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Determination of Micro-Scale Plastic Strain caused by Orthogonal Cutting

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Abstract:

An Electron Beam Lithography technique has been used to produce microgrids in order to measure local plastic strains, induced during an orthogonal cutting process, at the microscopic scale in the shear zone and under the machined surface. Micrograms with a 10 µm pitch and a line width less than 1µm have been printed on the polished surface of an aluminium alloy AA5182 to test the applicability of the technique in metal cutting operations. Orthogonal cutting tests were carried out at 40 mm/sec. Results show that the distortion of the grids could successfully be used to compute plastic strains due to orthogonal cutting with higher accuracy compared to other techniques reported in the literature. Strain maps of the machined specimens have been produced and show high strain gradients very close to the machined surface with local values reaching 2.2. High resolution strain measurements carried out in the primary deformation zone also provide new insight into the material deformation during the chip formation process.

Key words: Orthogonal cutting, micro-grid, large strains, plastic deformation

1. Introduction

Machining is a manufacturing process that is commonly used in the manufacture of mechanical components. During the process, parts of the workpiece are removed as chips through an interaction with a harder cutting tool. While the chips are forming, the material undergoes a severe plastic deformation which affects the integrity of the machined surface and changes the hardness as well as other mechanical properties of both the chip and the machined surface.

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Several models including analytical and finite element models have been developed to simulate machining operations. Most of these models, e.g. the famous fundamental Merchant model [1], make the assumption of 2D plane strain orthogonal metal cutting conditions [1-7] and must be validated by comparing predicted results with available experimental data such as cutting forces [2-4] and residual stresses [5-7]. The distribution of plastic strains can also be used for the validation of cutting models as it directly shows the deformed state of the material and therefore provides more insight into the predictive capability of these models.

Since the material deformation in metal cutting is highly localised near the machined surface and inside the chip formation zone, the determination of such strains requires the application of special techniques that produce measurements with high accuracy.

The grid technique is one of the most accepted techniques to determine strain distributions and material flow in deformed specimens [8]. Using this technique, a well defined pattern of grids, whose size varies depending on the application, is laid on the surface of the workpiece material. Since the grids are bonded to the workpiece, they will undergo the same deformation as the workpiece material. By analysing the distortion of the deformed grids, the magnitude of plastic strains can be determined.

Various methods including photolithography [9], scribing [10,11], electropolishing [12], deposition [13], electro-resist method [14] and micro electro-lithography [15] have been used to produce microgrids in order to measure local in-plane plastic strains [10, 12-15] and/or local displacement fields [11] in the loaded specimens. The reported size of the produced grids using the different techniques varies from 1 mm using scribing and deposition methods [10,13] down to 5µm, using gold dots, as in the micro electro-lithography method applied by Allais et al [15] to study the local deformation of metal matrix composites under tensile loading.

Several attempts have also been made to use microgrids to analyse the material flow and plastic strains beneath the machined surface during chip formation. Bitans and Brown [16] studied the nature of material flow and shear plane angle during orthogonal cutting of a wax specimen using cast grids with a pith of 380µm. Childs [17] and Leopold and co-workers [18-20] used microgrids in combination with a visioplasticity technique to study flow patterns and velocity fields during orthogonal cutting. However the distortion of the grids was not used to determine plastic strains in the chip formation zone and below the machined surface. Child [17] used scratched microgrids with a pitch of 25 μm and a line width equal to 5 μm while Leopold et al. used printed and electro-polished grids with a pitch size ranging from 85 to 20 μm. An embossing method was developed to lay grids with a pitch of 12.7μm on the polished surface of orthogonally machined disc shaped specimens [21,22]. The deformed grids were analysed after machining to obtain plastic strains under the machined surface while strains in the chip formation zone were not measured.

It is worth noting that scratches produced by inscribing or embossing methods to lay grids onto the surface of samples increase the local stress concentration which in turn may influence the material deformation [17,21,22], as stresses during the machining operations are very high and plastic deformation is highly localized. Additionally, the low definition of the produced engraved lines, along with the inconsistency in the width and spacing of the grid lines cannot generate high resolution strain measurements, especially in areas of high strain gradients as experienced by metals around the chip formation zone.

A better grid definition was obtained using photo- resist [23] and photo printing methods [24,25]. Lee [23] measured plastic strains at the chip root printing square grids with a 50μm pitch while arrays of microgrids with a 20μm pitch and a line width equal to 5 μm were used by Sadat and Reddy [24,25].Plastic strain maps reported in [23] show zero strain for the material layers below the machined surface. This might have been due to the relatively large size of the printed grids that could not accurately show the highly localised material deformation in these layers. Shear plastic strains were determined within the subsurface layers of the machined workpiece in Refs. [24,25] even though the accuracy of the measurements would have been affected by the relatively large width of the grid lines compared to the pitch size. In that study, no results related to the material deformation in the chip formation zone were reported.

In spite of all developments made with the application of microgrid techniques to metal cutting operations, very few works have reported on local strain measurements around the chip formation zone. Furthermore, none of the studies have produced results with the level of accuracy required to measure the full strain distribution in the highly localised deformation areas that surround the chip and below the machined surface where high strain gradients are generated.

In the present paper Electron Beam Lithography (EBL) has been used to produce microgrids in order to measure plastic strains during a simple 2D orthogonal cutting operation. Ultra-fine microgrids of gold with a pitch size of 10μm and a line width less than 1 micron has been laid on the surface of specimens. The distortion of the grids has been used to measure plastic strains below the machined surface and in the chip formation zone of orthogonally machined specimens with high accuracy.

2. Experiment

An experimental test rig was designed to locate test specimens that were to be machined under orthogonal cutting conditions. Orthogonal cutting has been adopted for the ease of interpretation of test results [21-25]. Details of the rig and testing methodology are given in section 2.2.

Square cross section test specimens with a side size of 25 mm and a thickness of 6 mm were manufactured from an aluminium alloy *AA 5182* in a stress relieved condition, at 300 °C for an hour, after experiencing 50% reduction through a hot rolling process. A high speed steel cutting tool (K520- Dormer Co.) with back rake and clearance angles of $7^{0'}_{-20'}$ and $5^{0'}_{-20'}$, respectively, was used to machine the specimens.

2.1. Microgrid Technique

Figure 1 shows various steps required to print microgrids using Electron Beam Lithography (EBL) technique. PMMA (Poly Methyl Methacrylate) was used as the electro-resist resin which was spread over the polished surface of the specimens using a specially designed spreading machine, figure 1-a. The machine enabled accurate control of the thickness and the uniformity of the resin which are vitally important for creating high quality grids.

The resin is spread under rotation of the specimen and the thickness is controlled by changing the rotational velocity of the motor through a frequency inverter. The resin was then polymerised at 140°C for 30 minutes to obtain a solid layer of plastic resin covering the polished surface of the specimen.

A conventional Scanning Electron Microscope (SEM) was used to produce the microgrids by scanning the resin layer with the electron beam in a controlled way, figure 1-b.

Accurate control of the stage displacement enabled grids to be printed along the edge of the specimen. Following scanning, the burnt resin was dissolved in a solution of Butanone and Propanol for about 90 seconds, figure 1-c. A thin layer of gold then coated the specimens, figure 1-d. Gold is used as it provides better contrast in an electron microscope compared to other techniques used to develop grids. Gold atoms adhere to the surface of the specimens and fill the grooves created by the removed burnt resin, forming an array of straight orthogonal lines with fine intersections. The entire resin was then removed from the specimen leaving the printed connected square microgrids of gold with sharp corners on the surface, figure 1-e.

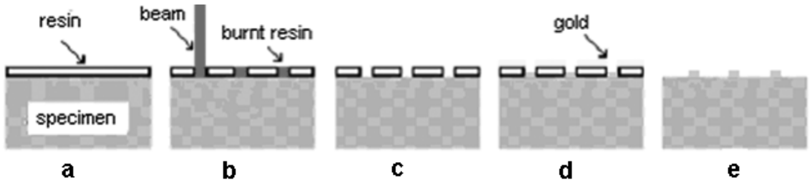


Figure 1- Microgrid formation: (a) Resin spreading, (b) Irradiation of the resin by the electron beam, (c) Removing the burnt resin, (d) Gold coating, (e) Removing the remaining resin and developing the grids

The produced microgrids with 3.5 μm is shown in Figure 2. Even though it is possible to produce microgrids with smaller pitches, down to 1 micron, grids with a 10μm pitch were considered to be suitable for this study.

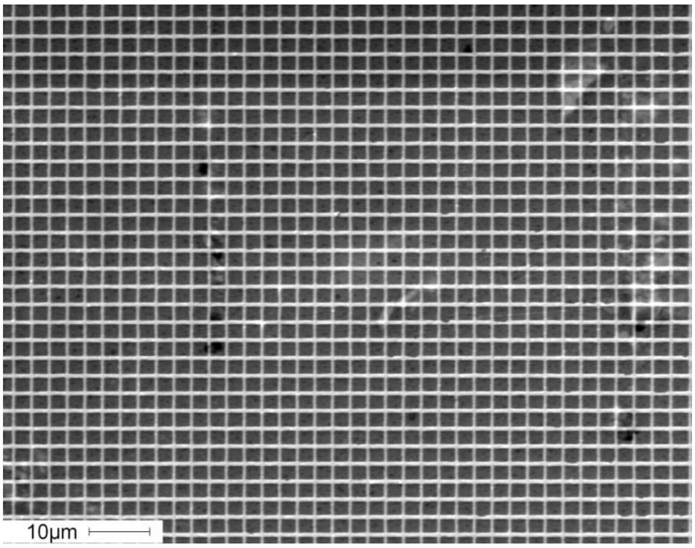


Figure 2- Microgrids with a 3.5μm pitch printed on the surface of specimens

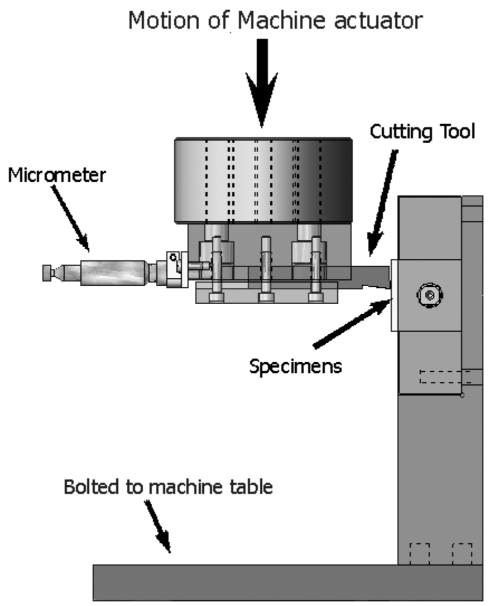
2.2. Cutting Test

To facilitate cutting tests in orthogonal and plane strain conditions, a fixture was designed to be mounted on a servo-hydraulic test machine capable of performing tensile and compression tests.

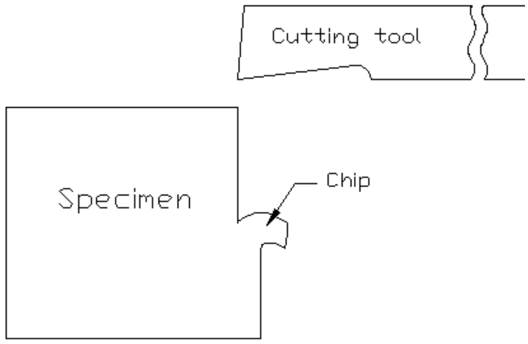
In the fixture, figure 3, the tool holder is attached to the machine actuator which is located above the machine table. The tool holder contains a micrometer with an accuracy of 1μm to set the depth of cut along with a mechanism that clamps the cutting tool after setting the machining parameters. The specimens are fixed firmly in the fixture, which is bolted to the rigid machine table. The cutting operation is performed by moving the cutting tool down towards the specimens after setting the cutting depth. The orthogonal cutting conditions are satisfied as the cutting edge is perpendicular to the direction of relative velocity between the tool and the specimen, which is the cutting velocity direction.

A cutting speed of 40 mm/sec was used and the depth of cut was set to 0.5 mm to an accuracy of 1μm. A rapid disengagement of the cutting tool by a reverse movement of the tool was also implemented to freeze the chip formation process. The direction of the cutting tool movement was then reversed, leaving a part of the formed chip attached to the workpiece. This enabled the study of the material deformation during the chip formation process.

A pair of samples was polished and microgrids were printed on one of them, figure 4. The specimens were then placed in the fixture in such a way that their polished faces was in contact (figure 4) and then clamped firmly together. Compressive forces, due to clamping, press the specimens together restricting the out of plane displacement at the contact faces. This makes the specimens behave as one single part during the deformation. Under this condition the face on which the micrographs have been laid, which corresponds to the mid plane of the assembly, undergoes deformation assumed to be close to a plane strain mode with restricted side spreading.



(a)



(b)

Figure 3- Schematic of the cutting test setup (a) and machined specimens at the end of the cutting process (b)

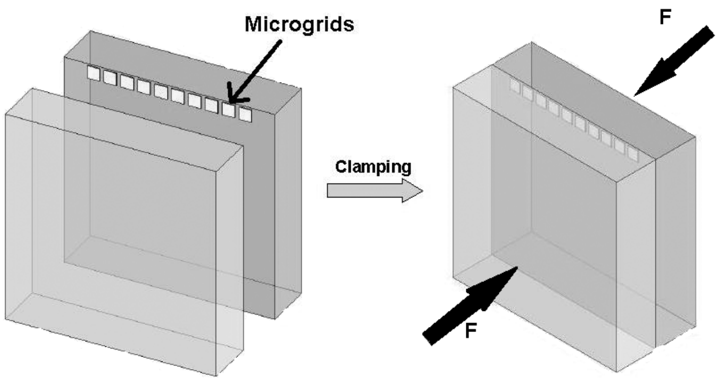


Figure 4- Polished specimens with the microgrids printed along an edge are clamped in the illustrated direction to satisfy plane strain and orthogonal cutting conditions

Moreover the width of the cutting tool was chosen to be two times wider than the thickness of the specimens and the ratio of the cutting width to the depth of cut (uncut chip thickness) was greater than 24, in accordance with the assumption of orthogonal cutting [26].

3. Results

After freezing the cutting operation, the two parts of the specimen were separated and the deformed microgrids observed with a SEM. Figure 5 shows the distorted grids in the primary shear zone and in the chip root area. Moreover, it reveals that the technique applied to freeze the chip formation process has been successful. The chip freezing method allows plastic strains in the shear zone and in the vicinity of the cutting tool to be investigated, figures 5. The distortion of the grids at the chip root, figure 5, shows with high resolution the material deformation as the cutting tool moves forward together with the chip formation process due to the well established shearing mechanism. [27].

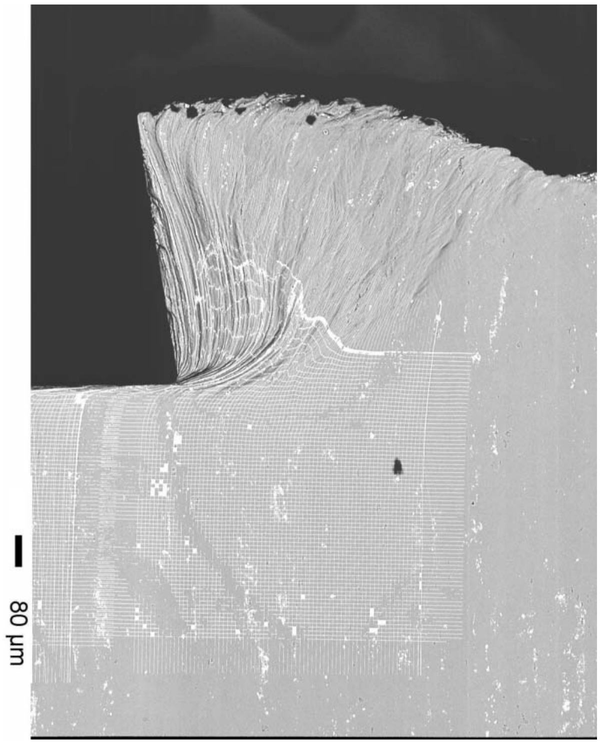


Figure 5- The grids in the chip root in the stress relieved specimen

The distorted grids were used to analyse the plastic deformation of the material during machining. Micrographs of the grids were taken before and after machining. A MATLAB subroutine, developed by Gutierrez [28], was then used to record the position of all grid intersections in both the undeformed and deformed configurations. Each grid element defined by four intersection points can be represented by two vectors X^I and X^{II} in the un-deformed configuration and x^I and x^{II} in the deformed configuration. Under the framework of large strain deformation, the in-plane deformation gradient tensor F can then be derived:

$$F = \begin{pmatrix} x_1^I & x_1^{II} \\ x_2^I & x_2^{II} \end{pmatrix} \begin{pmatrix} X_1^I & X_1^{II} \\ X_2^I & X_2^{II} \end{pmatrix}^{-1} \qquad (1)$$

With x_i and X_i for i=1,2 being the vector coordinates in the deformed and undeformed configurations respectively.

This non-singular deformation gradient tensor, *F*, can then be decomposed into a rigid rotation tensor *R* and a distortion tensor *U* as follows:

$$F = R.U \qquad (2)$$

U can be diagonalised in an orthogonal base using the following equation:

$$U = Q^t DQ \quad \text{(t stands for transposition)} \qquad (3)$$

with D being the diagonal tensor and Q a tensor giving the orientation of the principal directions of the distortion. The logarithmic strain tensor is then computed from:

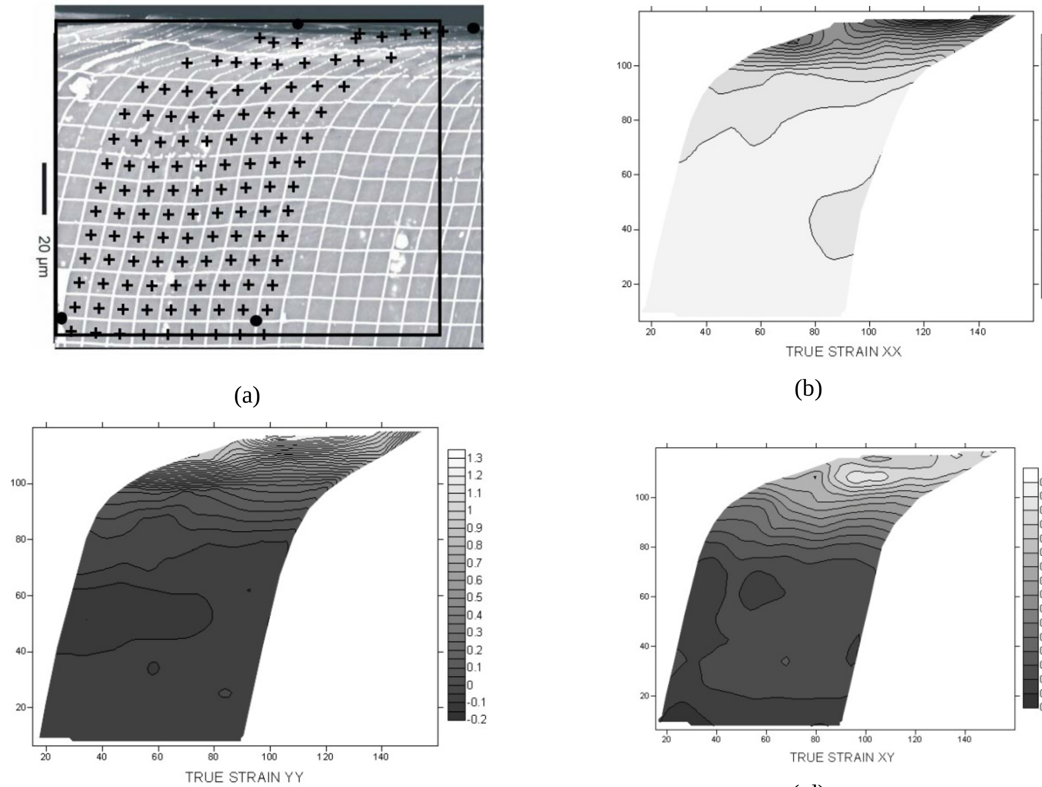
$$E^{Log} = Q^t \ln(D) Q \qquad (4)$$

Using the subroutine, plastic strains were calculated at the centroid of each grid element. Strain maps were then created by means of a surface mapping software, over the previously determined area, by interpolating between the data points at the centroid of the grids highlighted by small crosses in figures 6 and 8.

The plastically deformed material below the machined surface is shown in figure 6-a where the plastic strains were determined within the highlighted areas. The severe distortion of the grids reveals that the intensity of plastic strains decreases from the vicinity of the machined surface towards the centre of the specimen. Elongation of the grids also indicates that the cutting operation was performed from left to right (X direction) on the micrograph.

The plastic strain component in the cutting direction (ε_{XX}), figure 6-b, is compressive while ε_{YY} , figure 6-c, is tensile and smaller than ε_{XX}, in magnitude. Analysis of the strains maps shows that plastic strains are uniformly distributed, from near the machined surface towards the centre of specimen.

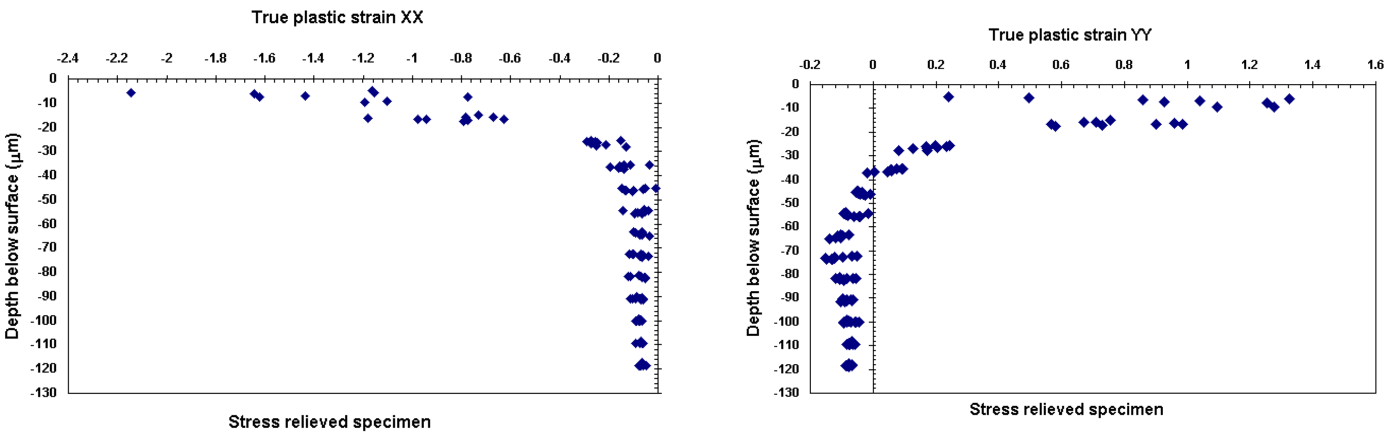
Using calculated strains a quantitative distribution of the plastic strains below the machined surface were also plotted in figure 7. All data points in the highlighted areas of figure 6 are illustrated in the plots in such a way that each horizontal set of data points belongs to a row of grids at the similar depth. The plots also represent the large strain gradient near the surface wherein plastic strains change drastically in the first 20μm below the machined surfaces. However the scale bars shown on the strain maps, figure 6 show different magnitudes for plastic strains compared to those shown in figure 7. This is related to the interpolation function used by the mapping software to produce strain maps.



(a) (b) (c) (d)

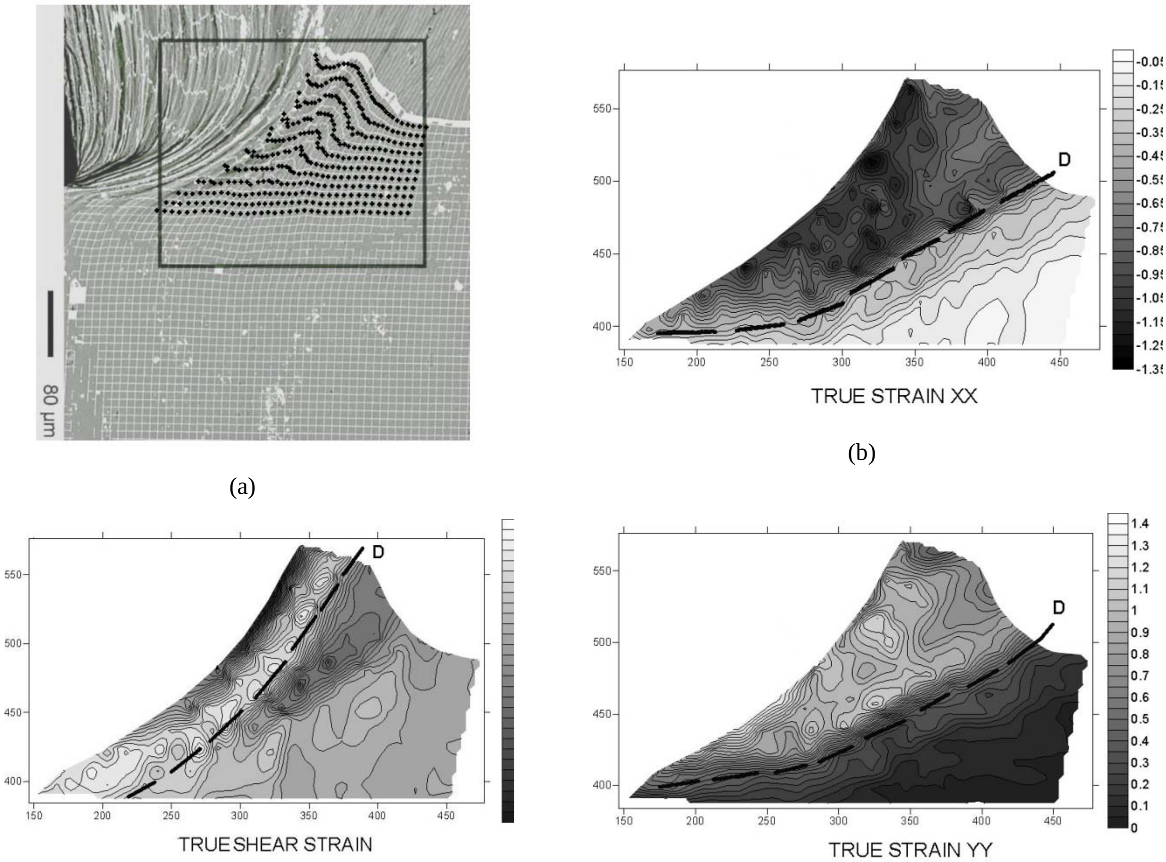
Figure 6- (a) The grids distortion below the machined surface with the small crosses at the centroid of the analysed grids, (b) Distribution of plastic strain in X (ε_{XX}) and (c) Y directions (ε_{YY}) and (d) shear strain distribution (ε_{XY})

Plastic strains determined in the primary deformation zone are given in Figure 8 along with the distorted grids within the chip formation zone. The configuration of the deformed grids illustrates that as the cutting tool moves forward the material ahead of the tool tip is separated into two parts. One part forms the chip and experiences the subsequent deformation in front of the tool rake face, while the other one is compressed under the flank face of the tool to be a part of the machined surface. Plastic strain maps show how the chip forms in relation to the strain distribution. As the cutting tool moves forward the axial plastic strains (ε_{XX} and ε_{YY}) increase. They reach their maximum value at about the same location highlighted by the dashed line D in the figures 8-b and 8-d. However, the location of the maximum shear strain in figure 8-c does not coincide with that of the maximum value for ε_{XX} and ε_{YY} .



(a) (b)

Figure 7- Plastic strains (a) ε_{XX} and (b) ε_{YY} distributions through the thickness of specimens along the cutting direction



(a) (b) (c) (d)

Figure 8- (a) Analysed grid region and (b, c and d) plastic strain distribution in the primary shear zone in the specimen

4. Discussion

Results show that Electron Beam Lithography (EBL) is a suitable technique to produce microgrids in order to accurately study the material deformation during orthogonal cutting. Unlike other techniques [16, 17, 21, 22] the EBL technique does not damage the surface of the specimens and therefore does not create any stress concentrations which might interfere with the material deformation during the chip formation. Moreover, using the EBL technique it is possible to produce microgrids with very fine pitches that are not achievable with scratching [16, 17], embossing [21,22] or even photo resist methods [23-25].

With the higher resolution of the grids produced by the EBL technique, large plastic strain gradients can be quantified, especially close to the machined surface where accurate measurements are needed. As mentioned by Leopold [18] such measurements were not possible using other techniques [18-20]. Plastic strain maps, shown in figure 6, revealed how plastic strains vary along the cutting direction and below the machined surface. The high strain gradient generated by the cutting process very close to the machined surface, shown in Fig. 7, has been resolved accurately using the technique developed in this work. Such a localised strain variation, with local strain values up to 2.2, could not be measured using other techniques such as the photo-resist method used by Lee [23] which showed zero plastic strains below the machined surface. This might have been due to the grid pitch used, 20μm, which is relatively large in comparison to the scale of the local strain fluctuations. In the present work, the accuracy of the EBL technique is further increased through the use of gold as the grid material since gold provides a good contrast in the SEM with respect to the underlying deformed metal. This is of particular importance in areas of high strain gradients where the grids are severely distorted and therefore more difficult to resolve.

The distortion of the grids shown in figure 8 illustrates how the material deforms in the chip formation zone where the deformation is highly localized. This localization of the deformation is likely to result in plastic instability that is reported as one of the major mechanisms of chip formation [27,29]. These instabilities produce shear bands that are more visible in high speed cutting and hard turning processes [23,30]. Strain maps in figure 8 show the distribution of the axial plastic strain as well as the position of the shear band (dashed line D in figure 8-c) that was not reported in previous studies.

The borders of the analyzed region are similar to those predicted by the slip-line field theory method [31]. However, the variation of plastic strains reveals that severe axial deformation is followed by deformation of the material in shear mode which may result in the creation of shear bands.

Results obtained above show that the experimental procedure developed in this work provides the means to accurately measure plastic strains in the various deformation zones during the orthogonal cutting process with high resolution compared to other methods. The range of application of the EBL technique could also be extended to other machining operations whereby the workpiece experiences higher temperatures close to the melting temperature of gold. In that case grids could be engraved using etching as described in studies related to the hot deformation of steels using plane strain compression tests [32,33].

The information gained from these measurements can therefore bring more insight into the mechanisms under which the material deforms during the chip formation. Results could also be useful to models that simulate the chip formation process and for which experimental validation is needed.

5. Conclusions

An Electron Beam Lithography technique was used to produce microgrids in order to study the material deformation during orthogonal cutting. Ultra-fine microgrids with a pitch of 10μm and a line width of less than 1μm were printed on the surface of specimens made out of an aluminium alloy AA 5182. Results from the orthogonal cutting tests showed that using the produced microgrids, plastic strains can be accurately determined from the distorted microgrids, even in regions with large strain gradients. Strain distributions have been measured at the micro-scale in various deformation areas surrounding the chip formation zone with higher accuracy than other techniques reported in the literature. Local strain values as high as 2.2 have been measured close to the machined surface where grids become severely distorted. The experimental method developed in this work which has been validated for the simple orthogonal cutting process could also be extended to other cutting operations.

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