Science Arts & Métiers (SAM)

is an open access repository that collects the work of Arts et Métiers Institute of Technology researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: https://sam.ensam.eu
Handle ID: .http://hdl.handle.net/10985/8505

To cite this version :

Serafino CARUSO, José OUTEIRO, Domenico UMBRELLO, Antonio BATISTA - Residual Stresses in Machining of AISI 52100 Steel under Dry and Cryogenic Conditions: A Brief Summary - 2014

Any correspondence concerning this service should be sent to the repository Administrator : scienceouverte@ensam.eu

Arts et Métiers Institute of Technology

Residual Stresses in Machining of AISI 52100 Steel under Dry and Cryogenic Conditions: A Brief Summary

S. Caruso[1, a *], J.C. Outeiro[2, b], D. Umbrello[1, c], A.C. Batista[3, d]

[1] Department of Mechanical, Energy and Management Engineering, University of Calabria, Rende CS 87036, Italy.

[2] LaBoMaP, Arts et Metiers ParisTech, 71250 Cluny, France

[3] X-Ray Diffraction Center for Materials Research, University of Coimbra, 3030-380 Coimbra, Portugal

[a]serafino.caruso@unical.it, [b]jose.outeiro@ensam.eu, [c]d.umbrello@unical.it, [d]castanhola@fis.uc.pt

Keywords: Hard Turning, Cryogenic cooling, White layer, AISI 52100

Abstract. Residual stress is one of the most important surface integrity parameter that can significantly affect the service performance of a mechanical component, such as: contact fatigue, corrosion resistance and part distortion.

For this reason the mechanical state of both the machined surface and subsurface needs to be investigated. Residual stress induced by dry and cryogenic machining of hardened AISI 52100 steel was determined by using the X-ray diffraction technique.

The objective was to evaluate the influence of the tool cutting edge geometry, workpiece hardness, cutting speed, microstructural changes and cooling conditions on the distribution of the residual stresses in the machined surface layers.

The results are analysed in function of the thermal and mechanical phenomena generated during machining and their consequences on the white layer formation.

Introduction

All over the world, machining operations such as turning, milling, drilling and shaping are consuming large amounts of money annually. In this context, hard turning is becoming more competitive because of its ability to properly merge factors of great interest, such as production costs, productivity and especially product quality. On the contrary, several issues related to this process require further investigations. Among these the main ones are associated with the high temperatures generated at the tool-chip and tool-workpiece interfaces that strongly affect the surface integrity and consequently the functional performance and life of a mechanical component.

Most of the mechanical energy spend in cutting is transformed in heat, which is concentrated in a very small zone, resulting in high temperatures, subsequently in high tool wear rate and surface integrity degradation of the machined component.

Surface integrity (roughness, microcracks, microstructural changes, phase transformations, residual stresses,…) 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. In order to improve surface integrity it is necessary to decrease the temperatures. This can be achieved by selecting the appropriated cutting tool geometry, cutting parameters and cooling conditions [1, 2].

Numerous studies have been carried out to investigate the influence of the cutting parameters on the residual stresses [3-5], as well as to study the white layer formation in machining of hardened steels [6-8]. However only few studies investigated the effects of lubrication/cooling, in particular the minimum quantity of lubricant (MQL), on both the white layer and residual stresses formations [8-9]. The main objective of this research is to provide a contribution in this direction, showing the the effects of the cutting tool edge geometry, workpiece hardness, cutting speed, microstructural changes and cryogenic cooling conditions on the residual stress distribution in the machined surface and subsurface induced by orthogonal machining of hardened AISI 52100.

Experimental Plan

Dry and cryogenic orthogonal cutting tests were conducted on hardened 52100 steel disks using a MAZAK high speed CNC turning center, equipped with ICEFLY^{TM} cryogenic fluid delivery system. These tests were performed using CBN cutting tools (SECO grade: CBN 100) with chamfered (ISO TNGN 110308S, chamfer = 20° x 0.1 mm) and honed edge geometries (ISO TNGN 110308E, tool edge radius = 0.015 mm), mounted on a CTFNR3225P11 tool holder, providing rake and clearance angles of -8° and 8°, respectively.

Disks were machined varying cutting speed, initial workpiece hardness and cutting tool edge geometry, both under dry and cryogenic cooling conditions (Table 1). The uncut chip thickness was kept constant and equal to 0.125 mm. In order to reach the mechanical and thermal steady-state conditions, the cutting time for each test was 18-20 s. In the machining tests, a very low flank wear of 0.03-0.05 mm was observed on the utilized CBN tools, thus the influence of tool-wear on the surface integrity can be neglected.

Cryogenic coolant was applied by a nozzle to the area of interest as shown in Fig.1.

After machining, samples of 5 mm x 5 mm were sectioned by wire-EDM, then polished and etched for 5 s using 5% Nital solution to observe microstructural changes using a light optical microscope (1000 X) and a scanning electron microscope (SEM).

Finally the residual stress state in machined surface and subsurface was analyzed by the X-Ray diffraction technique (XRD) using the $\sin^2\psi$ method [10]. The parameters used are reported in [11].

Both axial and circumferential residual were measured. 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 stress. 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 for XRD analysis.

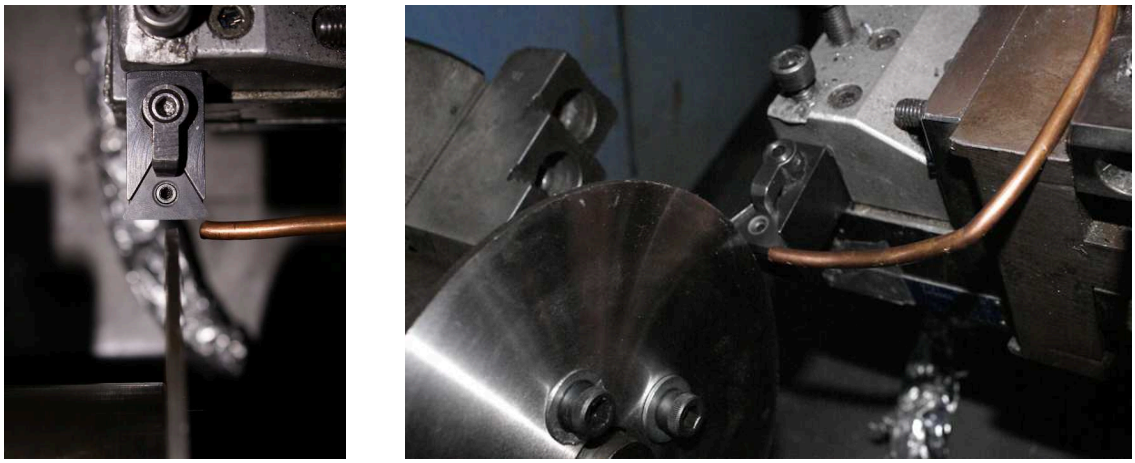

Figure 1. Experimental set-up: orthogonal cutting with cryogenic delivery nozzle position [12].

Table 1. Experimental test conditions

	Chamfer Tool				Hone Tool	Chamfer Tool
Test	1/2	3/4	5/6	7	8	9
Cutting Speed [m/min]	75	150	250	350	250	75
Hardness [HRC]	56.5/61	56.5/61	56.5/61	56.5	56.5	56.5
Cooling Condition	Dry	Dry	Dry	Dry	Dry	Cryogenic

Experimental Results and Discussion

In this paragraph, a detailed description of the influence of different cutting parameters, microstructural changes and cooling conditions on the surface and subsurface residual stresses distribution will be presented. To describe the influence of each single cutting parameter on the in-

depth residual stress profile, four different factors were considered (Fig. 2): a: *Surface Residual Stress;* b: *Maximum Compressive Residual Stress Below Surface;* c: *Penetration Depth;* d: *Thickness Affected by Machining Residual Stress.*

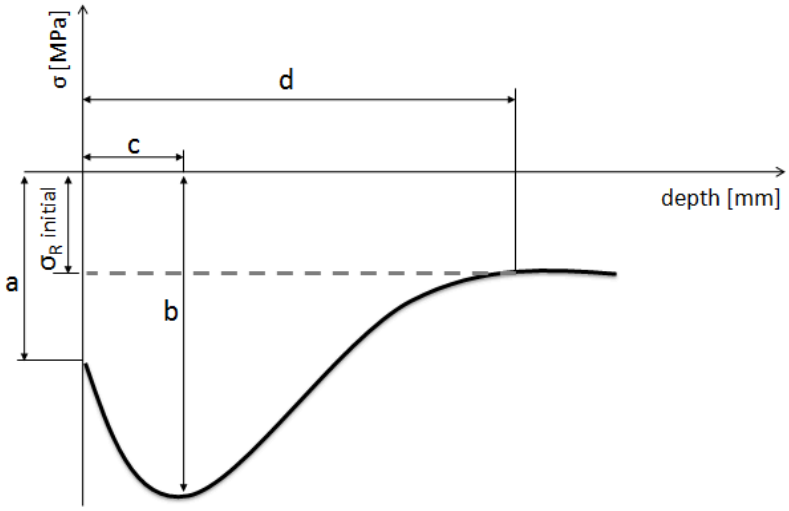

Figure 2. Parameters of the in-depth residual stress profile [9].

Influence of the Cutting Speed. Figure 3 shows the influence of cutting speed on the residual stress profile in dry cooling condition. Taking into account the four parameters above reported (Figure 2), it is possible to describe how both axial and circumferential residual stress curve are affected. The results for dry cooling condition show that surface residual stress becomes more compressive as cutting speed increases, either in the axial direction as well as in the circumferential one. Furthermore, the maximum compressive residual stress below surface becomes more compressive when cutting speed increases and its location is shifted further from surface. In contrast, a slightly decrease of the thickness affected by machining residual stresses is registered with the increase of the cutting speed. The same results were observed during cryogenic machining [13].

These results are related to the structure of the white layer, that becomes harder and thicker when cutting speed increases [11].

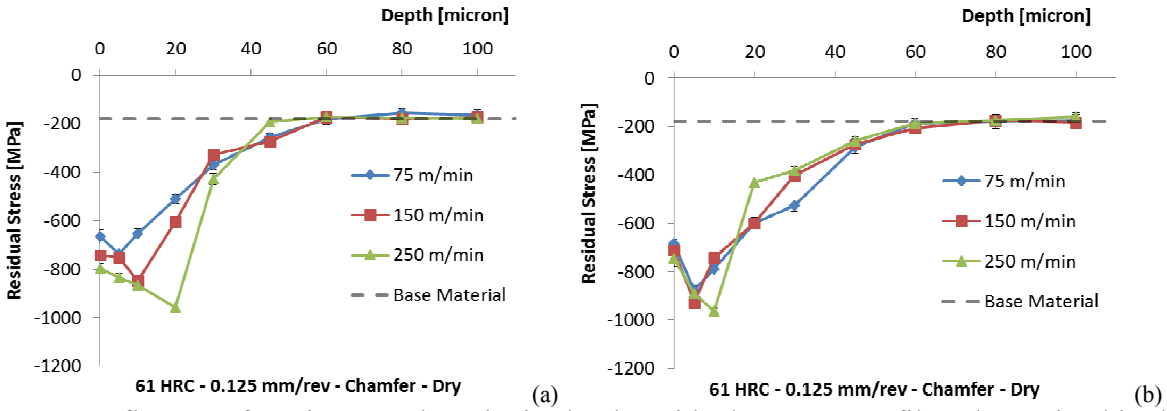

Figure 3. Influence of cutting speed on the in-depth residual stresses profiles, determined in the axial (a) and circumferential (b) directions (workpiece hardness of 61 HRC, dry machining) [9].

Influence of the Tool Geometry. Figure 4 shows the influence of the cutting tool edge geometry on the in-depth residual stresses profiles in dry cutting. Concerning to the surface residual stress and maximum compressive stress below surface, this figure shows that honed-edge tool geometry generates lower axial and circumferential compressive residual stress when compared with those profiles generated by chamfered-edge tool. However, no variation in the penetration depth parameter is reported for both axial and circumferential. The same trends were observed under cryogenic cooling condition [13].

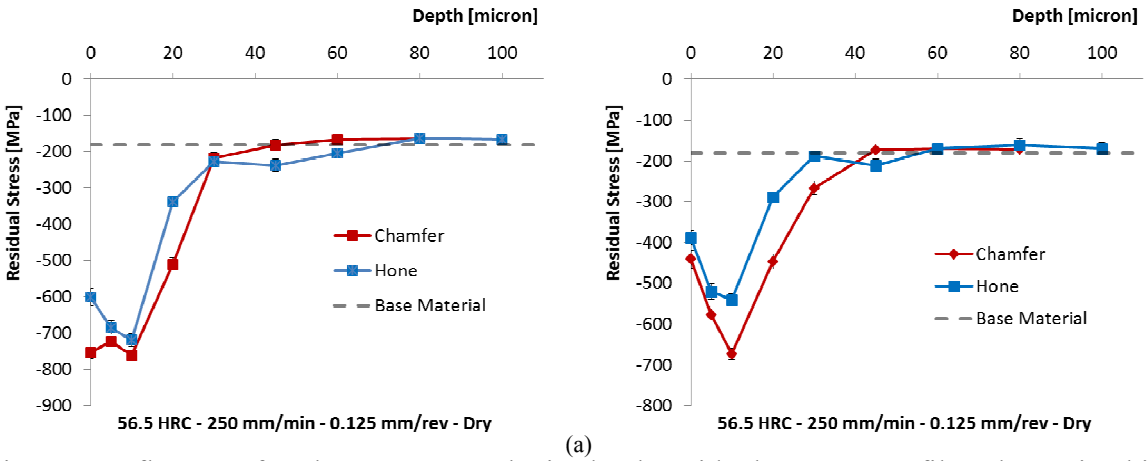

Figure 4. Influence of tool geometry on the in-depth residual stresses profiles, determined in the axial (a) and circumferential (b) directions (workpiece hardness of 56.5 HRC, dry machining) [9].

Influence of the Workpiece Hardness. Figure 5 shows the influence of the initial workpiece hardness on the in-depth residual stresses profiles in dry cutting. The reported trends show that the increase of workpiece hardness results in a shift of whole in-depth axial and circumferential residual stresses profiles towards compression. However, the location of maximum compressive stress below surface remains almost constant. The same results were observed during cryogenic machining [13]. The reason is once more related to the hard structure present on the machined surface caused by phase transformation during machining, which produces more compressive residual stresses [14]. Furthermore, when the initial workpiece hardness decreases a slightly decrease of the thickness affected by machining residual stress is observed.

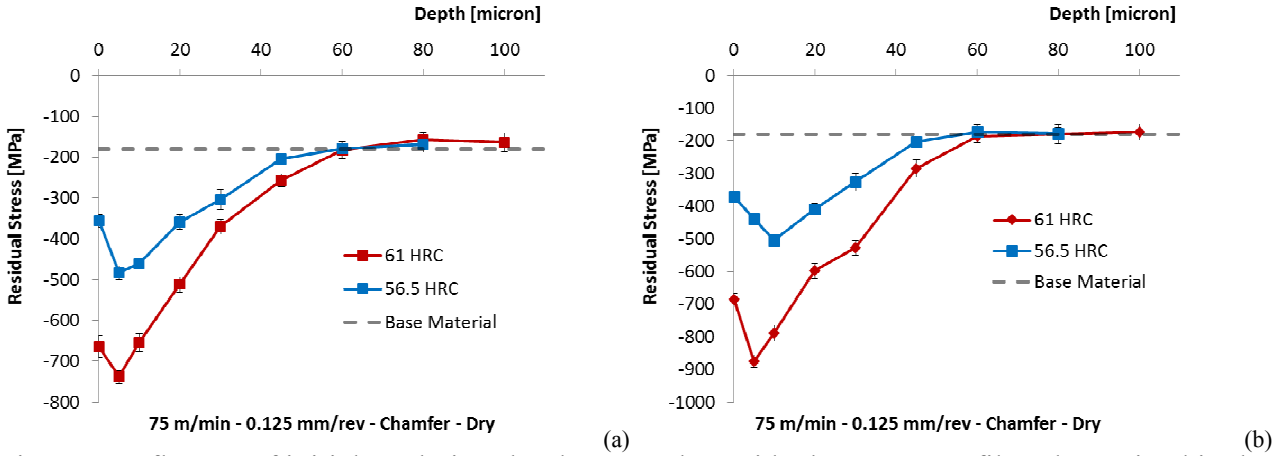

Figure 5. Influence of initial workpiece hardness on the residual stresses profiles, determined in the axial (a) and circumferential (b) directions (chamfered-edge geometry, dry machining) [9].

Influence of the Microstructural Changes (White and Dark Layers). Figure 6 shows the influence of the white and dark layers on the in-depth residual stresses profiles in dry cutting for tests 2 and 6. The results show that when machining is conducted at lower cutting speed the maximum compressive residual stress for both the axial and circumferential directions is located in the white layer region, while at higher cutting speed this maximum is located near the white-dark layer interface (circumferential direction) or in the dark layer (axial direction) region. Similar results were obtained for specimens having a hardness of 56.5 HRC. The reason for these evidences is related to the fact that both white layer thickness and location of the penetration depth increase with the increasing of the cutting speed.

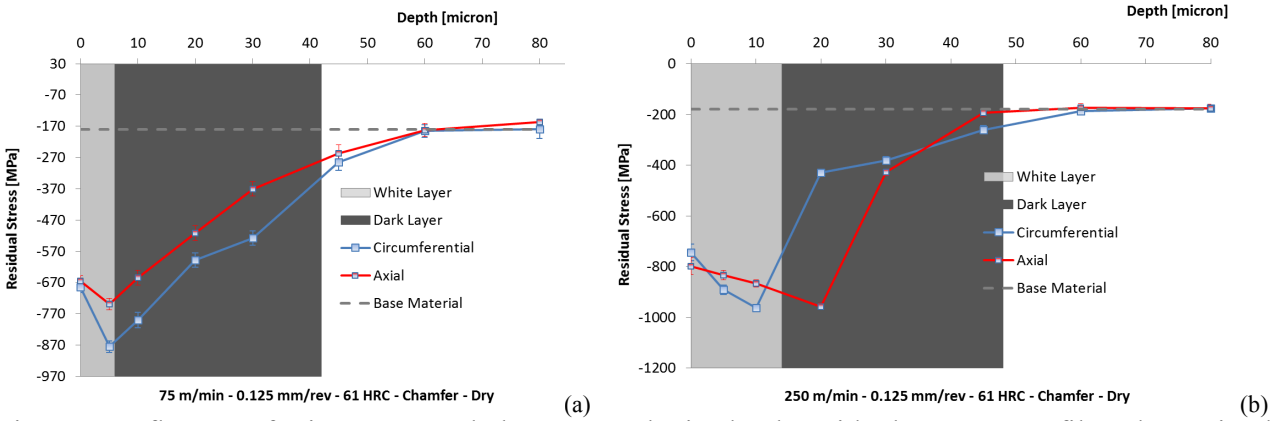

Figure 6. Influence of microstructural changes on the in-depth residual stresses profiles, determined for a cutting speed of 75 m/min (a) and 250 m/min (b) (workpiece hardness of 61 HRC) [9].

Influence of the Cooling Condition (Dry vs. Cryogenic). Figure 7 shows the influence of the cryogenic cooling on the in-depth residual stresses profiles, when comparing to dry machining. The results show that residual stresses are always compressive in both dry and cryogenic machining, although cryogenic cooling produces lower compressive or even tensile stress values when compared to dry machining. The reason for the lower compressive residual stresses values can be attributed to the lower hardness values observed on the machined surface and the sub-surface due to lower generation of white layer (characterized by untempered martensitic structure) [11].

Another aspect of great importance is the influence of the cooling conditions on the location of the penetration depth parameter, which shifts towards higher depths when dry machining is performed. This is once more related to the thickness of white layer that increases when dry machining is performed [15].

In fact, it is widely demonstrated that the maximum compressive residual stress for both the axial and the circumferential directions is strictly related to the white-dark layer transition [9]. So, when cryogenic machining is conducted the thickness of the white layer decreases and consequently the location of the maximum compressive residual stress value below surface is shifted nearer the surface.

As far as the fatigue life of the machined component is concerned, the compressive stress area, which represents the area limited by the compressive part of the residual stress profile and the x-axis, is of prime importance [16-21].

Figure 7 shows that these areas are inferior for cryogenic machining when compared to those areas observed for dry machining. This is mainly due to the lower generation of white layer that results in lower compressive values for surface residual stress (parameter a), lower maximum compressive residual stress below surface (parameter b) and lower thickness of the layer affected by compressive residual stresses induced by machining (parameter d).

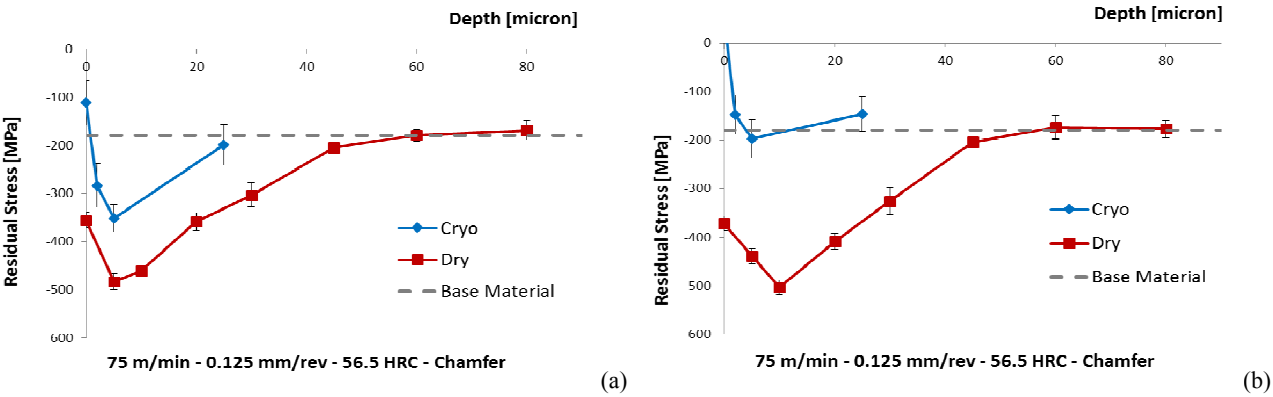

Figure 7. Influence of dry and cryogenic cooling on the in-depth residual stresses profiles, determined in the axial (a) and circumferential (b) directions.

Table 2 summarizes the influence of cutting speed, cutting tool edge geometry, workpiece hardness and cooling conditions on the white layer and compressive residual stress area.

Table 2. Influence of each parameter in the white layer and residual stress.

CUTTING SPEED ↑	White Layer ↑	Compressive Area ↑
WORKPIECE HARDNESS ↑	White Layer ↑	Compressive Area ↑
HONED -> CHAMFERED TOOL GEOMETRY	White Layer ↑	Compressive Area ↑
CRYOGENIC COOLING -> DRY CUTTING	White Layer ↑	Compressive Area ↑

Conclusions

In this paper the influence of the cutting speed, cutting tool edge geometry, microstructural changes and cooling conditions on the in-depth residual stress profiles induced by both dry and cryogenic machining of AISI 52100 was investigated.

It was found that both axial and circumferential surface and subsurface residual stresses become more compressive with increasing the cutting speed, for harder workpiece material and using chamfered tools.

Finally, experimental observations reported in this study suggest that the use of cryogenic coolant significantly affects the in-depth residual stresses profiles. In particular, cryogenic cooling conditions limit the white layer thickness resulting in a shift of the residual stress profile nearer the surface. This leads to a less compressive value of the surface residual stress and maximum compressive residual stress below surface with the consequently decrease of the compressive stress area. In contrast, dry machining shift of the residual stress profile further the surface, thus would contribute to improved fatigue life, although it produces a thicker white layer which is detrimental for the product's performance and relative cost (necessity of secondary removal operation).

Acknowledgements

The authors gratefully thank the Institute for Sustainable Manufacturing, ISM, at the University of Kentucky, for allowing to use the experimental equipment and Prof. I.S. Jawahir and Prof. O.W. Dillon Jr. for their help. The authors gratefully acknowledge the help provided by Dr. A. Jayal and T. Lu during the experimental work conducted at the ISM.

References

[1] N.R. Dhar, S. Paul, A.B. Chattopadhyay, "Role of cryogenic cooling on cutting temperature in turning steel", Transactions of the ASME 124,2002, pp. 146–154.

[2] N.R. Dhar, M. Kamruzzaman, "Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition", International Journal of Machine Tools and Manufacture 47,2007, pp. 754–759.

[3] J.A. Bailey, S. Jeelani, S.E. Becker, "Surface integrity in machining AISI 4340 steel", Ttrans. ASME, J. Eng. Ind, 1999, 98/3: pp. 999-1006.

[4] J.C. Outeiro, A.M. Dias, J.L. Lebrun, V.P. Astakhov, "Machining residual stresses in AISI 316L steel and their correlation with the cutting parameters", Machining Science and Technology, 2002, 6/2: pp. 251-270.

[5] C.R. Liu, M.M. Barash, "Variables governing patterns of mechanical residual stress in a machined surface", ASME J. Eng. Ind., 1982; 104: pp. 257–264.

[6] H.K. Tonshoff, H.G. Wobker, D. Brandt, “Hard turning influences on the workpiece properties”, Trans. NAMRI/SME, 1995, XXIII: pp. 215-220.

[7] J. Barry, G. Byrne, “Chip formation, acoustic emission and surface white layers in hard machining”, Ann. CIRP, 2002; 51: pp. 65–70.

[8] S. Akcan, S. Shah, S.P. Moylan, P.N. Chabra, S. Chandrasekar, H.T.Y. Yang, “Formation of white layers in steels by machining and their characteristics”, metallurgical and materials transactions, 2002, 33: pp. 1245-1254.

[9] D. Umbrello, S. Caruso, J.C. Outeiro, L.Filice, F. Micari, “An experimental investigation of residual stresses in hard machining of AISI 52100 steel”, Procedia Engineering, Vol. 19, pp. 67-72 (Special Issue of the 1st CIRP Conference on Surface Integrity (CSI)), 30 Jan - 1 Feb 2012 - Bremen, Germany, ISSN: pp. 1877-7058.

[10] I.C. Noyan, J.B. Cohen, “Residual stress – measurement by diffraction and interpretation”, springer, New York, (1987).

[11] D. Umbrello, “Influence of material microstructure changes on surface integrityt in hard machining of AISI 52100 steel”, International Journal of Advanced Manufacturing Technology 54 (9): pp. 887-898.

[12] D. Umbrello, S. Caruso, S. Di Renzo, A.D. Jayal, O.W. Dillon, I.S. Jawahir, “Dry vs. Cryogenic Orthogonal Hard Machining: an Experimental Investigation”, 14th International Esaform Conference on Material Forming, Belfast (United Kingdom), 27–29 April, 2011, Vol. 1353, pp. 627-632

[13] D. Umbrello, F. Micari, I.S. Jawahir, “The effects of cryogenic cooling on surface integrity in hard machining: a comparison with dry machining”, CIRP Annals - Manufacturing Technology, 61, (1), 2012: pp. 103-106.

[14] J.D. Thiele, S.N. Melkote, R.A. Peascoe, T.R. Watkins, “Effect of cutting-edge geometry and workpiece hardness on surface residual stresses in finish hard turning of AISI 52100 steel”, ASME J. Manuf. Sc. & Eng., 2000; 122: pp. 642-649.

[15] Z. Zurecki, R. Ghosh, J.H. Frey, “Investigation of white layer formed in conventional and cryogenic hard turning of steels”, ASME International Mechanical Engineering Congress and Exposition, Washington, November 2003, pp. 16-21.

[16] Field M, Kahles JF. “Review of surface integrity of machined components”, Ann CIRP 1971, 20: pp. 107–8.

[17] Bannantine J, Comer J, Handrock J. “Fundamentals of metal fatigue analysis”, Englewood Cliffs NJ: Prentice Hall; 1990. pp. 13–17.

[18] Huang Q, Ren JX. “Surface integrity and its effects on the fatigue life of the nickel-based superalloy GH33A”, Int J Fatigue 1991;13: pp. 326–32.

[19] Abrao A, Aspinwall D. “The surface integrity of turned and ground hardened bearing steel”.Wear 1996; 196: pp. 279–84.

[20] Matsumoto Y, Hashimoto F, Lahoti G. “Surface integrity generated by precision hard turning”, Ann CIRP 1999; 48: pp. 59–62.

[21] Y. Matsumoto, F. Hashimoto, G. Lahoti, “Surface integrity generated by precision hard turning”, Ann. CIRP 48 (1999), pp. 59–62.