Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 87 (2020) 83–88

www.elsevier.com/locate/procedia

5th CIRP CSI 2020

Experimental identification of a surface integrity model for turning of AISI4140

Benedict Stampfer[a,*], David Böttger[b], Daniel Gauder[a], Frederik Zanger[a], Benjamin Häfner[a], Benjamin Straß[b], Bernd Wolter[b], Gisela Lanza[a] and Volker Schulze[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany*
[b]*Fraunhofer Institute for Nondestructive Testing (IZFP), Campus E3 1, 66123 Saarbrücken, Germany*

* Corresponding author. Tel.: +49-721-608-42455; fax: +49-721-608-45004. *E-mail address:* benedict.stampfer@kit.edu

Abstract

In this work an experimental study of the turning of AISI4140 is presented. The scope is the understanding of the workpiece microstructure and hardness-depth-profiles which result from different cutting conditions and thus thermomechanical surface loads. The regarded input parameters are the cutting velocity (v_c = 100, 300 m/min), feed rate (f = 0.1, 0.3 mm), cutting depth (a_p = 0.3, 1.2 mm) and the heat treatment of the workpiece (tempering temperatures 300, 450 and 600°C). The experimental data is interpreted in terms of machining mechanisms and material phenomena, e.g. the generation of white layers, which influence the surface hardness. Hereby the process forces are analyzed as well. The gained knowledge is the prerequisite of a workpiece focused process control.

Keywords: adaptive machining; white layer; microhardness

1. Introduction

Surface engineering is the scientific field of controlling surface states to improve the quality of a processed component. Generally, a large number of parameters determines surface engineering, such as chemical composition, microstructure, dislocation density, hardness, local strength, residual stress tensor and topography [1]. It must be emphasized that the enumeration is non-exhaustive and many surface states are interdependent. The overarching goal of this work is the realization of surface engineering in a closed-loop control when turning AISI4140. This system should be capable of restoring relevant surface states and maintaining the workpiece quality through the adjustment of suitable actuating variables.

In the following section, mechanisms are analyzed, that influence the surface integrity when turning hardenable steels. The main focus lies upon the generation and evaluation of so called white layers on machined surfaces. The term refers to their white and featureless appearance in an optical microscope, which is a consequence of light dispersion at their nanocrystalline structure [2, 3].

Barry and Byrne [2] investigated face turning of BS 817M40 and a tool steel, both consisting of a martensitic microstructure. White layers of the thickness 2–3 µm were generated with worn tools only. These layers had a nanocrystalline microstructure, contained retained austenite and were compared to adiabatic shear bands in segmented chips. This led to the conclusion, that the initial martensite undergoes an austenitic-martensitic phase transformation, which is triggered by adiabatic shearing. Akcan et al. [3] investigated finish turning of the hardened steels AISI4340, AISI52100 and M2. White layers were exclusively detected on the steels AISI4340 and AISI52100 after machining with worn tools. With approximately 1200°C the austenitisation temperature of M2 is significantly higher than those of AISI4340 and AISI52100, which could impede an austenitic phase transformation. Nanoindenter tests revealed

10.1016/j.procir.2020.02.067

that the hardness of white layers is approximately 25% higher than the hardness of the martensitic bulk material. Rech and Moisan [4] conducted finish turning tests on case hardened 27MnCr5. It was shown that the generation of white surface layers is correlated with the occurrence of tensional residual surface stresses and that both phenomena are mainly caused by the evolution of the flank wear. The increase of the surface roughness R_a with the flank wear however is less significant. Thus the occurrence of white layers was named a decisive factor for the necessity of a tool change in hard turning. Hosseini [5] investigated hard turning of AISI52100 within a large field of cutting parameters. In addition to the transformation induced white layers examined in [2, 3, 4] Hosseini identified nanocrystalline layers which did not show the signs of a phase transformation. To explain this, a model was deduced for the generation of white layers when turning AISI52100. The model is based on the superposition of thermal and mechanical surface loads. High mechanical and low thermal loads induce nanocrystalline surface layers by dynamic recrystallization without an austenitic phase transformation. High thermal loads in machining generate surface layers which are both, grain fined and phase transformed. Furthermore high surface temperatures lead to thermal elongations and plastic deformations, which induce tensile stresses after the workpiece cooled down. This is why thermally induced white layers are also associated with tensile residual stresses.

Regarding the material AISI4140, a wide range of heat treatments is applied to meet the demands of specific use-cases. This makes the steel an interesting example to probe the transferability of Hosseini's white layer formation model. In the following publications are reviewed, which contributed to this topic is. Schulze et al. [6] investigated orthogonal turning of AISI4140 QT 450 (quenched and tempered at 450°C). During the experiments with the cutting velocity 75 m/min, cutting zone temperatures of 400°C were measured, which did not lead to the occurrence of white layers. When turning with the cutting velocity 300 m/min, the measured temperatures increased to 800°C and white layers of the thickness 5 µm occurred. The generation of those layers was successfully modeled as austenitisation and subsequent martensite transformation in a FEM chip forming simulation. Ambrosy et al. [7] analyzed orthogonal turning of AISI4140 QT 450 with the cutting velocities 75 and 100 m/min, the uncut chip thicknesses 30 and 50 µm and different cutting edge radii. The nanocrystalline surface layers generated with these parameters did show no signs of a phase transformation and were regarded as the result of severe plastic deformation and dynamic recrystallization. Vickers measurements revealed an increase of the surface hardness, which can be explained by the fine-grained microstructure and the Hall Petch effect. The ratio of the edge radius and the uncut chip thickness $r_β/h$ was identified as a crucial factor for the mechanical loading and the generation of nanocrystalline surfaces. E.g. when increasing $r_β/h$ from 0.3 to 1.4, the specific passive force increased from 2200 N/mm² to 3000 N/mm². The thickness of nanocrystalline surface layers with a grainsize smaller than 100 nm increased from 0.6 µm to 1.3 µm, when increasing $r_β/h$ from 0.3 to 1.0. Buchkremer and Klocke [8] conducted orthogonal cutting tests of AISI4140 QT 400 with the cutting velocities 50 m/min and 150 m/min and the uncut chip thicknesses 50 and 200 µm. White surface layers were detected on the workpiece, consisting of equiaxed grains with minimum sizes of 20 nm and dynamic recrystallization was identified as formation mechanism. The cutting velocity and the uncut chip thickness equally increased the thickness of the nanocrystalline layers, which ranged from 2.5 to 4 µm.

Regarding the machining of AISI4140, both types of white layers have been reported. Mechanically induced white layers occurred at cutting velocities lower than 150 m/min, while thermally induced white layers occurred at higher speeds. In the reviewed literature only orthogonal cutting tests were conducted, but no longitudinal turning. The occurrence of both types of white layers in one experimental setup has not been reported and the role of the tempering temperature, feed, tool wear and the depth of cut is largely unexplored.

2. Experimental setup

In this work longitudinal dry turning tests were conducted with TiCN-coated carbide inserts. Coated tools were used, because they represent the industrial standard when turning AISI4140. The cutting parameters and the insert geometry are specified in Table 1. Here v_c denotes the cutting velocity, f the feed, a_p the depth of cut, $α$ the clearance angle, $γ$ the rake angle, $κ$ the principal cutting edge angle, $λ$ the cutting edge inclination and $r_ε$ the tool corner radius.

Table 1. Cutting parameters and insert geometry for the turning tests.

v_c	f	a_p	$α$	$γ$	$κ$	$λ$	$r_ε$
[m/min]	[mm]	[mm]	[°]	[°]	[°]	[°]	[mm]
100, 300	0.1, 0.3	0.3, 1.2	7	0	95	0	0.4

The material AISI4140 was machined in three tempering states. The heat treatment according to DIN10083 involved quenching and subsequent tempering at 600°C for 1 h, which is labeled QT 600. Workpieces tempered at 450°C or 300°C were machined as well (AISI4140 QT 450 or 300). Those materials are likely to be used in finishing operations, thus only machining tests with a_p = 0.3 mm were conducted. Unworn and initially worn inserts were used. The wear was generated by machining of AISI4140 QT 600 with the cutting parameters v_c = 300 m/min, f = 0.3 mm and a_p = 0.3 mm. Each tool was worn by 25 consecutive cuts along a workpiece length of 145 mm. The resulting mean flank wear of three tools was 119 µm with a standard deviation of 6 µm. In the figure labeling the use of preworn tools is noticed as VB.

The setup of the experimental turning tests is depicted in Fig. 1 a). During machining the process forces were measured by a dynamometer. The coordinate system shows, how the cutting force F_c, the feed force F_f and the passive force F_p act on the cutting tool. After the machining tests, circular discs were cut from the workpiece, ranging from the axial position a = 10 to 20 mm. The discs were further cut into four equal segments. Two of those segments were embedded into one specimen as shown in Fig. 1 b). A tester of the type Qness Q 10 was used for hardness measurements HV 0.005. This test load was chosen to realize small indentation dimensions, which is necessary to measure within layers, whose thickness may not exceed 10 µm. The Vickers hardness was tested on both segments of a specimen and by three indentation rows on each segment, i.e. the hardness-depth-profiles result of six repetitions. The presented micrographs were etched by a 2% nitric acid solution for 8 s.

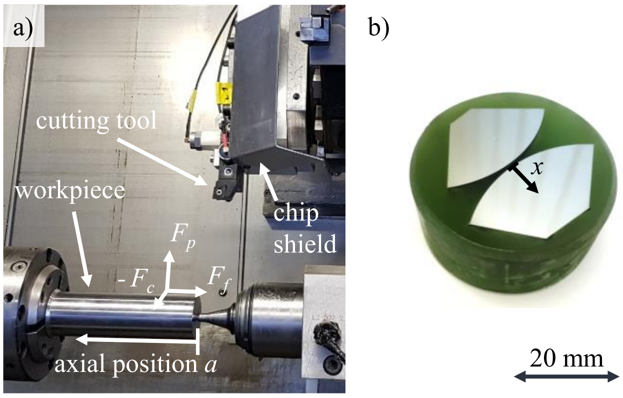

Fig. 1 a) Turning test setup the machining centre Index G200
b) Specimen with embedded workpiece segments.

3. Results

3.1. Effect of the cutting parameters

Hardness profiles, which result from the turning of AISI4140 QT 600 with unworn tools and the depths of cut 0.3 and 1.2 mm are depicted in Fig. 2, 4 and 5. The data of the cutting parameters $v_c = 100$ m/min and $f = 0.1$ mm is omitted, because no significant hardening occurs in the subsurface. For reasons of clarification, the standard deviation bars are neglected.

Regarding Fig. 2 with the parameters $v_c = 100$ m/min and $f = 0.3$ mm, the higher depth of cut induces a hardness increase of approximately 100 HV in the subsurface compared to approximately 50 HV with the smaller depth of cut. In further investigations the specimen with the depth of cut 1.2 mm was etched and observed in a light microscope. The referring micrograph is depicted in Fig. 5. A fine surface microstructure and subsurface deformations are present. Yet, the surface grains are large enough to appear not as a white layer. Work hardening and dynamic recrystallization are likely reasons for the hardness increase.

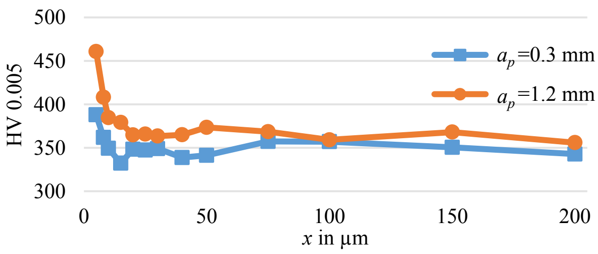

Fig. 2 AISI4140 QT 600, $v_c = 100$ m/min, $f = 0.3$ mm and a_p varied

In Fig. 3 hardness profiles with the cutting parameters $v_c = 300$ m/min and $f = 0.1$ mm are depicted. With the depth of cut 0.3 mm a hardness increase occurs only at the topmost measurement point. A significant subsurface hardness increase is detected with the depth of cut 1.2 mm. The referring micrograph in Fig. 6 indicates a minor surface drag. Work hardening is thus a likely reason for this increase. The darker appearance of parts of the subsurface could indicate cementite precipitation, which leads to an additional hardening.

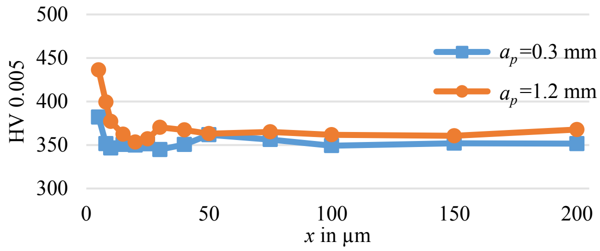

Fig. 3 AISI4140 QT 600, $v_c = 300$ m/min, $f = 0.1$ mm and a_p varied

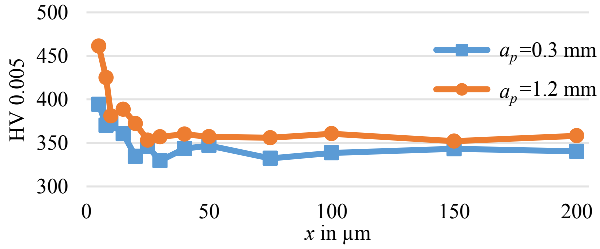

Fig. 4 AISI4140 QT 600, $v_c = 300$ m/min, $f = 0.3$ mm and a_p varied

Regarding Fig. 4 with the parameters $v_c = 300$ m/min and $f = 0.3$ mm, a significant hardness increase is present for both depths of cut. However it is more pronounced with the depth of cut 1.2 mm. The referring micrograph in Fig. 7 shows a fine grained surface. Again dynamic recrystallization is a likely reason for the hardness increase.

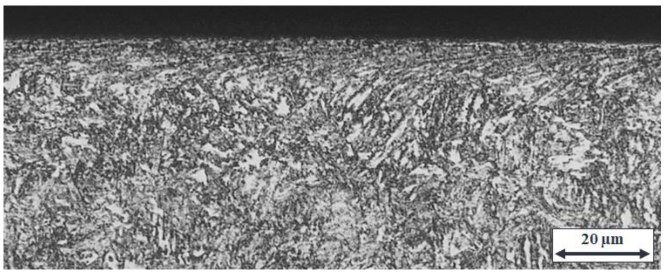

Fig. 5 AISI4140 QT 600, $v_c = 100$ m/min, $f = 0.3$ mm and $a_p = 1.2$ mm

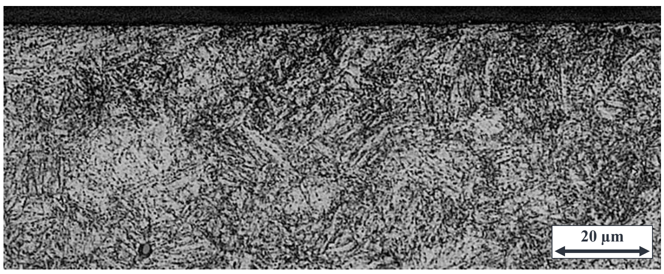

Fig. 6 AISI4140 QT 600, $v_c = 300$ m/min, $f = 0.1$ mm and $a_p = 1.2$ mm

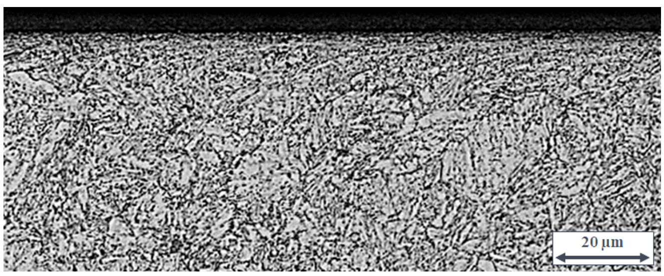

Fig. 7 AISI4140 QT 600, $v_c = 300$ m/min, $f = 0.3$ mm and $a_p = 1.2$ mm

The generation of thermally induced white layers is improbable during turning of AISI4140 QT 600 with unworn tools. A possible hardness increase is caused by work hardening and grain refinement, but not by phase transformation. When machining with the depth of cut 0.3 mm, a significant hardness increase was detected with the higher feed. When machining with the depth of cut 1.2 mm, it was possible to induce a surface hardness increase of approximately 100 HV. It has been more effective to raise the mechanical load by increasing the feed from 0.1 mm to 0.3 mm, than raising the thermal load by increasing the cutting velocity from 100 m/min to 300 m/min.

The terms thermal and mechanical load refer to contact temperatures and stresses which are difficult to measure during machining. But the process forces result from the local stresses and could thus be an alternative indicator for the mechanical load. When cutting tests with different feeds and depths of cut are compared, usually the specific forces are given. In Table 2 the absolute values are presented as well, to discuss which one is meaningful with regard to mechanical surface loads.

Table 2. Mean process forces of the turning tests with unworn tools

v_c	[m/min]	100	300	300	100	300	300
f	[mm]	0.3	0.1	0.3	0.3	0.1	0.3
a_p	[mm]	0.3	0.3	0.3	1.2	1.2	1.2
F_c	[N]	253	92	226	849	344	819
k_c	[N/mm²]	2806	3080	2507	2359	2866	2274
F_f	[N]	82	50	66	390	248	340
k_f	[N/mm²]	905	1678	733	1084	2067	945
F_p	[N]	142	75	136	159	85	161
k_p	[N/mm²]	1576	2507	1507	442	705	448

According to on the hardness values, the mechanical surface load during turning with the depth of cut 1.2 mm was higher than with 0.3 mm. Yet the specific cutting and the specific passive forces with the depth of cut 1.2 mm are lower than with 0.3 mm. The specific feed forces with the feed 0.1 mm are much higher than with the feed 0.3 mm, which is contrary to the surface hardness. This shows that the specific forces are not suited for the estimation of mechanical surface loads when different cutting parameters are compared.

Regarding a single factor variation of the feed or the depth of cut, the tendencies of the absolute process forces are generally in accordance with the hardness measurements, e.g. higher forces lead to an increased surface hardness. When increasing the cutting velocity, the surface hardness maintains. Yet the cutting and the feed forces decrease, which is a well-known tendency due to higher process temperatures and material softening. Thus these forces are a questionable indicator for the mechanical surface load. The passive force tendencies due to the cutting parameter variations are in good agreement with the surface hardness. This is reasonable from a mechanism based point of view, as the passive force acts normal to the machined surface as a compressive load. The results are in accordance with Ambrosy et al. [6], who proved the interdependence between the hardness increasing cutting edge radius on the one hand and the passive force on the other hand. Still it must be noticed that multi factor variations are difficult to interpret. E.g. when increasing the depth of cut from 0.3 to 1.2 mm while decreasing the feed from 0.3 to 0.1 mm, the passive force decreases, while the surface hardness increases.

3.2. Effect of heat treatment

The experiments were continued with preworn tools and the cutting parameters $v_c = 300$ m/min, $f = 0.3$ mm and $a_p = 0.3$ mm. At first AISI4140 QT 600 was turned to exclusively investigate the effect of the tool wear on the thermomechanical load, the surface hardness and the microstructure. During machining the tool wear retained on a constant level. The mean passive force reached 214 N, which is significantly higher compared to turning with unworn tools at the same cutting parameters. The increase is likely caused by a larger tool workpiece-contact-area at the tool flank. Assuming a constant contact pressure, the force would be proportional to the area.

The hardness profile, which resulted when machining AISI4140 QT 600 with the preworn tool is depicted in Fig. 8.

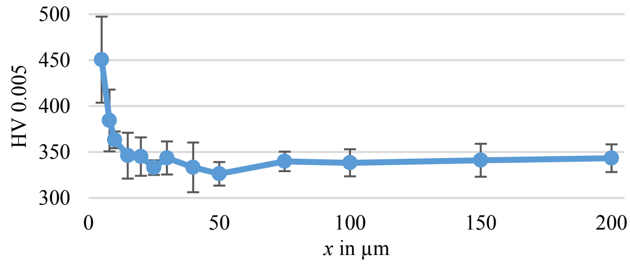

Fig. 8 AISI4140 QT 600, $v_c = 300$ m/min, $f = 0.3$ mm, $a_p = 0.3$ mm, VB

Compared to the bulk material, the hardness in the range $x < 20$ µm is significantly increased. Besides the topmost mean hardness is approximately 50 HV higher than the referring value in Fig. 4 with the unworn tool. This variation lies within the failure bars and a fundamental change due to the worn tool is not seen. The micrograph of the specimen machined with the worn tool in Fig. 9 shows subsurface shearing and a fine grained workpiece edge. The presence of a nanocrystalline surface layer with a depth of less than 5 µm is possible. Yet the occurrence of an extended phase transformation is ruled out, because hardness values of more than 600 HV are expected for martensitic structures [9, 10].

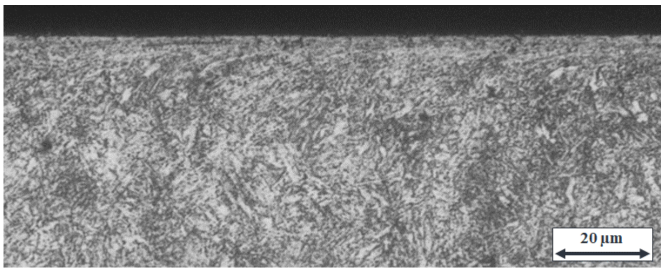

Fig. 9 AISI4140 QT 600, $v_c = 300$ m/min, $f = 0.3$ mm, $a_p = 0.3$ mm, VB

The surface hardness after machining AISI4140 QT 600 was restricted to values lower than 500 HV, despite high cutting parameters and the use of a worn tool with increased passive forces. The risk of generating thermally induced, transformed surface layers is low when machining this material state. Work hardening and grain refinement can however be caused by mechanical surface loads, which lead to a moderate hardness increase. These changes are expected to involve compressive residual stresses and to enhance the component life under alternating loads.

White layer formation is caused by thermomechanical surface loading and should thus be affected by the initial hardness of the machined material. To probe this hypothesis AISI4140 QT 450 was machined with a preworn tool in the most severe cutting conditions. During the experiment the tool wear proceeded until VB = 179 µm and the passive force increased to a mean value of 390 N, which indicates high surface loads. In Fig. 10 the resulting hardness profile is depicted.

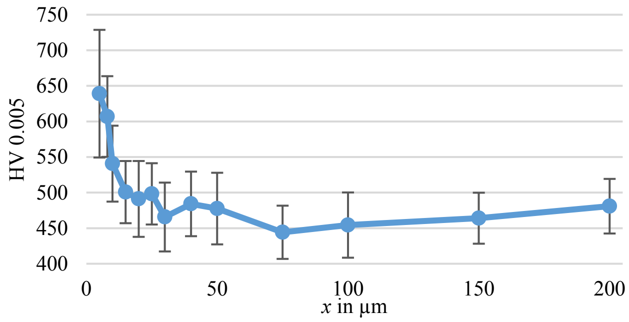

Fig. 10 AISI4140 QT 450, v_c = 300 m/min, f = 0.3 mm, a_p = 0.3 mm, VB

The subsurface hardness is increased by almost 200 HV, compared to deeper parts of the specimen. The topmost mean value is increased to 639 HV. Given that Lv et al. [9] measured 616 HV in quenched AISI4140, this is a sign of a martensitic phase transformation. For the hardness deviations two main causes are identified. The bulk material shows an inevitable spatial inhomogeneity, which is revealed by small indentation dimensions. In addition the hardness of the transformed surface layer is significantly affected by relatively small temperature variations during the turning process. This was shown by Totik et al. [10], who measured 620 HV to 800 HV in induction hardened AISI4140, depending on the maximum heating temperature, which ranged from 815°C to 875°C. Fig. 11 depicts the microstructure, which refers to turning of AISI4140 QT 450.

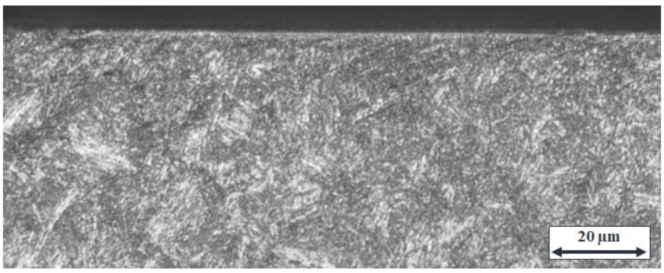

Fig. 11 AISI4140 QT 450, v_c = 300 m/min, f = 0.3 mm, a_p = 0.3 mm, VB

The bulk material has a typical tempering structure. At the specimen edge, a thin white layer is visible, which indicates a nanocrystalline surface structure. Yet the appearance is less impressive than implied by the hardness increase. The subsurface until a depth of approximately 10 µm appears fine grained and darker then the bulk material. This indicates a carbide enrichment of initially light ferritic structures due to further tempering.

To investigate the effect of a high initial hardness and a high surface load, AISI4140 QT 300 was turned with a preworn tool in the most severe cutting conditions. Thereby the tool wear proceeded, which finally led to a breakage of the cutting edge and the passive force reached a mean value of 896 N. These conditions were chosen to test the limits of the cutting process and to investigate the most critical surface states. In Fig. 12 the hardness profile of the machined specimen is depicted. The bulk material has a hardness of approximately 600 HV, which is only slightly lower than for quenched AISI4140. A mean hardness increase up to 735 HV is seen for depths lower than 75 µm, which is a clear sign of a rehardened subsurface. The hardness deviations can be explained by the same reasons as mentioned for AISI4140 QT 450 after Fig. 10. To investigate the surface structure, an exemplary micrograph is depicted in Fig. 13.

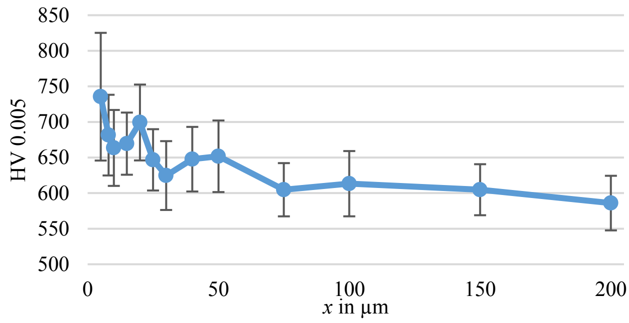

Fig. 12 AISI4140 QT 300, v_c = 300 m/min, f = 0.3 mm, a_p = 0.3 mm, VB

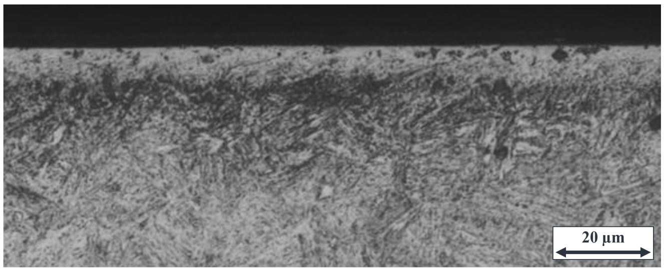

Fig. 13 AISI4140 QT 300, v_c = 300 m/min, f = 0.3 mm, a_p = 0.3 mm, VB

The bulk material has a lath martensitic structure, which is expected for the tempering state. A white layer extends along the specimen edge and reaches a maximum thickness of approximately 10 µm. On additional micrographs, white layer sectors with a thickness of a few microns are also found. The white layer is followed by a dark layer. Its extension is varying, ranging up to a depth of 50 µm, which is correlated to an intermediate hardness in Fig. 12. This is explained as follows. The martensite hardness is to a large extend determined by the solute carbon content and the darkened structure indicates a high density of cementite precipitations. As the carbon shifts form the martensite solution to the precipitations, the martensite hardness decreases.

4. Conclusions

The presented, pronounced surface hardening during turning of AISI4140 QT 450 and 300 came along with high passive forces. Regarding all process forces, the passive force is the most promising indicator for the workpiece loading. The cutting and the feed forces are not suited, because they are mainly resulting from stresses in the primary and secondary shear zone, which lie above the newly generated surface. This issue can not be solved by force normalization with the cutting cross section. Besides it is not convenient to account for the cutting cross section when the contact between the tool and the newly generated surface is decisive, which makes the specific passive force inappropriate as well. The passive force acts normal to the workpiece surface and is thus an indicator for the mechanical load. Given that the shear stresses in the tool-workpiece-contact increase with the normal pressure, the frictional heat and the temperatures increase as well. Hence the passive force also comprehends thermal loads which are decisive for the generation of rehardened surface layers during machining.

When turning AISI4140 QT a variety of surface states can arise, depending on the cutting parameters, the tool wear and the tempering state. In the analyzed field of parameters the surface states of AISI4140 QT 600 were restricted to hardness values lower than 500 HV. This is explained by the low basic hardness of the material, which not leads to the high cutting temperatures that induce an austenitic-martensitic phase transformation. From this point of view it can be stated that the tested cutting parameters were well suited.

When turning AISI4140 QT 450 with a worn tool, the surface hardness reached values in the order of quenched martensite. The hardness of the bulk material led to high thermomechanical loads during machining, e.g. the passive forces were nearly twice the number as when turning AISI4140 QT 600 with the same parameters. The micrograph of the specimen with the tempering temperature 450°C shows that a possible white layer formation is restricted to the specimen edge. This matches the hardness diagram with mean values of more than 600 HV only for surface depths of less than 10 µm. The results indicate a high risk of residual tensile stresses. It is concluded, that a passive force measurement could enable an on-line estimation of critical process states during turning of AISI4140 QT 450. Hereby additional process knowledge could be taken into account, because the surface loading is furthermore determined by the area on which the force acts and the respective time duration. From the results presented for the cutting of AISI4140 QT 600 it can already be seen that a reduction of the feed is suited to reduce the passive force and the surface hardening. By transferring this to the turning of AISI4140 QT 450, a process control is conceivable.

Turning of low tempered AISI4140 QT 300 led to the formation of extended, thermally induced white surface layers. These are known for its brittle structure and residual tension stresses, which are detrimental for the component life. During machining the passive force increased to more than twice the value of AISI4140 QT 450 with the same cutting parameters. This caused mean a hardness increase to more than 650 HV up to a surface depth of 20 µm. Due to the rapid tool wear and the microstructure modifications the chosen cutting parameters are not advised for the machining of AISI4140 QT 300. Yet they unveil which are the reasons for a hardness increase when turning low tempered AISI4140 QT and help to interpret unwanted surface modifications, which were caused by less critical cutting conditions.

In future works roughness and residual stress measurements will be carried out to comprehensively examine the surface integrity. Besides the regarded passive force it is planned to take into account further measurement techniques like acoustic process emissions or micromagnetic surface layer analysis in order to realize a machining control based on nondestructive testing data. For the application of a turning process control, different scenarios can be imagined. In one scenario the process productivity should be optimized while avoiding rehardening layers when turning AISI4140 QT 450. Here the cutting parameters must be reduced with an increasing tool wear. Another scenario is the adjustment of a compressive residual stresses and a constant grain refinement, which is beneficial in terms of a component's fatigue limit. Hereby the results of machining AISI4140 QT 600 with the depth of cut 1.2 mm are a good starting point.

Acknowledgements

The scientific work has been supported by the DFG within the research priority program SPP 2086 (SCHU 1010/65-1, LA 2351/46-1, WO 903/4-1). The authors thank the DFG for this funding and intensive technical support.

The comprehensive metallographic work of Daniel Kleiner in terms of specimen preparation and hardness measurements is gratefully acknowledged.

References

[1] Scholtes B, Macherauch E. Auswirkungen mechanischer Randschicht-verformungen auf das Festigkeitsverhalten metallischer Werkstoffe. In: Zeitschrift für Metallkunde 77 (5), 1986: 322-337.
[2] Barry J, Byrne G. TEM study on the surface white layer in two turned hardened steels. In: Mater Sci Eng A 325 (1-2), 2002: 356-364.
[3] Akcan S, Shah WIS, Moylan SP, Chandrasekar S, Chhabra PN, Yang HTY. Formation of white layers in steels by machining and their characteristics. In: Metall Mater Trans A Phys Metall Mater Sci 33 (4), 2002: 1245-1254.
[4] Rech J, Moisan A. Surface integrity in finish hard turning of case-hardened steels. In: Int J Mach Tools Manuf 43 (5), 2003: 543-550.
[5] Hosseini, SB. White Layer Formation During Hard Turning of Through-hardened Martensitic and Bainitic AISI 52100 Steel. Chalmers University of Technology 2015.
[6] Schulze V, Michna J, Zanger F, Faltin C, Mass U, Schneider J. Influence of cutting parameters, tool coatings and friction on the process heat in cutting processes and phase transformations in workpiece surface layers. In: HTM J. Heat Treatm. Mat. 68 (1), 2013: 22-31.
[7] Ambrosy F, Zanger F, Schulze V, Jawahir IS. An Experimental Study of Cryogenic Machining on Nanocrystalline Surface Layer Generation. In: Procedia CIRP 13, 2014: 169-174.
[8] Buchkremer S, Klocke F. Modeling nanostructural surface modifications in metal cutting by an approach of thermodynamic irreversibility: Derivation and experimental validation. In: Continuum Mech. Thermodyn. 29, 2017: 271–289.
[9] Lv F, Fu LM, Sun YL, Shan AD. Microstructure and mechanical behaviour of ultra-high strength of fine-grained AISI 4140 steel. In: Materials Research Innovations 19 (4), 2015: 64–67.
[10] Totik Y, Sadeler R, Altun H, Gavgali M. The effects of induction hardening on wear properties of AISI 4140 steel in dry sliding conditions. Materials & Design 24 (1) 2003: 25–30.