An Experimental Study of Cryogenic Machining on Nanocrystalline Surface Layer Generation

Florian Ambrosy a,*, Frederik Zanger a, Volker Schulze a and I.S. Jawahir b

a wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany
b Institute for Sustainable Manufacturing (ISM), University of Kentucky, 523 CRMS Building, Lexington, KY 40506-0108, USA

* Corresponding author. Tel.: +49-721-608-45290; fax: +49-721-608-45004. E-mail address: Florian.Ambrosy@kit.edu.

Abstract

This paper presents an analysis of in-process liquid nitrogen cryogenic cooling on the generation of nanocrystalline workpiece (AISI4140) surface layer in machining. Samples from cryogenic machining demonstrate nanocrystalline grain refinement with beneficial properties, e.g., favorable wear characteristics. Correlations are established among process and geometry parameters, cooling conditions, cutting forces and surface layer states. Parameters studied are cooling state, depth of cut \( h \) and cutting edge radius \( r \). Cutting forces are measured and a detailed analysis of micro/nano-structural surface layer conditions was carried out using Focused Ion Beam system, Atomic Force Microscopy and Nanoindentation. It is shown that the obtained micro/nano-structure strongly depends on the cooling conditions. In particular, the affected depth is influenced by the cooling state.

Keywords: Cryogenic machining; Surface integrity; Grain size

1. Introduction

Surface integrity of machined components has a major impact on their functional performance [1, 2]. Grain refinement within the workpiece surface layer has been proven to be an effective method to enhance the functional performance of metallic materials, such as fatigue life [3] and wear resistance, whereby the main tribological objective in generating nanocrystalline surface layers involves shortening the running-in phase of tribosystems and improving their reliability in a stationary regime [4]. The formation of these tribologically-induced surface layers already starts during manufacturing of the workpiece with a change in properties in the near-surface of the workpiece material [5]. In recent years severe plastic deformation (SPD) has been established itself as a significant procedure for producing ultrafine grains in solid materials, and various methods for high-grade plastic deformation have been developed [6, 7, 8]. However, these processes are focused on the production of grains in the bulk material rather than on a preconditioning of the workpiece surface layer [9].

There are already well-known surface treatment procedures capable of generating nanocrystalline surface layers. When a local shear force starts to act, smooth rolling and deep rolling can lead to the formation of nanocrystalline grains in the sub-surface region [10]. By applying ultrasound Piezopeening, a local shear deformation in the form of after-treatment marks takes place, and underneath the surface, nanocrystalline grains are generated [11]. Due to friction stir processing, shear deformation is generated by a wear-resistant rotating tool that slides on the workpiece surface and grain refinement is initiated [12]. The possibility of using machining under proper control of the cutting conditions as a surface enhancement tool, thus avoiding expensive and time-consuming post-treatment processes, has not yet been well investigated. Cryogenic machining has been reported to effectively improve tool-life [13, 14]. However, little research has been conducted to investigate the influence of liquid nitrogen application on grain refinement of the newly machined surfaces [2].
During machining, alterations within the workpiece surface layer occur due to initiated temperatures, strains and strain-rates. Grain refinement can be generated in machining due to dynamic recrystallization (DRX) occurring during the massive material deformation generated by the cutting process under high temperatures, large shear strains and highly localized strain-rates, confined to a few micrometers within the workpiece subsurface. Dynamic recrystallization occurs under certain machining conditions and may produce ultrafine/nano-grained microstructures. Machining was recently found to be a method to introduce massive grain refinement in the workpiece surface layer [15, 16]. In addition to copper and aluminium alloys [17], nanostructures were reported in metallic materials, including iron [18], Inconel 718 [18] and titanium [19]. While most of the studies on microstructural changes induced by machining are focused on the chips, there is only little research focus on machined surface [2].

The development of a machining operation for generating a grain refinement underneath the workpiece surface by inducing a massive plastic deformation can be carried out by modifying the process and geometry parameters of a machining process. Parameters that mainly influence strain, strain-rate and process temperature have to be taken into account. This includes: cutting speed $v_c$, cutting edge radius $r_\beta$ and depth of cut $h$ [20]. Nonlinear scaling effects for decreasing depth of cut $h$ were investigated for normalized AISI 1045 steels in orthogonal cutting, where the nonlinear scaling behavior of the specific cutting force $k_c$ for decreasing depth of cut $h$ is described by the Kienzle-Equation [20]. Particularly when the depth of cut $h$ becomes of the same order as the cutting edge radius $r_\beta$, the ploughing process becomes increasingly important and it strongly influences the chip formation process [21]. The output quantities show this nonlinear scaling behavior for a decrease of depth of cut $h$ caused by the minimum chip thickness [22] and the resulting size effects [23, 24]. The phenomenon of squeezed material underneath the cutting edge was also analyzed on the basis of the deformation fields by simulation [20]. Higher ratios of cutting edge radius $r_\beta$ to depth of cut $h$ lead to deeper plastic deformation as a result of the pronounced squeezing of the material [21]. With an increase in cutting edge radius $r_\beta$, the stagnation point is moved a longer distance, first up and then down along the cutting edge. Thus, this distance qualitatively describes the amount of plastic deformation that the material below this point has to endure throughout the cutting process [25].

2. Experimental Set-up

The test samples were made of AISI 4140 steel (the German steel 42CrMo4) in a state quenched and tempered at 450°C for one hour. All experiments were carried out with equilateral triangular indexable inserts made from uncoated cemented carbide produced by Walter AG. The main cutting edge has a clearance angle $\alpha$ of 7°, a rake angle $\gamma$ of -7° and a wedge angle $\beta$ of 90°. A Hass TL2 CNC lathe was used for orthogonal cutting of the workpiece. The measurements of the cutting forces were carried out using a three-component dynamometer of the type Kistler 9257B. The experimental set up can be seen in Fig. 1(a). Variations of depth of cut $h$ were within the range of 30 - 50 $\mu$m, and two cutting speeds ($v_c$) were used: 75 and 100 m/min. The geometry of the tools was preconditioned with cutting edge radii $r_\beta$ of 15, 30 and 70 $\mu$m by abrasive grinding on a DF 4815 OTEC Präzisionsfinish GmbH drag finishing machine. The edge radii $r_\beta$ were determined for each cutting tool by a confocal light microscope of company NanoFocus AG.

![Fig. 1. Experimental set-up displaying a) machining process and b) temperature gradient within the AISI 4140 surface layer after pre-cooling.](image-url)
and is displayed in Fig. 1(b). The deviation of the measurement point at the depth of 2 mm could be an artefact generated by the temperature measurement.

Surface roughness of the workpiece after machining was measured using a Zygo equipment utilizing a non-contact method with a white light interferometer. The micro- and nanohardness with variation in depths from the machined surface were measured using a Vickers Indenter and Nanoindentation. For microstructural analysis, metallurgical samples were cut from the machined discs. After cold mounting, grinding and polishing, the samples were investigated by atomic force microscopy. Evaluation of grain size within the workpiece surfaces after machining was undertaken using a Focussed Ion Beam system. The Focused Ion Beam images were quantitatively evaluated by Axio Vision Image Analysis Software produced by Carl Zeiss AG. All cross-sections of the samples tested show the affected surface layer in machining direction.

3. Results and Discussion

3.1. Cutting Forces and Surface Roughness

Fig. 2 shows the dependencies of the specific cutting force $k_c$ and specific passive force $k_p$ on cooling type and cutting edge radius $r_{ß}$.

An increase in specific cutting force $k_c$ and specific passive force $k_p$ with increasing cutting edge radius $r_{ß}$ can be observed, both for cryogenic cooling and dry machining. The larger specific force values, especially in the thrust direction with larger cutting edge radius $r_{ß}$, were attributed to the increased ploughing effects. Increased ploughing effects are desirable for the occurrence of strain-induced grain refinement since greater plastic deformation is initiated within the machined sub-surface of the workpiece.

Furthermore, specific cutting force $k_c$ and specific passive force $k_p$ are higher during cryogenic cooling with lower temperature leading to increased strength in the workpiece material compared to dry machining with higher temperature. The increased cutting forces generated due to cryogenic cooling lead to an increased plastic deformation within the workpiece surface layer and thus generating a greater grain refinement. However, the benefit of larger cutting forces generated by cryogenic machining leading to grain size reduction can also have negative consequences, e.g., higher surface roughness and reduced tool-life.

Fig. 3 displays the dependencies of arithmetic mean roughness $R_{a}$ and average roughness depth $R_{z}$ on cutting edge radius $r_{ß}$ and cooling type. For the same cooling conditions, machining using larger cutting edge radii $r_{ß}$ led to a reduction in $R_{a}$ and $R_{z}$. With cryogenic cooling, using same cutting edge radius $r_{ß}$, the surface roughness tends to increase in comparison to dry machining, especially at smaller cutting edge radii $r_{ß}$.

Fig. 2. Dependencies of specific cutting force $k_c$ (a) and specific passive force $k_p$ (b) on cutting edge radius $r_{ß}$ and cooling type for machining at $v_c = 100$ m/min and $h = 50 \, \mu$m.

Fig. 3. Dependencies of arithmetic mean roughness $R_{a}$ (a) and average roughness depth $R_{z}$ (b) on cutting edge radius $r_{ß}$ and cooling type for machining at $v_c = 100$ m/min and $h = 50 \, \mu$m.
3.2. Microstructural Analysis

In Fig. 4 the dependencies of hardness on depth of workpiece surface layer after cryogenic machining at $v_c = 75$ m/min, $r_p = 30$ μm and $h = 30$ μm are presented, measured by nanoindentation. The hardness of the machined surface after cryogenic machining with a ratio $r_p/h = 1$ was increased on the basis of the hardness value within the workpiece bulk material. In addition to grain size, work hardening could be another important factor that influences the hardness.

Fig. 4. Martens hardness of surface layer affected by cryogenic machining at $v_c = 75$ m/min, $r_p = 30$ μm and $h = 30$ μm.

Fig. 5 shows an Atomic Force Microscopy (AFM) phase image of the workpiece surface layer after cryogenic machining at $v_c = 75$ m/min, $r_p = 30$ μm and $h = 30$ μm, measured by contact mode. A featureless layer which indicates the zone of massive plastic deformation can be seen in the top surface layer of the workpiece, some grain-like features beneath was observed at greater depths. The cutting process seems to lead to a massive plastic deformation of the subsurface material beneath the newly generated workpiece surface after cryogenic machining.

Fig. 5. AFM image of surface layer affected by cutting after cryogenic machining at $v_c = 75$ m/min, $r_p = 30$ μm and $h = 30$ μm.

Fig. 6 shows that the effect of the grain refinement depth increases with increasing ratio $r_p/h$ for cryogenic cooling within the workpiece surface layer. The depth of surface layer up to which the surface layer states are nanocrystalline with an average grain size smaller than 100 nm are marked by red lines. In addition, the grain diameter in terms of depth profile decreases with greater ratio $r_p/h$. Due to a larger ratio $r_p/h$ specific passive force $k_p$ as well as ratio $k_p/k_c$ increase, causing a greater proportion of plastic deformation within the machined workpiece surface layer.

Fig. 6. FIB images of the surface layers in AISI 4140 steel affected by cutting after cryogenic machining at $v_c = 75$ m/min and $r_p = 30$ μm for a) $h = 100$ μm and b) $h = 30$ μm.

The hardness variation measured by Vickers Indenter within the depth of affected workpiece surface layer and on the workpiece surface after machining with different conditions is shown in Fig. 7. Here, the measurement of the hardness on the workpiece surface is shown as measurement point at 0 μm depth. Using the same cutting edge radius $r_p$, the hardness increase at the workpiece surface was higher after cryogenic machining conditions. In addition to grain size, work hardening is another important factor that influences the hardness of
the material. The more pronounced increase of hardness during cryogenic cooling compared to dry machining could be caused by more severe work hardening and smaller induced grain size. Machining with a larger cutting edge radius \( r_s \) initiates a greater ploughing effect on the workpiece surface, similar to a burnishing process, thus inducing more severe plastic deformation, which can be found 20 \( \mu m \) below the surface.

![Fig. 7. Dependencies of Vickers hardness on depth of surface layer and cooling state after machining at \( v_c = 100 \) m/min and \( h = 50 \) \( \mu m \) for \( a) r_s = 15 \) \( \mu m \) and \( b) r_s = 70 \) \( \mu m \).](image)

**4. Conclusions**

Observation of the surface layer after machining of AISI 4140 steel shows microstructural changes affected by the ratio \( r_s/h \) and cooling type, which have significant effects on the mechanical aspects within the surface layer. The micro geometry of the indexable inserts with a large ratio \( r_s/h \) affects the initiation of strong plastic deformation in the near-surface area of the workpiece by squeezing material underneath the cutting edge. The hardness near the machined surface was increased compared to the initial value during all machining conditions. The largest increase occurred under...
cryogenic cooling when using higher ratio $r_g/h$. Thus, a final machining process with relevant conditions imposed enables the production of nanocrystalline surface layers. Higher $r_g/h$ ratios clearly lead to deeper plastic deformation as a result of the pronounced squeezing of the material, which is beneficial to the generation of nanocrystalline grains. The intensity of grain refinement was more remarkable under cryogenic conditions by inducing higher cutting forces. With respect to tribological properties of the generated surfaces, cryogenic machining tends to increase surface roughness, but leads to reduced grain size and increases surface hardness, which overall, can be beneficial for tribological applications. Furthermore, higher cutting edge radii $r_g$ can hereby reduce surface roughness.

Acknowledgements

The authors gratefully thank the Institute for Sustainable Manufacturing (ISM) at the University of Kentucky for their support for this research work. The authors also would like to acknowledge Dr. John Balk and Julius Schoop for their help in experimental work and analysis of results.

References

[1] M'Saoubi, R., Outeiro, J.C., Chandrasekar, H., Dillon, O.W., Jawahir, I.S., 2008. A review of surface integrity in machining and its impact on functional performance and life of machined products, International Journal of Sustainable Manufacturing 1, p. 203-236.

[2] Jawahir, I.S., Brinksmeier, E., M'Saoubi, R., Aspinwall, D.K., Outeiro, J.C., Meyer, D., Umbrello, D., Jyal, A.D., 2011. Surface integrity in material removal processes: Recent advances, CIRP Annals - Manufacturing Technology 60, p. 603-626.

[3] Villegas, J.C., Shaw, L.L., Dai, K., Yuan, W., Tian, J., Liaw, P.K., Klarstrom, D.L. 2005. Enhanced fatigue resistance of a nickel-based hadlestoyl induced by a surface nanocrystalization and hardening process, Philosophical Magazine Letters 85, p. 427-438.

[4] Rigney, D.A., 200. Transfer, mixing and associated chemical and mechanical processes during the sliding of ductile materials, Wear 245, p. 1-9.

[5] Berlet, P., Dienwiebel, M., Scherge, M., 2010. The effect of sample finishing on the tribology of metal/metal lubricated contacts, Wear 268, p. 1518-1523.

[6] Valiev, R.Z., Paradoxes of severe plastic deformation, 2003. Adv. Eng. Mater. 5, p. 296-300.

[7] Valiev, R.Z., Alexandrov, I.V., Zhu, Y.T., Lowe, T.C., 2002. Paradox of strength and ductility in metals processed by severe plastic deformation, J. Materials Research 17, p. 5-8.

[8] Tsuji, N., Saito, Y., Utsunomiya, H., Tanigawa, S., 1999. Ultra-fine grained bulk steel produced by accumulative roll-bonding (ARB) process, Scripta Materialia 40, p. 795-800.

[9] Pippan, R., Hohenwarter, A., Scheriau, S., Bachmaier, A., 2010. Nanokristalline Metalle: Neue Werkstoffe aus plastischer Hochverformung, Phys. Unserer Zeit 41, p. 23-29.

[10] Altenberger, I., Stach, E.A., Liu, G.Y., Nalla, R.K., Ritchie, R.O., 2003. An in situ transmission electron microscopy study of the thermal stability of near-surface microstructures induced by deep rolling and laser-shock peening, Scripta Materialia 12, p. 1593-1598.

[11] Berg-Pollack, A., Voellmecke, F.-J., Sonsino, C.M., 2011. Fatigue strength improvement by ultrasonic impact treatment of highly stressed spokes of cast aluminium wheels, International Journal of Fatigue 33, p. 513-518.

[12] Aladjah, S.H., Ajayi, O.O., Fenske, G.R., David, S., 2009. Effect of friction stir processing on the tribological performance of high carbon steel, Wear 267, p. 350-355.

[13] Hong, S.Y., Markus, J., Jeong, W., 2001. New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V, International Journal of Machine Tools and Manufacture 41, p. 2245-2260.

[14] Bermingham, M.J., Kirsch, J., Sun, S., Palanisamy, S., Dargusch, M.S., 2011. New observations on life time, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V, International Journal of Machine Tools and Manufacture 51, p. 500-511.

[15] Chandrasekar, S., Guo, Y., Saldana, C., Compton, W.D., 2011. Controlling deformation and microstructure on machined surfaces, Acta Materialia 59, p. 4538-4547.

[16] Pu, Z., Dillon, O.W., Jawahir, I.S., Pulco, D.A., 2010. “Microstructural Changes of AZ31 Magnesium Alloys Induced by Cryogenic Machining and Its Influence on Corrosion Resistance in Simulated Body Fluid for Biomedical Applications,” Proceedings of ASME International Manufacturing Science and Engineering Conference, p. 271-277.

[17] Ni, H., Alpas, A.T., 2003. Sub-micrometer Structures Generated During Dry Machining of Copper, Materials Science and Engineering A 361, p. 338-349.

[18] Liu, X., De Vor, R.E., Kapoor, S.G., Ehrmann, K.F., 2004. The mechanics of machining at the micro scale: assessment of the current state of science, Journal of Manufacturing Science and Engineering, p. 666-678.

[19] Shankar, M.R., Rao, B.C., Lee, S., Chandrasekar, S., King, A.H., Compton, W.D., 2006. Severe Plastic Deformation (SPD) of Titanium at Near-ambient Temperature, Acta Materialia 54, p. 3691-3700.

[20] Autenrieth, H., 2009. Numerische Analyse der Mikrozerspanung am Beispiel von normalisiertem C45E, Dissertation, Universität Karlsruhe (TH).

[21] Albrecht, W., 1960. New developments in the theory of the metal cutting process Part I the ploughing process in metal cutting, Transactions of the ASME November, p. 348-357.

[22] Swaminathan, S., Shankar, M.R., Lee, S., Hwang, J., King, A.H., Kezar, R.F., Rao, B.C., Brown, T.L., Chandrasekhar, S., Compton, W.D., Trumble, K.P., 2005. Large Strain Deformation and Ultra-fine Grained Materials by Machining, Materials Science and Engineering A 410-411, p. 358-363.

[23] Tamminiai, D.A., Hautzenberg, J.H., 1991. Bluntness of the tool and Process Forces in High-Precision Cutting, CIRP Annals 40(1), p. 65-68.

[24] Chuzhoy, L., DeVor, R.E., Kapoor, S.G., Beaudoin, A.J., Bammann, D.J., 2003. Machining Simulation of Ductile Iron and Its Constituents, Part I: Estimation of Material Model Parameters and Their Validation, Journal of Manufacturing Science and Engineering 125, p. 181-191.

[25] Delonnoy, L., Hochrainer, T., Schulze, V., Löhe, D., Gumbsch, P., 2005. Similarity considerations on the simulation of turning processes of steels, Zeitschrift für Metallkunde 96, p. 761-769.