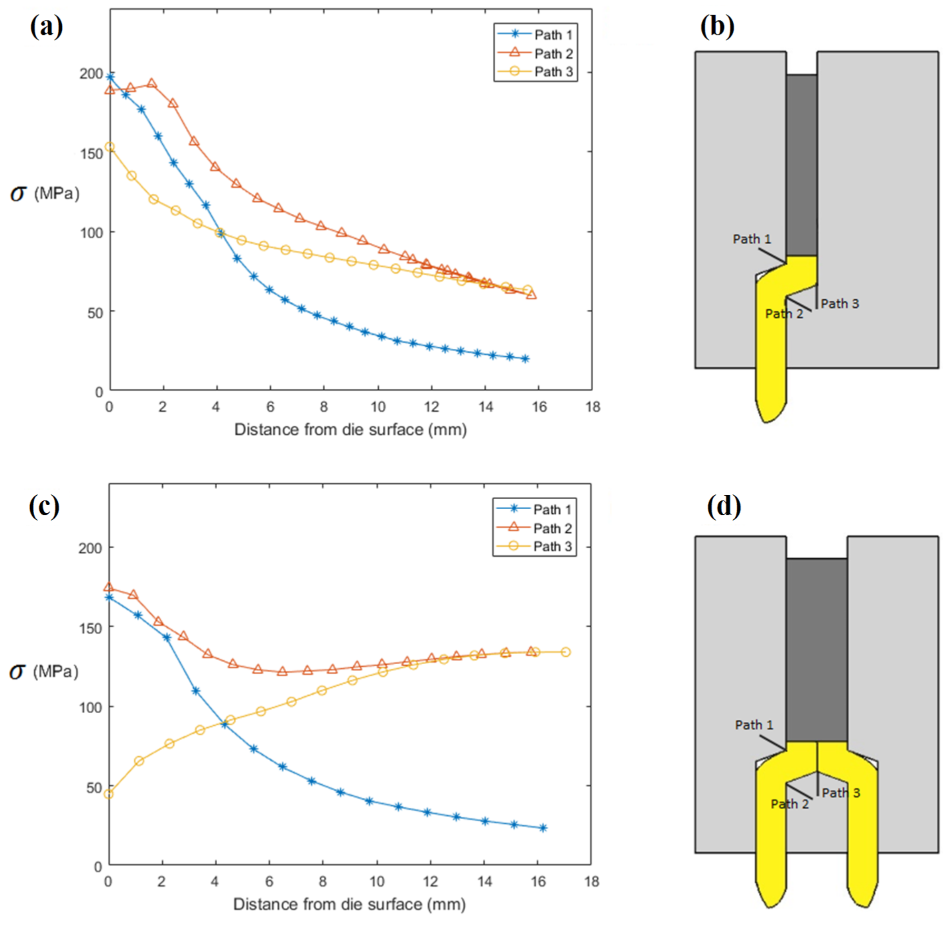

Fig. 5. Effective stress profiles at the second step at different paths, a) SPACE method, b) SPACE method, c) TPCAE method, and position states of the specimens in the processes and definition of paths for both methods, d) TPACE method.

In the latter method, the paths 2 and 3 are the ones at which there are no sudden changes due to the existence of the nose in this method. Generally, it can be said that the stress field is more distributed in the later method rather than the former one, which is an advantage of the TPCAE method with respect to the SPCAE one.

Verification of the stress field results obtained from the FEM simulation should be conducted in order to validate the simulation results. Verification can be conducted by the comparison of the experimental and simulated stress along Y axis, named σ_y, for the punch through TPCAE process. Considering the uniform distribution of the stress throughout the punch, the experimental stress is calculated by the division of the experimental force imposed by the mechanical screw press to the cross-section of the punch. The force displacement curve during deformation presented in the previous paper can be used since all the details in the simulation are consistent with that work [19]. On the other hand, the simulated stress is obtained at the centroid of the punch from FEM simulation. Fig. 6 illustrates the comparison of simulated and experimental stress during deformation.

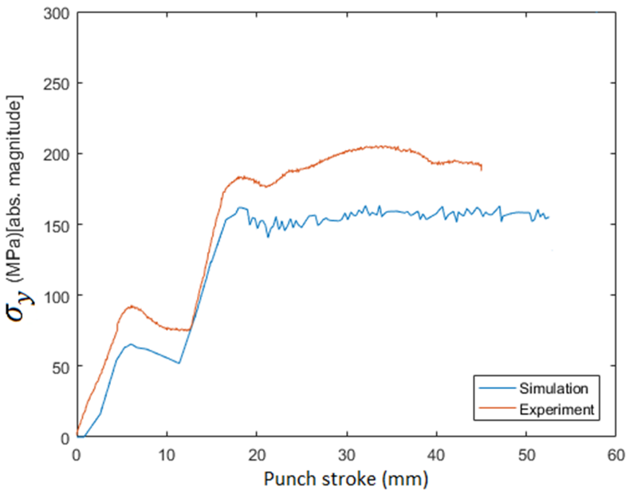

Fig. 6. Experimental and simulated stress along Y axis for the centroid of the punch during deformation in TPCAE method.

As can be seen in Fig. 6, the same trend exists between the simulation and experiment. There is a good agreement for the initial steps of deformation. However, the simulation underestimates the real stress in the punch for approximately 20 percent in the last steps. The reason is that in plane strain analysis just the effect of the friction on the lateral surfaces in the die has been taken under consideration, while the two frictional surfaces in the XY plane are eliminated and consequently, the friction forces produced by these surfaces have not been under consideration. However, the simulation results are reliable since the same trend in the experiment has been predicted with some deviation of stress magnitude. Hence, the conducted simulation can be used for comparison of TPCAE and SPCAE methods.

For stress investigation of the punch in both methods, it can be found from Fig. 2 and Fig. 3 that the overall effective stress magnitudes in the TPCAE method are around 25MPa (15 percent) lower than SPCAE one at the first step. Moreover, the asymmetric pattern of stress is obvious in the SPCAE method and the symmetric pattern in TPCAE one.

In the previous work [19], the stability increase of the punch in the TPCAE method was discussed from the viewpoint of the moment of inertia and Euler's formula [22]. From this viewpoint, the increase of punch cross-section area causes the increase of moment of inertia and increases the critical load above which the punch collapses. Moreover, it was claimed that the punch in the SPCAE method has instability because of the asymmetric stress distribution of underlying materials causing a bending moment, while the one in the TPCAE method has more stability because of the symmetric stress distribution in the underlying materials compensating the opposite bending moments [19]. Here, this is possible to prove this claim by stress analysis of the punches in two methods. For this purpose, the Y component of stress at the second step, which is approximately the final step of the simulation, is used to calculate bending moments applied to the punches. Fig. 7 and Fig. 8 illustrate the stress distribution at the second step along the Y axis in the punch for SPCAE and TPCAE methods, respectively.

In the (a) parts of the figures, the absolute magnitudes of stress below the punches, and in the (b) parts, the stress contours over the entire bodies of punches are illustrated. In the (b) parts, the negative sign of the stresses shows that these are imposed in the opposite direction of the Y axis. As can be seen, the stress distribution in the line AB has an asymmetric pattern and an absolute maximum of 212MPa in the SPCAE method (Fig. 7a), while the stress distribution in that line has a complete symmetric pattern and an absolute maximum of 198MPa in TPCAE method (Fig. 8a). The stress contours over the entire body of punches show the more symmetric pattern in the later method (Fig. 8b) than the former (Fig. 7b).

The accumulation of bending moments applied to each punch can be calculated as below [22]:

$$M = \int x\sigma_y(bdx) \tag{1}$$

where dx is a linear increment along X axis on the line AB in Fig. 7 and Fig. 8, b is the thickness of the punch (taken as 10mm according to the reality), σ_y is the stress component along Y axis applied to the line AB, and x is the distance of any increment to the center of the line AB, named point O here. It is obvious that bending moments applied to the right side of point O are clockwise, while the bending moments applied to the left side are counterclockwise. Therefore, the more the applied Y stresses have a symmetric pattern along line AB, the more the accumulation of opposite incremental bending moments would be close to zero. The accumulation of incremental bending moments were determined about 780N.mm and 64N.mm for the SPCAE and TPCAE methods, respectively.

From the above results, it can be concluded that the symmetric design in the TPCAE method makes the symmetric pattern of stress in the materials beneath the punch and subsequently, a symmetric pattern of stress in the die and punch. So, not only does the stability of the punch increase from the viewpoint of Euler's formula in TPCAE method, but it increases because of the symmetric design of this method as well. Hence, it can be said that in addition to the aforementioned advantages of the TPCAE method as a new SPD technique in the previous studies [19, 21], it brings about more benefits with respect to the SPCAE, including lower stresses in the punch and lower stress concentrations in the die, which are beneficial for increasing the lifetime of the tools and assisting the process of industrialization of this SPD technique.

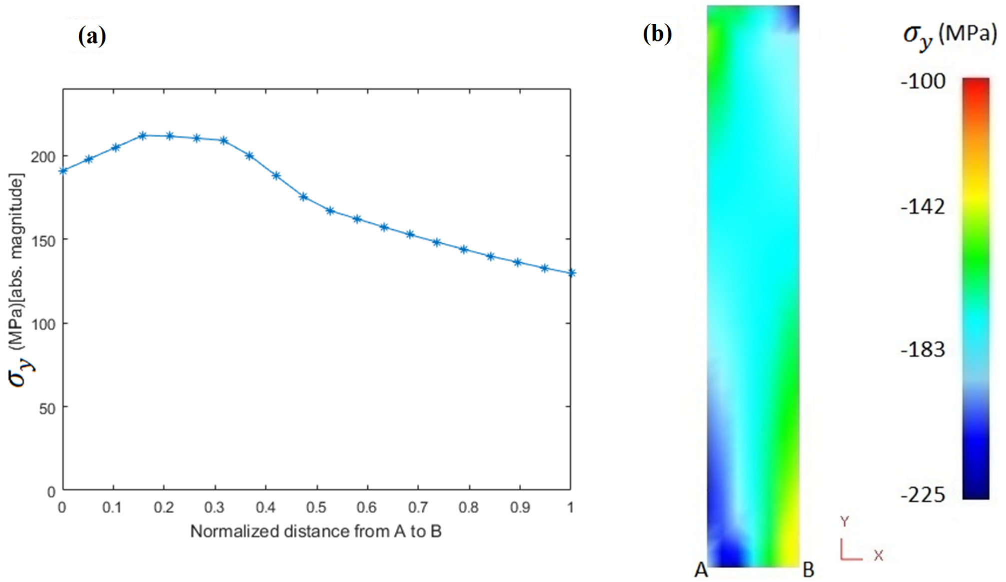

Fig. 7. Y-stress distribution in the punch at the third step in the SPACE method, a) Absolute profile along AB path, b) Algebraic distribution throughout the punch.

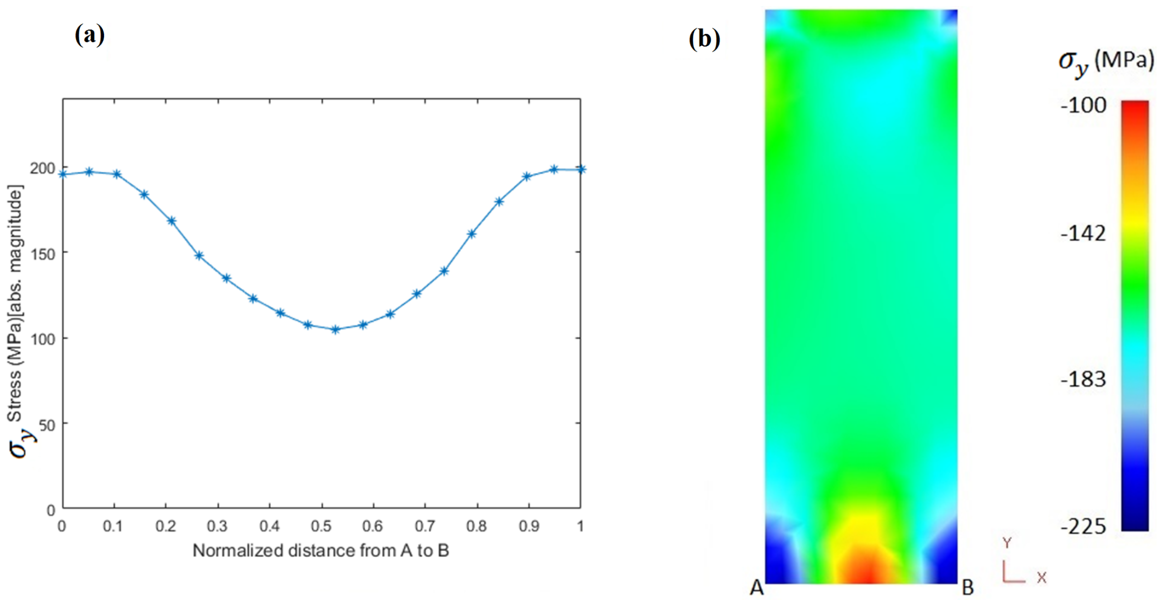

Fig. 8. Y-stress distribution in the punch at the third step in the TPACE method, a) Absolute profile along AB path, b) Algebraic distribution throughout the punch.

4. Conclusions

The finite element simulations of TPCAE and SPCAE methods were conducted in order to investigate the stress analysis of the tools. It is deduced that TPCAE has more lifetime rather than SPCAE according to the following results:

1. In TPCAE, the effective stress is distributed sufficiently, so that there are stress concentration points with lower magnitudes in the die, while the concentrated stress points have higher magnitudes in SPCAE.

2. Overall effective stress magnitudes in the punch are around 15 percent lower in the TPCAE method with respect to the SPCAE one. In addition, on the contrary to the SPCAE method, a symmetric pattern of effective stress is made in the punch in the TPCAE method, which is intensified in the last stages of the process.

3. In addition to the symmetric pattern of effective stress in the punch in the TPCAE method, there is also a symmetric pattern of the Y-stress component bringing about the possibility of compensation of the opposite bending moments imposed by two specimens to the punch. On the other hand, there is one deforming specimen in SPCAE, causing just one bending moment applied to the punch, which cannot be compensated due to the asymmetric design of the process. So, there is an asymmetric stress distribution of the Y component in the punch in this method.

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References

[1] R.Z. Valiev, R.K. Islamgaliev, I.V. Alexandrov, Bulk nanostructured materials from severe plastic deformation, Prog. Mater Sci., 45(2) (2000) 103-189.

[2] S.H.C. Park, Y.S. Sato, H. Kokawa, Microstructural evolution and its effect on Hall-Petch relationship in friction stir welding of thixomolded Mg alloy AZ91D, J. Mater. Sci., 38(21) (2003) 4379-4383.

[3] P. Kumar, M. Kawasaki, T.G. Langdon, Overcoming the paradox of strength and ductility in ultrafine-grained materials at low temperatures, J. Mater. Sci., 51(1) (2016) 7-18.

[4] L.S. Toth, C. Gu, Ultrafine-grain metals by severe plastic deformation, Mater. Charact., 92 (2014) 1-14.

[5] E. Bagherpour, N. Pardis, M. Reihanian, R. Ebrahimi, An overview on severe plastic deformation: research status, techniques. classification, microstructure evolution, and applications, Int. J. Adv. Manuf. Technol., 100(5-8) (2019) 1647-1694.

[6] R.Z. Valiev, T.G. Langdon, Principles of equal-channel angular pressing as a processing tool for grain refinement, Prog. Mater Sci., 51(7) (2006) 881-981.

[7] E. Bagherpour, M. Reihanian, N. Pardis, R. Ebrahimi, T.G. Langdon, Ten years of severe plastic deformation (SPD) in Iran, part I: equal channel angular pressing (ECAP), Iran. J. Mater. Form., 5(1) (2018) 71-113.

[8] A.P. Zhilyaev, T.G. Langdon, Using high-pressure torsion for metal processing: Fundamentals and applications, Prog. Mater. Sci., 53(6) (2008) 893-979.

[9] Y. Beygelzimer, V. Varyukhin, S. Synkov, D. Orlov, Useful properties of twist extrusion, Mater. Sci. Eng., A, 503(1-2) (2009) 14-17.

[10] F. Heydari, H. Saljoghi, S.H. Nourbakhsh, Numerical investigation of the cross-section and twist extrusion die angle on the distribution of plastic strain and microstructure of Al7050 Alloy, J. Stress Anal., 4(2) (2020) 1-8.

[11] Y. Saito, H. Utsunomiya, N. Tsuji, T. Sakai, Novel ultra-high straining process for bulk materials-development of the accumulative roll-bonding (ARB) process, Acta Mater., 47(2) (1999) 579-583.

[12] M. Reihanian, E. Bagherpour, N. Pardis, R. Ebrahimi, N. Tsuji, Ten years of severe plastic deformation (SPD) in Iran, part II: accumulative roll bonding (ARB), Iran. J. Mater. Form., 5(2) (2018) 1-25.

[13] N. Pardis, R. Ebrahimi, Deformation behavior in Simple Shear Extrusion (SSE) as a new severe plastic deformation technique, Mater. Sci. Eng., A, 527(1-2) (2009) 355-360.

[14] H. Mozafari, F. Akbaripanah, Changes in Grain Size, Texture, and Mechanical Properties of AZ31/(TiO_2)p Nanocomposites Processed by Isothermal Multidirectional Forging, J. Stress Anal., 4(2) (2020) 45-53.

[15] Y. Nishida, H. Arima, J.C. Kim, T. Ando, Development of the ECAP with a rotary die and its application to AC4C aluminum alloy, Journal of Japan Institute of Light Metals, 50(12) (2000) 655-659.

[16] L. Zuyan, W. Zhongjin, Finite-element analysis of the load of equal-cross-section lateral extrusion, J. Mater. Process. Technol., 94(2-3) (1999) 193-196.

[17] G.I. Raab, Fizika i Tekhnika Vysokikh Davleniy, Physics and Engineering of High Pressures, 14(4) (2004) 83.

[18] G. Raab, Plastic flow at equal channel angular processing in parallel channels, Mater. Sci. Eng., A, 410-411 (2005) 230-233.

[19] M. Abdi, R. Ebrahimi, Twin parallel channel angular extrusion as a development of ECAE in parallel channels, SN Appl. Sci., 2 (2020) 548.

[20] M. Abdi, R. Ebrahimi, Friction Effect on the Required Load in Twin Parallel Channel Angular Extrusion The 9th International Conference on Materials Engineering and Metallurgy, Tehran, Iran. (2020).

[21] M. Abdi, R. Ebrahimi, XRD Analysis of Cell Size and Dislocation Density in Twin Parallel Channel Angular Extrusion, The 28th Annual International Conference of Iranian Society of Mechanical Engineers-ISME2020, Tehran, Iran, (2020).

[22] F.P. Beer, E.R. Johnston, J.T. DeWolf, Mechanics of Materials, 3rd edn, Columns. In: N.S. Prasad, S. Krishnamurthy (ed), Tata McGraw-Hill, New Delhi, (2004).