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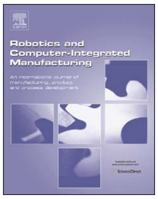

Residual stresses evaluation in precision milling of hardened steel based on the deflection-electrochemical etching technique

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ABSTRACT

Machining operations generate residual stresses in both the surface and subsurface of the workpieces. These residual stresses have a big influence on the functionality of the machined parts, thus their evaluation is of great importance. In terms of the fatigue strength and stress-corrosion cracking resistance, the compressive residual stresses are preferred to the tensile ones. In the present study, the generation of residual stresses in the precision milling of steels is evaluated by using the deflection-electrochemical etching technique. Two different materials were used to compare the obtained results: DIN X210Cr12 and DIN 17210-86. For the first one, two different states were tested: hardened and unhardened. The results showed different trends for the materials tested. Thus, the higher residual stresses were found at the surface for the DIN X210Cr12 while the maximum values were obtained in the subsurface for the DIN 17210-86. Finally, when comparing to the X-ray diffraction method, it is stated that both the deflection-electrochemical etching and X-Ray diffraction methods can be used to evaluate the state of the surfaces, though the destructive one can give more detailed information about the residual stresses distribution.

1. Introduction

Surface integrity plays a major role in the functional performance of the machined components and thus it has been an important topic for the research community in the last decades [1]. Materials mechanical, physical and chemical properties are important in order to assess the machinability of the materials [2]. To characterise the machined surfaces, the residual stresses are usually evaluated and numerous both analytical and experimental studies were performed in the past [3]. Among the experimental methods, it is possible to highlight the hole drilling method (destructive method), and neutron and X-ray diffraction (non-destructive method) [4].

The importance of the stresses in machining is due to the redistribution of residual stresses induced by the machining process [5]. Residual stresses greatly influence the strength, fatigue life and dimensional stability of components [6]. Two types can be identified: compressive and tensile. According to Ulutan and Ozel [7], many researchers have analysed this type of stresses finding different results. Some claim that the tensile stresses appear on the surface while others claim that their nature is compressive. The importance of the nature of stresses is explained by the fact that the compressive ones improve the fatigue strength [8] though both types can induce the deformation of the parts and destroy their geometric precision [9]. Moreover, it is often required to post-process the machined parts with techniques such as shot peening and burnishing to reduce the level of tensile residual stresses [4].

In order to compare the results obtained using the destructive method, the X-ray diffraction ("$\sin^2\psi$") was used and discussed in Section 4. The X-ray diffraction method is currently the least used method for both laboratory and industrial measurements. The destructive methods detect only stresses of the type I (macro residual stress that develop in the body of a component on a scale larger than the grain size of the material) and provide information about the stresses across the entire material volume [10]. The mechanical destructive methods can be used irrespective of the metal structural composition. The X-ray diffraction method provides information about the state of the surface layer to a maximum depth of 5 µm distinguishing type II and III stresses [11]. However, the X-ray diffraction method is difficult to apply to materials with crystals of large sizes (10 µm), in which the diffraction line disintegrates [12].

The study of the residual stresses has been accomplished by both experimental and theoretical methods identifying the influence of several parameters on their results. For instance, Su et al. [13] presented a model for the residual stresses in milling that used the

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cutting process conditions such as cutting speed, depth of cut, and feed rate along with tool geometry and material properties as inputs for the model.

The machining parameters and the characteristics of the workpiece material are of special interest for the residual stresses generation [14]. For instance, the tool geometry is recognised as a relevant factor to control the residual stresses. In particular, the influence of the tool nose radius on the residual stresses during the milling of Ti-6Al-4V was recognised by Wyen et al. [15]. Arunachalam et al. [16] analysed the influence of the geometry on the residual stresses in the facing of hardened Inconel 718 with cubic boron nitride (CBN). Authors found that both compressive and tensile residual stresses appeared when using round tools, while only tensile residual stresses appeared when using square geometries. The depth of cut is also an important parameter for the residual stress generation. In this sense, Li et al. [17] evaluated the effect of the depth of cut on the residual stresses in the milling of Al2024-T3. In the study, a clear influence of the depth of cut on the profile of the residual stresses was found. In particular, it was identified that as the depth of cut decreases from roughing to finishing, the residual stresses decreases accordingly.

In addition to the tool geometry, the tool wear generated in the hard machining showed an influence on the residual stresses [18]. As the flank wear increases, so does the frictional energy between the tool flank and the workpiece surface as well as the depth of the compressive stress induced by mechanical loading. Thus, a higher tool wear leads to larger tensile residual stresses near the surface, followed by a steep stress gradient with a larger compressive stress further below the surface. The stress pattern with less overall change was generated by a tool with less flank wear. Tang et al. [19] also recognised the influence of the tool wear on the residual stresses in the milling of aluminium alloys. Authors stated that the small flank wear produced lower stresses on the surface, and the stresses shift from compressive to tensile with an increase in the flank wear.

Several researchers have examined the effect of other machining parameters on the residual stresses generation. For instance, Matsumoto et al. [20] identified the influence of the feed rate in the residual stresses generation near the surface in hard turning, while no noticeable effect of the depth of cut was recognised. According to Hua et al. [14], as the feed rate is increased, it is expected to get more compressive residual stresses. The statistical analysis performed by Coto et al. [21], in the turning of AISI 4340 steel, states that the optimum (less tensile residual stresses) is obtained when using the lowest feed rate and highest cutting speed. Li et al. [22] investigated the residual stresses in the milling of the Ti-6Al-4V titanium alloy. Authors recognised the generation of compressive stresses using the X-ray diffraction method. Moreover, the higher the cutting speed and feed rate, the higher the compressive residual stresses. Finally, the influence of the hardness of the workpiece material is evaluated by Hua et al. [14]. In their study, researchers found that the high workpiece hardness allows the generation of more compressive residual stresses.

The present study analyses the residual stresses generated in the precision milling of two different materials: DIN X210Cr12 (hardened and unhardened) and DIN 17210-86 by using a destructive method. In particular, the deflection-electromechanical etching technique was selected to perform the analysis. After the revision of the main literature on the study of the residual stresses presented in Section 1, the experimental setup is presented in Section 2. Then, the evolution of the residual stresses on the workpieces is evaluated in Section 4 and main conclusions are summarised in Section 5.

2. Materials and methods

A CNC milling machine TOS FV 25 with a programmable controller Heidenhain TNC 310 was used for all the milling operations. Cubic boron nitride and polycrystalline cubic boron nitride are being used as base materials for cutting tools in hard machining [23]. In these tests, the cutting tools used were circle CBN - RCHT 12 04 M0 CB50. The main characteristics of the tools are listed in Table 1.

Table 1
Properties of the tested RCHT 12 04 M0 CB50 cutting insert.

Property	Value
Coating	Uncoated
Corner radius (mm)	6
Clearance major angle (°)	7
Cutting edge count	2

Table 2
DIN X210Cr12 nominal composition (%).

C	Mn	Si	Cr	V	Mo	Ni	P	S
2.00%	–	–	11.50%	–	–	–	–	–

Table 3
DIN 17210-86 nominal composition (%).

C	Mn	Si	Cr	P	S
0.14–0.19%	1.10–1.40%	0.17–0.37%	0.80–1.10%	Max 0.035%	Max 0.035%

Two types of workpiece materials were used: DIN X210Cr12 (Table 2) and DIN 17210-86 (Table 3). Their dimensions were 30×15×10 mm. The workpieces made of DIN X210Cr12 were used in two different states: unhardened and hardened in order to evaluate the influence of the state on the residual stresses.

The milling parameters selected for the tests were fixed at one level to analyse the influence of the workpiece material in isolation. These parameters include: cutting speed, depth of cut, feed rate and spindle speed. The values selected for them are listed in Table 4.

The removal of layers is an adequate method to measure residual stresses in parts where the residual stresses are known to vary uniformly with the depth from the surface [6]. The electrochemical or chemical method was selected for removing surface layers because it allows removing layers with practically no additional stresses on the workpiece. Moreover, it is an adequate method because of the small amount of material to be removed. By removing layers of the material, the equilibrium of stresses is changed to a different one and a deflection (or displacement) of the workpiece is produced. Thus, a layer of material is removed by the electrolytic dissolution based on the procedures developed in the laboratories of the Czech Technical University in Prague (CTU). In Fig. 1, it is depicted the scheme of the equipment used for measuring the deflection by the electrolytic dissolution of the surface layer. The terms of the electrolytic dissolution are listed in Table 5. For the experiment with the DIN 17210-86 steel, the electrolyte was adjusted by adding hydrofluoric acid (HF).

The experimental method uses also the classic equations for the deflection of a cantilever taken from the Mechanics of materials. The deflection sensed by the linear voltage displacement transducer had a magnitude and direction that depends on the characteristics of the stress in the layer removed. Thus, by measuring the changes in deflection, it is possible to compute the residual stresses. The results were recorded with software developed in the CTU.

Table 4
Milling parameters.

Cutting speed (m/min)	115
Feed rate (mm/rev)	0.10
Spindle speed (rpm)	538
Depth of cut (mm)	0.2