Juniper Online Journal Material Science
ISSN: 2575-856X

Research Article
Volume 3 Issue 1 - October 2017
DOI: 10.19080/JOJMS.2017.03.555605

JOJ Material Sci

Evaluation of Mechanical Properties using Micro Shear Punch Test; Analytical Approach and Experimental Verification

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Submission: September 21, 2017; **Published:** October 26, 2017

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Abstract

Severe plastic deformation (SPD) techniques have been developed to enhance the mechanical properties of materials by grain refinement. Formation of strain gradient and subsequently a heterogeneous grain structure during a SPD technique is usually inevitable. Samples processed by SPD are typically small in size and therefore their formability assessment becomes more complex due to the heterogeneous properties. In this research a dedicated theory has been developed to interpret the micro shear punch test (MSPT) results when a heterogeneous material is tested. The theory predicts the required shear punch force based on the developed pattern of the accumulated strain inside the material during SPD process. This extends the scope of the micro shear test beyond a comparative characterization and allows a more universal use of the measured data similar to that of a standard mechanical test. A case study is also presented where a heterogeneous specimen has been manufactured by the axi-symmetric forward spiral extrusion (AFSE). Based on the theory, a representative point (RP) was identified that corresponds to the overall measured MSPT force. The MSP results can be considered as the representative of the mechanical properties at the RP point. The corresponding heterogeneous mechanical properties of the AFSE specimens were assessed by micro shear punch test based on the developed theory and compared to experimental results.

Abbreviations: SPD: Severe Plastic Deformation; MSPT: Micro Shear Punch Test; AFSE: Axisymmetric Forward Spiral Extrusion; RP: Representative Point

Keywords: Micro shear punch test; Mechanical properties; Strain gradient; Severe plastic deformation

Introduction

Severe plastic deformation (SPD) techniques have been developed to enhance the mechanical properties of materials by producing ultrafine-grained structure. Different SPD techniques have been proposed but they often can produce small quantities of materials which limit making tensile specimens for assessing the impact of the process on the properties. Furthermore, formation of strain gradient is usually expected within the material during SPD techniques like high pressure torsion (HPT) [1], Equal channel angular pressing (ECAP) [2] and axi-symmetric forward spiral extrusion (AFSE) [3]. Although micro hardness test can provide strength information of the processed specimens, however the relatively small region of the specimen which is deformed during micro hardness testing leads to data scattering.

Miniature specimen test techniques, which are more experimentally feasible and do not need to consider the effects of specimen size, can be employed as an alternative to standard uniaxial tension test namely disk bend testing [4], ball indentation testing [5] and small punch (SP) test [6,7]. The SP test method was originally developed for assessing the DBTTs (ductile-brittle transition temperatures) of small amounts of metallic material [8]. Micro shear punch test (MSPT) is a miniature testing technique, which is based on blanking operation [9] for evaluating mechanical properties. By plotting shear stress against normalized displacement, MSPT curves are obtained which can be used for a comparative formability assessment of a material.

In the current literature see for example [6], the shear strength from MSPT data is calculated by dividing the maximum MSPT load by the shearing area. This gives a good estimation for homogenous material and conforms well to conventional tensile test results. However,in a case when heterogeneous samples produced by SPD techniques are concerned, this approach is not valid. The assessment of mechanical properties of aluminium that has been produced by ECAP using MSPT [10] shows large discrepancies with tensile results.

Therefore, assessment of heterogeneous material mechanical properties using MSPT deserves a dedicated approach. In this research, an analytical model for MSPT has been proposed for a specimen with heterogeneous structure. The model has been solved for a case where the heterogeneous structure has been produced by the AFSE. In order to extend the scope of MSPT beyond a comparative characterization test, a representative point (RP) was defined and identified for a sample processed by the AFSE. Experiments have also been under taken to verify the accuracy of the proposed case study solution.

Micro Shear Punch Model for AFSE

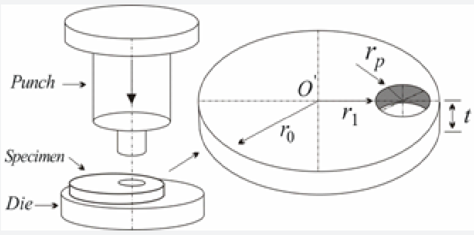

Figure 1: The schematic of micro shear punch process.

Figure 1 illustrates the schematic of the micro shear punch test (MSPT) and a disk shape specimen cut from AFSE sample with as its thickness. The punch penetration into the disk shape specimen blanks a hole with a radius of r-p. Considering a specimen radius of r-o, the hole position can be measured with respect to the specimen centre, O^' using a radial distance-1 shown in Figure 1.

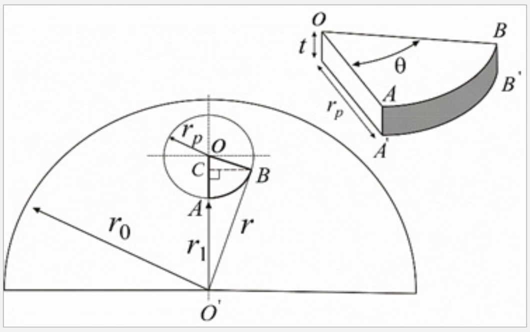

Figure 2: The trigonometry of the micro shear punch.

Figure 2 illustrates the half of the specimen with a typical point, B, to allow calculation of total shear punch force by integration. For the specimen segment shown in Figure 2, a cylindrical face AA' BB' represents the shearing surface during the MSPT. Therefore, one can calculate the required shear punch force, F as:

$$F=\int \tau \, dA \quad \text{..................(1)}$$

where τ is a typical shearing strength of the material at a typical point on the shearing edge and dA is the shear area increment, $dA=r_p \, t \, d\theta$. Due to the AFSE processing, an effective pre-strain¯(ε), has been accumulated at pointB with an arbitrary radius r. The effective pre-strain at point Bcan be estimated using a kinematic solution of AFSE as,

$$\bar{\varepsilon}=\frac{N}{\sqrt{3}}\frac{r}{r_0}\tan\gamma \quad \text{..........................(2)}$$

where N and γ are the number of AFSE passes, and helix angle, respectively. A power law has been assumed here to describe the material constitutive behaviour prior to the processing as,

$$\sigma=K\varepsilon^{-n} \quad \text{......................(3)}$$

where σ, K and n are von-Mises material tensile strength, work hardening coefficient and strain sensitivity factor, respectively. Assuming a pure shear mode of forming during AFSE, the effective yield in shear becomes τ= σ/√3.CombiningEqs. 2 and 3, τ can be derived as,

$$\tau=\frac{K}{\left(\sqrt{3}\right)^{n+1}}\left(N\frac{r}{r_0}\tan\gamma\right)^{n} \quad \text{..............................(4)}$$

Integration of Eq. 1 requires an expression between r and the angular position identifier, θ. According to Figure 2, r can be calculated as,

$$r=\sqrt{\left(r_1+AC\right)^2+BC^2} \quad \text{....................(5)}$$

Considering trigonometry in ΔCOB in Figure 2,

$$\cos\theta=\frac{OC}{r_p}$$

$$\sin\theta=\frac{BC}{r_p} \quad \text{........................(6)}$$

It can be seen that in Figure 2 that r_p=OC+AC. Combining this with Eq. 5 and 6, it can be concluded that:

$$r=\sqrt{\left(r_1\right)^2+2r_p\left(1-\cos\theta\right)\left(r_p+r_1\right)} \quad \text{..........................(7)}$$

The required micro shear punch force described by Eq. 1 can be calculated now as,

$$F=2\frac{K}{\left(\sqrt{3}\right)^{n+1}}\left(\frac{N}{\left(r_0\right)}\tan\gamma\right)^{n} r_p t\times\int_0^{\pi}\sqrt{\left(r_1\right)^2+2r_p\left(1-\cos\theta\right)\left(r_p+r_1\right)}\,d\theta \quad \text{......(8)}$$

Eq. 8 leads to a complete elliptic integral which doesn't have a closed form solution and therefore has to be solved numerically to estimate the MSPT force to blank the described hole within the heterogeneous disk shape specimen. However, the force corresponds to a relatively large footprint in which a heterogeneous structure exists. It is desirable to find a representative point (RP) such that the recorded load displacement from MSPT can be attributed to this specific point. The (RP) is a point which is located on the center line of MSPT punch footprint, AA as illustrated in Figure 3. The B^* is such a point on the punch footprint where the required MSPT force

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for shearing the area A_2 is equal to that of area A_1. To locate the B*, a dedicated Matlab program was developed. The program first calculates the MSPT force based on Eq. 8. Then the MSPT force was divided by two and equated to the relation similar to that of Eq. 8 while the integral limits were changed from 0 to θ*. Having found the θ*, the B*can be located and its corresponding RP location can be calculated based on trigonometry in Figure 3 as,

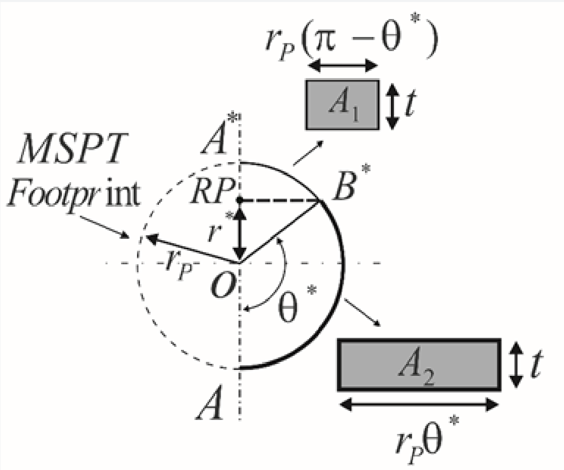

Figure 3: The illustration of RP in punch footprint.

$$r^* = r_p \sin\left(\theta^* - \frac{\pi}{2}\right) \quad (9)$$

where r* is the distance of RP from center of MSPT punch. A deviation factor, δ, is defined here which can be calculated as follows,

$$\delta = \frac{r^*}{r_p} \times 100 \quad (10)$$

δis a measure of deviation of heterogeneous specimen MSPT results from that of homogenously work hardened one. For a homogenous material as a special case, in which the MSPT force is evenly distributed around punch foot print, the θ* would be equal to90° and the RP and MSPT punch footprint center, O,would coincide which corresponds to δ=0. The experimental procedure was performed to verify the accuracy of the proposed model, which will be described next.

Experiments

The heterogeneous deformation was induced in the specimen by AFSE technique [3]. The material used in this study was an ultra-low-carbon Ti-IF steel (0.005% C, 0.003% N, 0.13% Mn, 0.084% Ti, 0.042% Al (in wt %)) with constitutive relation as $\sigma = 220\varepsilon^{-0.3}$ which has been obtained by torsion test. The cylindrical specimens of 9mm diameter and 20mm length were processed for 1, 2 and 4 pass of AFSE in room temperature with the helix angle, γ, of 23° [3]. The AFSE die setup is shown in Figure 4.

Figure 4: The AFSE setup under the press.

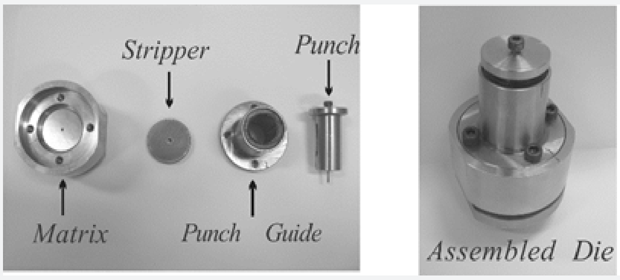

Figure 5: The micro shear punch die components and the assembled die.

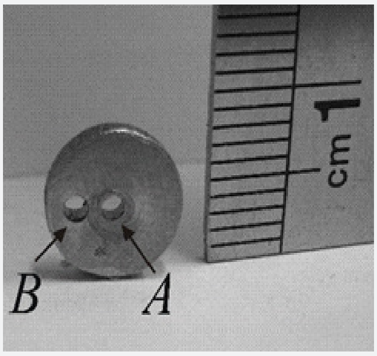

Figure 6: Processed specimen with AFSE; before (left) and after (right) micro shear punch tests performed at two positions A and B.

To perform micro shear punch test, the die components were designed and manufactured which are illustrated in Figure 5. A flat head micro punch with 1.5mm diameter $(r_p = 0.75mm)$ was used to punch specimens. The MSPT specimens were secured between the stripper and matrix (Figure 4) to minimize the effect of bending during MSPT. The processed specimens by AFSE were cut in discs perpendicular to the extrusion direction with the thickness of t=1.5mm prior to MSPT (Figure 6).

Two spots were punched for each specimen that are center point and the one which is 2mm away from specimen center $(r_1 = 2mm)$. The former and latter spots are designated by A and B, respectively, which are highlighted in Figure 6. The punch stroke was normalized using $\chi = \frac{z}{t}$, where z and tare micro shear

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punch displacement and the disc thickness, respectively. In the following sequel, the results of experimental MSPT and analytical calculations will be presented.

Results and Discussion

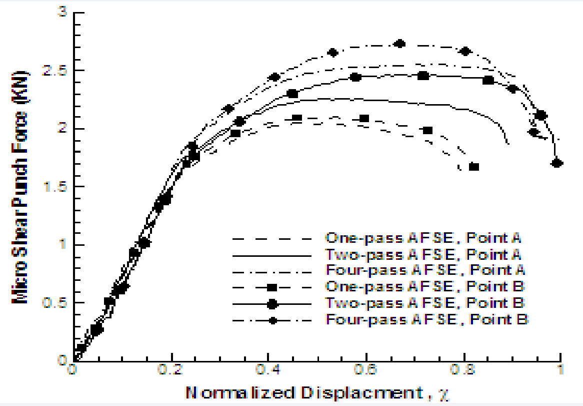

Figure 7: Micro Shear punch force versus normalized displacement.

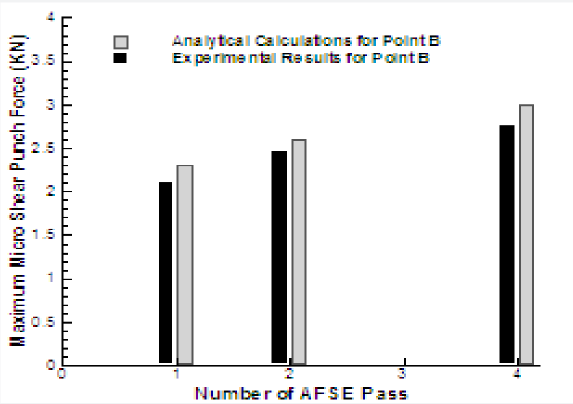

Figure 8: The Comparison of Micro Shear punch force between Analytical Calculations and Experimental Results.

Figure 7 shows the MSPT force versus χ for specimens. As can be seen the micro shear punch force is higher for point B in comparison for that of point A for the same number of AFSE pass. According to Eq. 2 the accumulated strain is higher at the periphery of the specimen (point B) in comparison to near its center (point A). As a result point B requires higher amount of shear force to be punched in comparison to point A. Also, as the number of AFSE passes increases, the maximum required shear force increases which is due to strain hardening effect inside the material. One can calculate the maximum required shear force using Eq.8 while considering the mentioned experimental parameters. Figure 8 shows the analytical calculation as well as the experimental results for point B. The predicted value for maximum MSPT force by analytical model is higher than that of experimental results.

The maximum discrepancy between the analytical and experimental results is 9% which can be attributed to the die-punch clearance. Although stripper was used in experimental MSPT, the die-punch clearance results into bending of specimen during experimental MSPT. As a result, state of stress in experimental MSPT is a combination of shear and normal stresses. Therefore, the slight difference between experimental results and analytical calculations can be attributed to their different corresponding state of stress. But, the reasonable agreement between the analytical calculations and the experimental results verified the accuracy of the presented MSPT model. The values of θ* and δ were calculated by implementation of the discussed Matlab program and Eq. 10, respectively, the results of which are summarized in Table.1.

Table1: The analytical results for point B.

Number of AFSE Pass	MSPT Force(KN), Eq. 8	θ*°	δ%
1	2.1	112	38
2	2.5	100	19
4	3.0	93	5

As can be seen from Table 1, the different amount of deformation leads to variation of the deviation factor. Therefore, it can be assumed that the MSPT results for heterogonous specimen that was produced by AFSE can be correlated to the mechanical properties of the RP the position of which deviates from MSPT punch center by factor of δ. Overall, the MSPT results can be attributed to the mechanical properties of the RP irrespective of the homogenous or heterogeneous strain distribution in the specimen. For the case of homogenous specimen the RP is located at the center point of MSPT punch while for that of heterogonous specimen it deviates from MSPT punch center point by factor of δ.

Conclusion

An analytical model for MSPT has been proposed for heterogeneous material. Experimental procedures were used in order to verify the proposed MSPT model. AFSE was implemented to produce specimens with heterogeneous mechanical properties. The results of MSPT test verified the heterogeneous behavior of mechanical properties of processed samples by AFSE. The reasonable agreement between the analytical calculations and the experimental results verified the accuracy of the proposed MSPT model. The slight difference between the analytical calculations and experimental results can be attributed to the different stress states in experiments and model that caused by die-punch clearance. The MSPT results can be correlated to the mechanical properties of RP, the location of which was calculated analytically. For the homogenous strain distribution along punch footprint RP coincides with the punch center while for that of heterogeneous one the RP deviates from specimen center by factor of the δ. Therefore, the developed theory extends the MSPT application for mechanical properties assessment of heterogeneous materials.

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Acknowledgment

The authors would like to acknowledge the help of Monash University Mechanical and Aerospace Engineering workshop for manufacturing the die components.

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