Strain Field Measurement in Orthogonal Machining of a Titanium Alloy

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Abstract

Improving the cutting processes by optimizing operating parameters necessarily involves understanding the thermo-mechanical mechanisms generated during chip formation. For this, numerical simulations are used to obtain the strain, stress and thermal fields near the tool tip. Nowadays, the validation of numerical simulation models of cutting is based on macroscopic results such as chip geometry and cutting forces generated by the machining process. However, it is not appropriate to validate local fields by macroscopic results. So, it is important to validate numerical cutting simulations on the bases of measured local strain fields.

This article aims to study the feasibility of strain field measurement in orthogonal machining of the titanium alloy Ti64. A high-speed camera was used to provide data for segmented chip formation analysis. A microscope was related to the camera to observe an area of about 0.7x0.7mm² around the tool tip. An optimum adjustment of camera settings, lighting, workpiece surface preparation and cutting conditions allowed to obtain an acceptable image quality for analyzing with Correli [1] software. At low cutting speed, Correli qualitatively identify the position of the primary shear band and its evolution over the time.

Introduction

Temperature and normal stress generated at the tool/chip interface are critical parameters for the tool wear and the workpiece material damage. Despite their important influence on tool life, these parameters are not well known because they are very difficult to access through experimentation. In order to overcome these experimental limits, significant effort has been devoted to the development of computational models of machining. The machining numerical simulation enables these parameters and their evolution with respect to the cutting conditions to be estimated.

Material behaviour and friction laws used in machining numerical simulation are validated, in all cases, by macroscopic results such as chip morphology, cutting forces and tool/chip contact length. Based on this global validation, one can access to stress, strain, strain rate and temperature fields for different cutting conditions. But these parameters are local material values. A numerical model validation based on local experimental values of temperature, deformation and strain rate would increase the numerical estimations reliability. So, the analysis of deformation fields from mechanical tests is a key ingredient to bridge the gap between experiments and simulations. Experimental measurement of parameters outlined above would also allow to assess the part of mechanical energy converted into heat during machining and to improve material behaviour laws. But the access to these parameters is experimentally very difficult and few studies have been carried out in this direction.

In 1971, Childs [2] estimated velocity and strain rate distributions by photographing the distortion of a grid inscribed onto a side of the workpiece at two instants in time separated by a very short interval. He estimated the stress strain curve of the workpiece material by combining this experimental data with a slip-line field analysis. In his study, the cutting speed was limited to 240µm/min, which is very low for an industrial cutting process. Using images correlation software Icasoft, Guégan et al. [3] estimated a shear rate of about $3000s^{-1}$ in the primary shear band during orthogonal cutting of a stainless steel, with a cutting speed of 3.16m/s and a feed of 2mm. No information is given about the size of the correlation area. If its size is much higher than the shear band width, the strain rate value is highly underestimated. Digital image correlation software Correli has been used by Tarigopula et al. [4] to measure large plastic deformations in a dual phase steel. They measured strains of about 85% in localized shear bands. The same correlation software is used in our study to estimate the strain field in the chip during machining process.

Experimental details

Experimental images acquisition system

The machining tests were carried out on a planer machine and in orthogonal cutting configuration. The tool is fixed and the cutting speed is applied to the machine table on which the workpiece is set up. The insert is a tungsten carbide tool and the workpiece is a titanium alloy Ti64 plate. The chip formation process is observed with a high speed camera (FASTCAM APX RS2) related to a high magnification microscope (Questar QM100) and an optic fiber lighting system (Fig. 1). The machining parameters, such as cutting speed and feed, are imposed by the quality of images to obtain, as explained further in the text. These cutting parameters generated serrated chips, also called sawtooth chips. The workpiece set up on the machine table moves perpendicular to the observation axis.

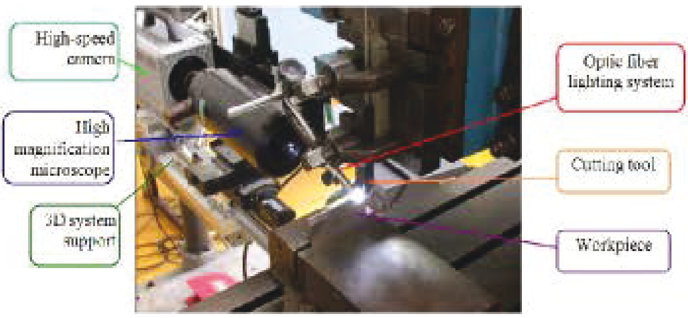

Fig. 1. Video acquisition system

Optimal conditions for images analysis

There are several parameters that affect the quality of recorded images, such as workpiece surface rendering, camera acquisition rate, shutter speed, lighting, etc… Concerning the workpiece surface rendering, its prior preparation must be carried out. An electrochemical attack (after a prior polishing and etching), carried out on the workpiece, enables to obtain a random texture on the analysed surface as small bright dots on a dark background. It is this surface preparation type that has been used to obtain a better analysis by images correlation. The camera acquisition rate is another important parameter towards the computing convergence on correlation software because the machining process involves high strain and strain rates. Indeed, the correlation software can follow only small strains between two consecutive images, which involves the use of the maximum acquisition rate to obtain the computing convergence. The acquisition rate also determines the resolution of the observation window. When increasing the acquisition rate, the size of the observation window decreases. But there is a minimum resolution needed to observe the entire deformation zone of the sawtooth chip. So, since the acquisition rate imposes a corresponding maximum resolution, one must choose the uncut chip thickness depending on the acquisition rate, in order to observe the entire chip deformation zone during machining. In these conditions, the maximum uncut chip thickness is 0.15mm. A cutting speed too high would require a very high acquisition rate, so the cutting speed was set at 6m/min, the minimum that our planer machine allows.

Prior images analysis

The principle of images correlation is to match the pattern of the studied area in the two images in order to determine the displacement of the centre of this area. It means that in the distorted image, one search the place where the maximum likelihood with the studied area considered in the reference image is reached. In Correli, the sought displacement field is decomposed into a basis of continuous functions using Q4P1-shape functions as proposed in finite element methods. This finite element frame-work was introduced by Besnard et al. [5] and enables a direct correspondence with FE simulations. The region of interest of the sample surface is then discretized into continuous Q4 finite elements (see Fig. 2). Each four nodes element is referred to as a zone of interest (ZOI) and bilinear shape functions are adopted to represent the displacements in each element. Nodal displacements are obtained by optimizing the mean quadratic difference between the grey levels of all the elements in the reference image and the corresponding elements in the deformed image. With the determined displacement field, it is possible to calculate the associated strain field.

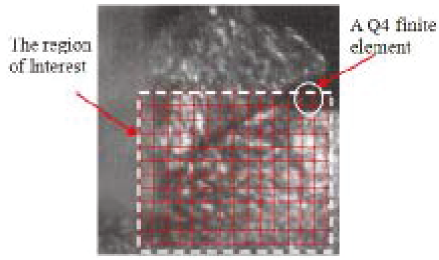

Fig. 2. "Meshing" of the Region of Interest by using a mesh size (or ZOI) of 8x8 pixels

The quality of the displacement measurement highly depends on the quality of the image texture. A prior analysis is implemented in Correli to estimate the image quality, and then helping to choose the size of ZOI. The texture analyse showed that the minimum ZOI size to consider for our images is of 16x16 pixels. The performance of the digital images correlation approach on the actual texture of the image was also priori evaluated in terms of displacement uncertainty. To obtain an estimation of the uncertainty associated with the correlation algorithm, an artificial image is created from the recorded picture by applying known displacements ranging from 0 to 1 pixel with 0.1 pixel increments. Such an image is generated in Fourier space using a phase shift for each amplitude [1]. Thereafter, the correlation algorithm is applied to this pair of images, thus allowing an evaluation of the uncertainty. The quality of displacement measurement is characterized by the standard displacement uncertainty, $_u$, defined as the mean of the standard displacement uncertainties. Even though the displacement uncertainty is lower for larger element sizes, the large displacements require using small sizes. This means that the displacement uncertainty and the corresponding spatial resolution are the result of a compromise. Thus, for an element size of 8x8 pixels, a displacement uncertainty of about 0.025 pixels and a standard strain uncertainty of $\sqrt{2}\sigma_u/2l \approx 2.2 * 10^{-3}$ are obtained.

The video film analyzed by images correlation software was obtained at an acquisition rate of 70000 i/s, a resolution of 128x128 pixels and an exposure time of 1/100000s. For these conditions, the physical size of one pixel is 2.4 µm.

Results and discussion

Shear band detection

The chosen chip segment formation is described by 175 successive pictures. In our study, image i is compared with image i-1 then, Correli takes into account every noted difference and shows at the end the calculated field of image i comparing with image 0 (or reference image). Fig. 3 shows the evolution of the strain field in direction 2 between the beginning and the end of a chip segment formation. The left picture in Fig. 3a is the reference image and the right one is the deformed image. The calculated strain field is then superposed on the reference image. The shear band is clearly identified and one notes the strain increase between the first and the last picture. The shear strain is concentrated in the shear band and lower deformations are observed in the rest of the chip segment. Nevertheless, few meshes are left between the reference and the 175th image and therefore the area where the strain is calculated is reduced.

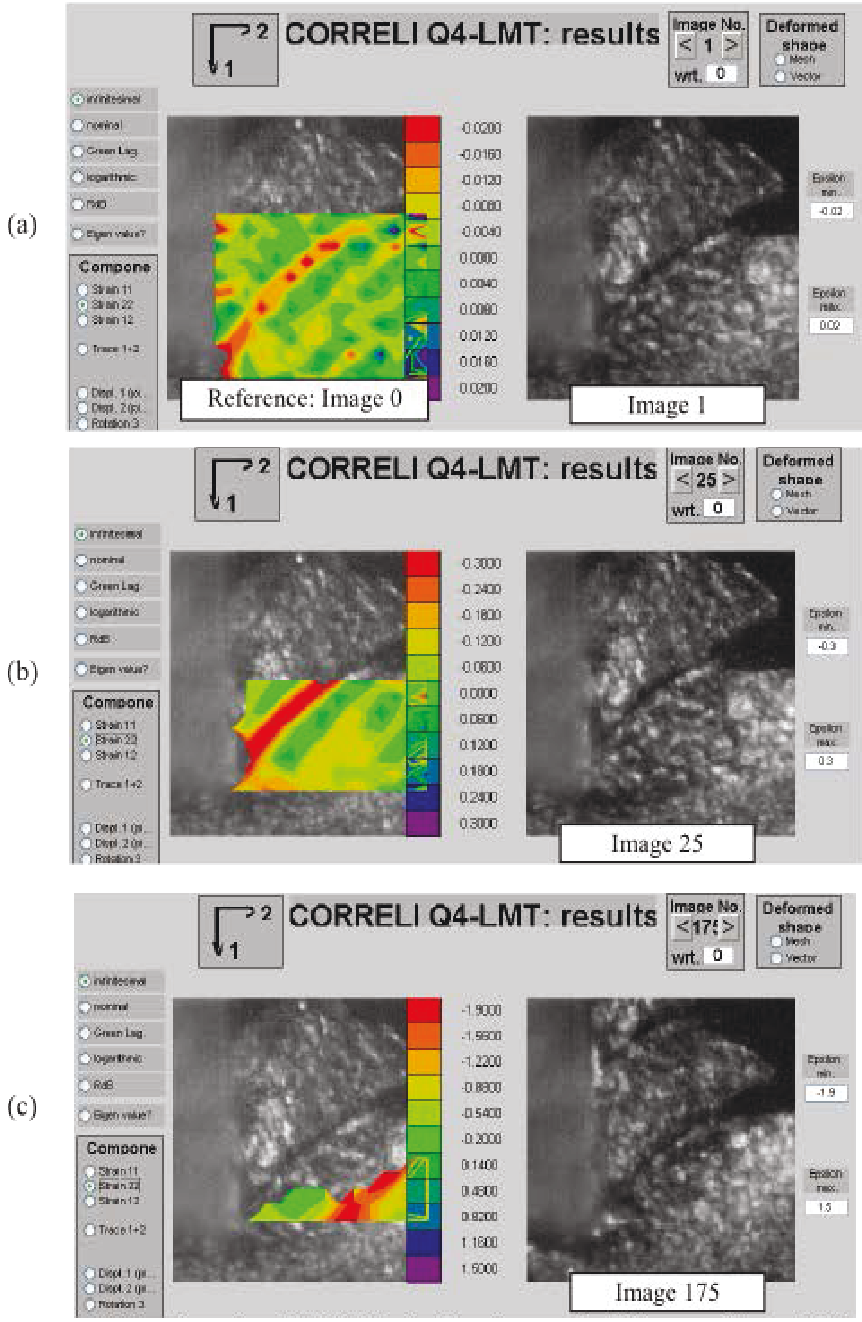

Fig. 3. Strain field in direction 2 (ZOI 8x8) a) at image 1; b) image 25 and c) image 175

Experimental/numerical strain field comparison

A numerical simulation of titanium alloy chip formation was carried out by using FORGE2D software. The cutting conditions are similar for both experimental and simulation cases: a cutting speed of 6m/min and an uncut chip thickness of 0.15mm. The mesh size in the shear band formation area is about 2μm. Material behaviour and friction laws used in numerical simulations are the same than in Calamaz et al. [6], i. e. TANH law and Coulomb friction law, with a friction coefficient of 0.3. Fig.4 shows a comparison between 22 (or XX) strain measured by Correli and the one estimated by numerical simulation.

As it can be seen in Fig.4a, the strain in the shear band, at the final stage of a shear band formation, is between 30% and 40%. At the same stage of shear band formation, the numerical simulation estimates a strain between 30% and 50% into the shear band, as shown in Fig.4b. The strain estimated by numerical simulation has the same order of magnitude than the measured one.

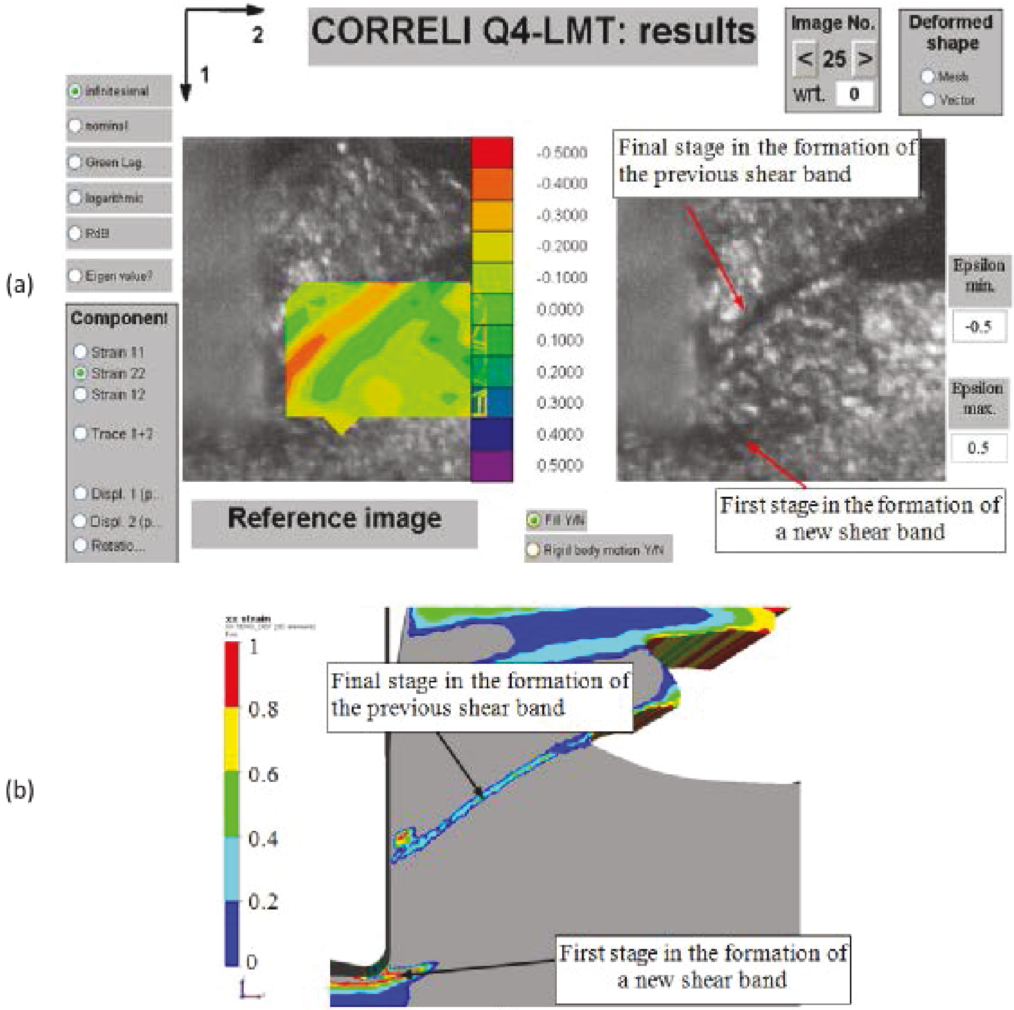

Fig. 4. 22 (or XX) strain at the final stage of a shear band formation (a) measured by Correli and (b) estimated by numerical simulation

At the same stage of the shear band formation as in the previous figure, the measured 11 (or ZZ) strain into the shear band ranges between 12% and 24% as shown in Fig. 5a, the strain being higher near the tool rake face. The numerical simulation estimates the ZZ strain between 6% and 22%, as it can be seen in Fig. 5b, also higher near the tool rake face.

The measured and simulated strain in the shear band have the same order of magnitude; the few differences may be due to a different mesh type and size used in digital images correlation and in the numerical simulation. Nevertheless, the results are very promising and the validation of numerical models from local experimental results is a key for mastering the machining process.

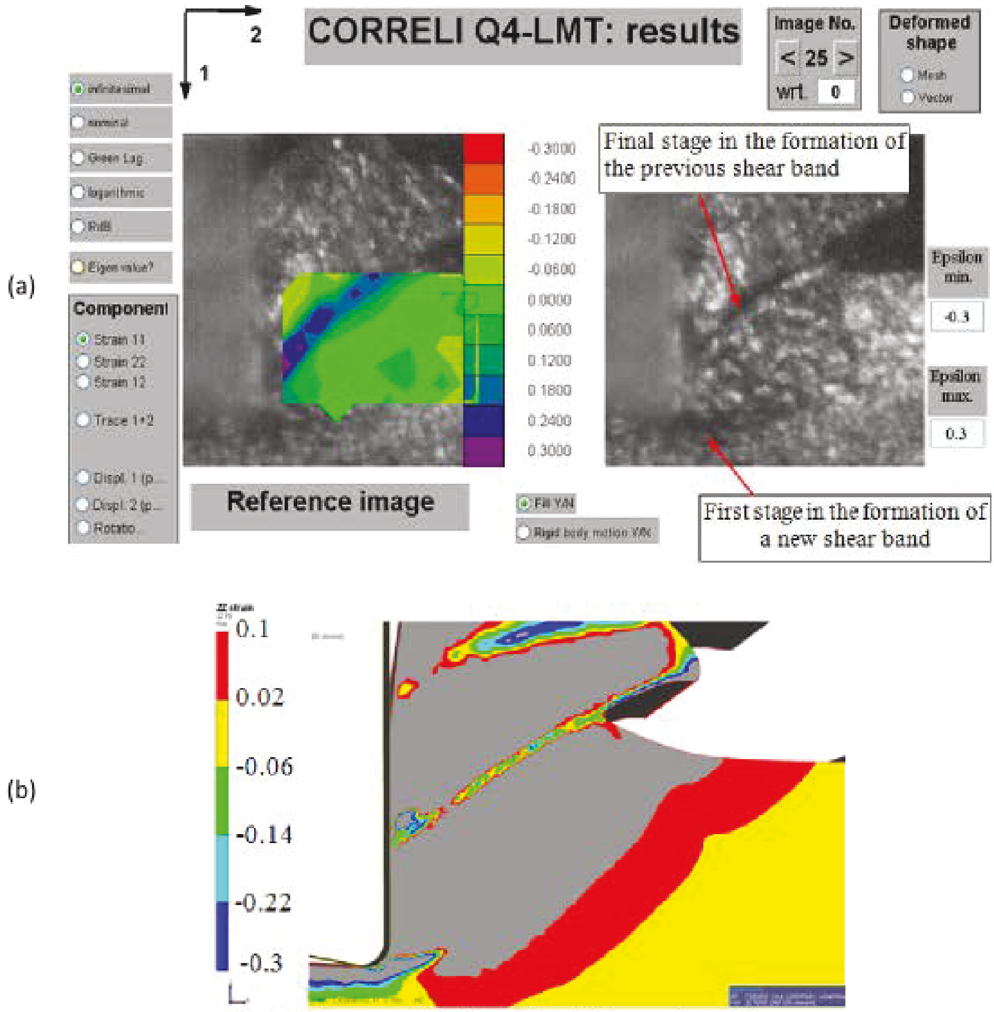

Fig. 5. 11 (or ZZ) strain at the final stage of a shear band formation (a) measured by Correli and (b) estimated by numerical simulation

Conclusions

This article showed that images correlation software enabled shear band detection during machining. The measured strain in the primary shear bands was also compared with numerical simulation results and similar values have been found. So, an optimum adjustment of camera settings, lighting, workpiece surface preparation and cutting conditions made possible to obtain an acceptable image quality (but perhaps still insufficient) for analyzing with Correli software. A higher resolution combined with a higher image acquisition frequency must enable a better image quality and thus a higher accuracy of the image digital correlation.

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