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Procedia Engineering 19 (2011) 67 – 72

Procedia Engineering

www.elsevier.com/locate/procedia

1st CIRP Conference on Surface Integrity (CSI)

An experimental investigation of residual stresses in hard machining of AISI 52100 steel

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Abstract

In this paper an experimental investigation was conducted to determine the effects of the tool cutting-edge geometry, workpiece hardness, cutting speed, and microstructural changes (white and dark layers) on the residual stresses in dry orthogonal hard machining of AISI 52100 steel. X-ray diffraction technique was used to obtain in-depth residual stresses profiles in both axial and circumferential directions. The results show that tool geometry, workpiece hardness and cutting parameters significantly affect the surface residual stress, maximum compressive residual stress below the machined surface and its location. Moreover, microstructural analysis shows that thermally-induced phase transformations have a significant impact on the magnitude and location of this maximum compressive residual stress peak.

Selection and peer-review under responsibility of Prof. E. Brinksmeier

Keywords: Cutting, Surface integrity, Residual stress

1. Introduction

Surface integrity of a machined component is an important aspect to take into account for the performance of the component in service; for this reason the quality of both the machined surface and subsurface needs to be carefully investigated. Surface integrity includes surface roughness, the presence

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doi:10.1016/j.proeng.2011.11.081

of microcracks, microstructural changes, phase transformation, residual stresses plastic deformation and changes in the microhardness. These factors determine the behaviour and service failures of the produced components. For the cited reasons related to the machined surface integrity, a comprehensive understanding of the machining process is essential in order to better design the machining process choosing the correct process conditions. Numerous studies have been conducted to investigate the relationships between machining process parameters and residual stresses [1-3], as well as to study the microstructural changes in the machined surface [4-6]; however only in few studies both these aspects were considered. Abrao and Aspinwall [7] examined the effects of tool wear in hard-turning of AISI 52100 steel showing that white layer is in a state of compressive residual stress and fatigue life of hard turned specimens is greater than ground specimens. Liu and Barash [3] suggested that an increase in edge radius results in a more compressive residual stress near the workpiece surface, based on the residual stress analysis for finish hard turning of AISI 52100 steel. Schwach and Guo [8] investigated the fatigue life of component subject to rolling contact found that a component free of a white layer had a life six times that of a component with white layer. Matsumoto et al [9] examined the effect of workpiece hardness on residual stresses produced in facing of case hardened AISI 4340 steel, they showed that, in the absence of phase transformation, residual stresses become more compressive when workpiece hardness increases. In contrast, Melkote et al [10] studied the residual stress profile induced by hard machining found that it is significantly more compressive in the specimen with white layer than that without presence of white layer. Consequently, fatigue life was found to be directly proportional to both the surface compressive residual stress and the maximum compressive residual stress in the specimen.

In this context and taking also into account that opposite treads can still recognized in literature, this work aims at investigating the effects of machining parameters (cutting speed, hardness and tool geometry) on the residual stress profiles during hard turning of AISI 52100, and correlating them with the microstructural phase transformations.

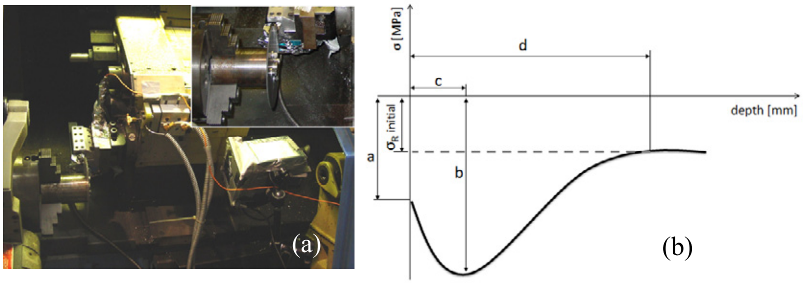
2. Experimental Procedure

2.1. Experimental machining set-up

Disks of hardened AISI 52100 steel (outer diameter = 150 mm, thickness = 2.5 mm) were prepared by sawing from a round bar stock, followed by machining, heat treatment, and gentle grinding to restore flatness and parallelism after the distortion caused during quenching. The disks were divided into two lots and different quenching and tempering treatments were used to have two different values of hardness, 56.5 HRC and 61.0 HRC, respectively. Dry orthogonal cutting tests were conducted on a stiff high speed CNC lathe by means of a radial cutting operation (Fig. 1 a) using PCBN tool inserts (CBN 50 vol.% and TiC binder) with two different edge geometries: chamfered (ISO TNGN 110308S) and honed (ISO TNGN 110308E) with edge radius of 0.015 mm. The tool inserts were mounted on a CTFNR3225P11 tool-holder, providing a rake angle of -8° and a clearance angle of 8°. The disks were machined with varying cutting speed, initial workpiece hardness and tool shape, as indicated in Table 1. Feed rate was kept constant and equal to 0.125 mm/rev.

Table 1. Experimental test conditions

	Chamfer Tool				Hone Tool
Test	1/2	3/4	5/6	7	8
Cutting Speed [m/min]	75	150	250	350	250
Hardness [HRC]	56.5/61	56.5/61	56.5/61	56.5	56.5



a: *Surface residual stress*

b: *Maximum compressive residual stress below surface*

c: *Penetration depth*

d: *Thickness affected by machining residual stress*

Fig. 1. (a) Experimental set-up. (b) Residual stress parameters.

2.2 Experimental optical and residual- stresses set-up

After machining, samples of 5 mm x 5 mm were sectioned by wire-EDM from each disk specimen for microstructure analysis. The samples were mounted in a hard resin for insuring edge retention and then ground, polished and etched for about 10 s using 2% Nital solution to observe white and dark layers using an optical microscope (500x). Scanning electron microscopy (SEM) was also used to examine the white layer and to conduct energy dispersive spectroscopy (EDS) analysis.

The white layer thickness values measured using an optical microscope were found to be consistent with those measured by SEM. Finally the residual stress state in machined disk surfaces was analyzed by X-Ray diffraction technique (XRD) using the $\sin^2\psi$ method [11]. This technique can be used to determine the surface and subsurface residual stress distribution. The parameters used in the X-Ray analysis are shown in Table 2.

Table 2. X-Ray diffraction parameters for residual stress measurement

X-Ray radiation	Young's modulus	Poisson ratio	Bragg angle 2θ	Lattice plane	Number of ψ angles (±40°)
Cr-Kα	210 GPa	0.3	156.3°	{2 1 1}	15

To determine the in-depth residual stress profiles, successive layers of material were removed by electro-polishing to avoid the alteration of machining-induced residual stresses. Further corrections to the residual stress data were made due to the volume of material removed. Due to the specific shape of the workpiece a rectangular mask was applied on the surface to limit the region of the X-Ray analysis.

3. Results and discussions

In this paragraph a detailed description of the influence of different cutting parameters and microstructural changes on the surface and sub-surface residual stresses profile will be shown. To better describe the influence of each single cutting parameter on the residual stress shape four different factors were considered (figure 1 b): a: *Surface residual stress*; b: *Maximum compressive residual stress below surface*; c: *Penetration depth*; d: *Thickness affected by machining residual stress*.

3.1. Influence of the cutting speed

Figure 2 shows the influence of the cutting speed on the residual stress profile; taking into account the four parameters above reported (and also depicted in Fig. 1 b), it is possible to describe how the residual stress profiles are affected (both for the axial and circumferential directions). In particular, the results highlight that with the increase of the cutting speed a deeper compressive surface residual stress is registered by the X-Ray analysis in the axial direction as well as in the circumferential one. In addition, the maximum compressive residual stress below surface becomes larger when cutting speed increases and its location is shifted further away from than surface. These variation are more evident on the axial direction.

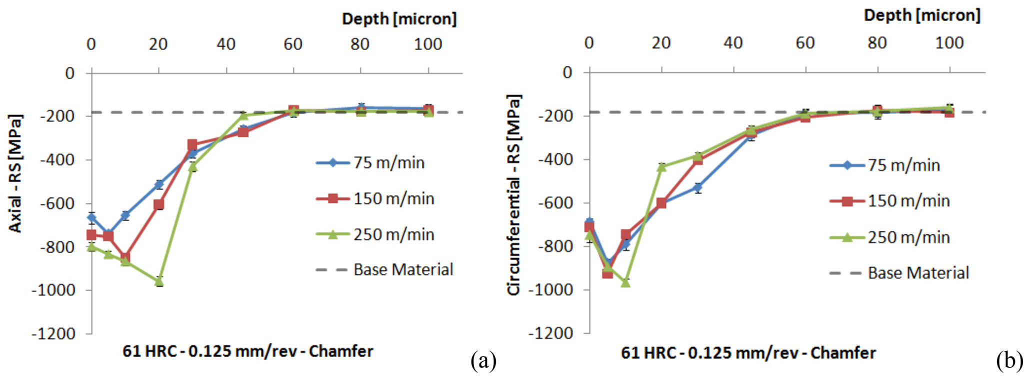


Fig. 2. Effect of cutting speed on the residual stress for 61 HRC along the axial (a) and circumferential (b) directions.

On the contrary when cutting speed rises the thickness affected by machining residual stresses decreases. The reason of these trends, as it will be better described in paragraph 3.4, is strictly related to the presence of the white layer, which becomes thicker and harder with increasing cutting speed [12].

3.2. Hardness influence

In figure 3 (a) is reported the influence of the initial workpiece hardness on the residual stress profile for given cutting speeds. It is evident that the increment of hardness produces more compressive axial and circumferential residual stress profiles while the position of maximum compressive stress below surface remains almost constant. Also the surface residual stress in both the directions increase with higher initial hardness. The reason is related to the hard structure on the machined surface which produces more compressive residual stresses [13]. Finally, the thickness affected by machining residual stress depth slightly increases with the increase of the initial workpiece hardness.

3.3. Tool geometry influence

Figures 3 (b) reports the influence of the tool geometries on the residual stress profiles. It shows that the use of a chamfered tool generates higher axial and circumferential compressive residual stresses than for the equivalent test case with a honed tool in terms of both surface residual stress and maximum compressive stress below surface. In contrast both the tool shapes report similar location of the penetration depth either for the axial direction or for the circumferential one.

3.4. Influence of the microstructural changes (white and dark layers)

Figure 4 shows the influence of the white and dark layers on residual stress state for tests 2 and 6. As can be observed, for a lower cutting speed (Fig. 4 (a)) the max. compressive residual stresses for both the axial and the circumferential directions are positioned in the white layer region. Such evidence was also observed for the specimens at 56.5 HRC machined at the same cutting speed. In contrast, at higher cutting speed (Fig. 4 (b)) the maximum compressive stress is positioned near the white-dark layer transition (circumferential direction) or in the dark layer (axial direction). Similar observations were done for specimens at 56.5 HRC. The reason of these evidences are related to the fact that both white layer thickness and position of the penetration depth increase with the increasing of the cutting speed, although the latter rises more than the white layer thickness.

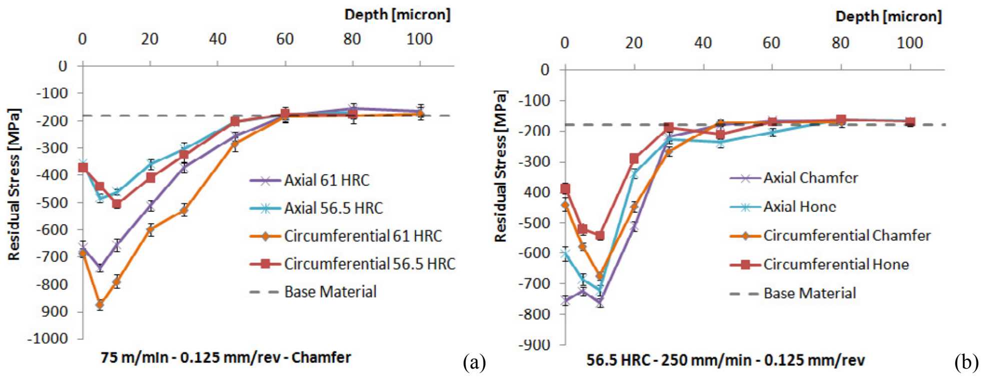


Fig. 3. Effect of initial workpiece hardness (a) and tool geometry (b) on the residual stress

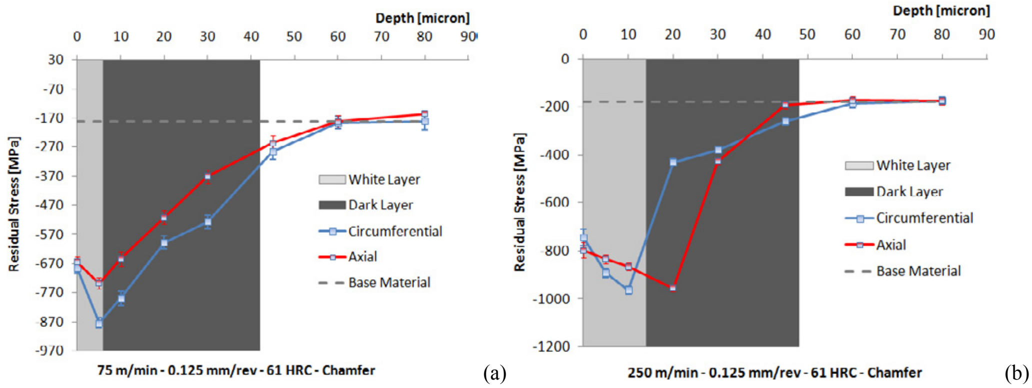


Fig. 4. Effect of the microstructural changes on residual stress profiles at 75 m/min (a) and 250 m/min (b) for specimens at 61 HRC.

Moreover, it is widely assessed that in orthogonal cutting of AISI 52100 with the increase of the cutting speed an increase in white layer and a decrease in dark layer thicknesses are registered; furthermore, when the initial workpiece hardness increases both white and dark layers thickness increase [12, 13]; also, Thiele et al [13] showed that with the increase of the hardness the residual stress state becomes more compressive. Therefore, taking into account all the investigated cases and the above mentioned knowledge, the overall reported in Table 3 can be drawn. Finally in the [12] was showed that the ratio $HRC_{max}/HRC_{initial}$ increases with the increase of the cutting speed and this (according also to Thiele et al [13]) leads to an increase in the compressive surface residual stress and in the maximum value of the compressive peak. In contrast, the thickness affected by machining residual stress is related to the dark layer thickness; in fact when the dark layer thickness increases the parameter *d* increases. Therefore, when cutting speed increases: (*i*) the hardness of the white layer increases [12] and consequently the residual stress state becomes more compressive [13]; considering Fig. 1 b, parameters *a* and *b* increase; (*ii*) dark layer thickness decreases [12] and consequently the thickness affected by machining residual stress decreases; considering Fig. 1 b, parameter *d* decreases.

Similar considerations can be done as concerned the residual stress profiles affected by the different initial workpiece hardness.

Table 3. Effect of cutting speed and hardness on the microstructural changes and residual stress

$HRC_{WHITE\text{-}LAYER} > HRC_{BULK\text{-}MATERIAL} > HRC_{DARK\text{-}LAYER}$				
Cutting Speed	↑	White Layer	↑	Dark Layer ↓
Hardness	↑	White Layer	↑	Dark Layer ↑
Hardness	↑	Compressive RS	↑	-

4. Conclusions

In this paper the effect on the cutting parameters and the microstructural alterations on the residual stress profiles were investigated. Particularly, when machining harder materials with chamfered tools, it was found that both the axial and the circumferential surface and subsurface residual stresses become larger (i.e., deeper) with increasing cutting speed. Also the location of the maximum compressive residual stress rises in a similar manner. Finally, microstructural changes deeply affect the residual stresses distribution and, for this reason, they have to be accurately taken into account during the process design.

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