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Influence of cutting edge geometry on deformation induced hardening when cryogenic turning of metastable austenitic stainless steel AISI 347

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Abstract

In recent years deformation induced surface hardening was carried out to enhance the component performance of metastable austenitic steels. To be able to induce such a phase transformation from austenite to martensite in the workpiece surface layer, high mechanical loads and low process temperatures are required. Therefore, cryogenic CO_2-snow cooling is an appropriate method to assure a low heat influence on the workpiece. High mechanical loads can be obtained by high feed. However, this causes relatively rough surfaces due to the process kinematics. In this context, the influence of cutting edge geometry on deformation induced surface hardening and resulting surface roughness is investigated. With a variation of the geometry of the cutting edge, especially the cutting edge radius, mechanical loads and thus the amount of martensite formed were adjustable.

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Keywords: Cryogenic machining; Cutting edge; Surface hardening;

1. Introduction

Requirements on the morphology of component surfaces are increasing continuously to extend lifetime and save resources. The surface layer of machined components often has to be hardened to improve wear resistance and fatigue strength. Metastable austenitic steels offer an opportunity of a deformation induced surface hardening as an alternative to classical heat treatments [1]. For this kind of surface hardening high plastic deformations are required to induce a phase transformation from austenite to martensite. In addition, the transformation-temperature during the deformation process must not exceed a critical value. This value depends on specific material properties. In general, the higher the plastic deformation and the lower the temperature the more martensite is formed [2]. Deep rolling is already applied successfully for deformation induced surface hardening [3]. For a further increase in productivity more manufacturing processes have to be substituted. To achieve a phase transformation during the first material removal process of the process chain, a powerful cooling system is needed to keep down the level of heat in the deformation zone. Therefore, cryogenic coolants like carbon dioxide-(CO_2-) snow [4] or liquid nitrogen (LN_2) [5] are a suitable alternative to bring down the cutting temperature in turning processes. In recent years cryogenic turning was investigated to achieve a deformation induced surface hardening. For this purpose, CO_2-snow is determined as a powerful coolant with good wetting behavior [6]. With this process the component performance can be increased in terms of wear resistance [7] as well as fatigue strength [8]. However, high feeds, needed to achieve high mechanical loads in the workpiece surface layer, lead to rough surfaces. As a consequence, there is always a compromise between high fraction of martensite and high surface quality [9].

By varying the cutting edge geometry, mechanical and thermal loads in the workpiece surface layer can be adjusted. Hence, high mechanical loads at low feed can be achieved [10]. In this paper, deformation induced surface hardening during cryogenic turning is investigated by varying feed and

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cutting edge geometry. To detect cause and effect relationships, mechanical and thermal loads are analyzed and their influence on phase transformation and surface quality is determined.

2. Experimental data

The cylindrical turning tests are carried out on a CNC lathe applying CO_2-snow-cooling (Fig. 1). Each workpiece has a diameter of 25 mm and a length of 48 mm. The machining length is 20 mm. The workpieces are prepared by dry turning down to a diameter of 14.4 mm without generation of any martensite in the workpiece surface layer. The CO_2 is stored in liquid state in a pressurized tank with 60 bar and is delivered through two nozzles with an exit diameter of 10 mm. One nozzle is pre-cooling the workpiece and one nozzle is cooling the contact zone from flank face direction. As a result of the chemical and physical properties, liquid CO_2 partly freezes and partly evaporates at atmospheric pressure at the nozzle exit. This CO_2-snow hits the workpiece surface as a solid-gas mixture with a temperature of 194.5 K [9]. With the applied flow rate each nozzle has a cooling power of 800 kJ/min. Due to a martensite start temperature of M_s = 192 K no martensitic transformation based on purely thermal effects can take place.

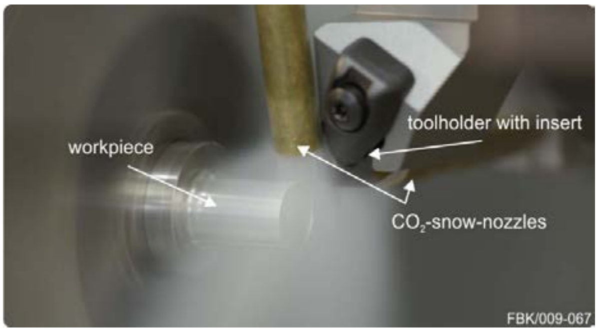

Fig. 1. Experimental setup including tool, workpiece and CO_2-snow-cooling.

2.1. Cutting tools and conditions

To achieve high mechanical loads in the workpiece surface layer, high passive forces are needed. Therefore, a tool holder with a negative tool orthogonal rake angle (γ = -6°) and tool cutting edge inclination (λ = -6°) is used for external cylindrical turning. To evaluate the influence of cutting edge geometry on deformation induced hardening, three different types of inserts are applied for the investigations within this paper. Cemented carbide (94.35 % WC, 5.20 % Co, and 0.45 % MC) as tool material with a multilayer coating ($TiN/TiCN/Al_2O_3$) and the macro geometry CNMA120416 are selected for all inserts. Figure 2 shows the differences of the chosen tools. Insert 1 has a chamfered cutting edge (0.2 x 20°) with an cutting edge radius of $r_{\beta 1}$ = 55 µm. Insert 2 and 3 have a cutting edge without chamfer. However, they differ in terms of cutting edge radius ($r_{\beta 2}$ = 55 µm; $r_{\beta 3}$ = 70 µm). To exclude the influence of wear on the cutting edge, a new tool is used for each cryogenic turning operation.

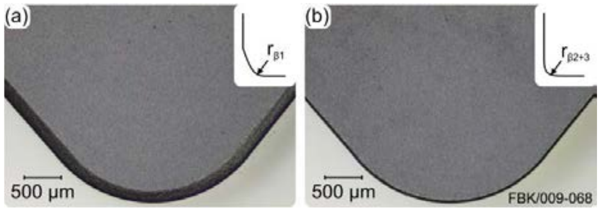

Fig. 2. Insert with (a) chamfered cutting edge and (b) rounded cutting edge.

For each insert the feed is varied (f_1 = 0.15 mm/rev; f_2 = 0.35 mm/rev). To keep the process energy and hence the generated heat at low values, a low cutting speed of v_c = 30 m/min is applied. The depth of cut is also chosen very small at a_p = 0.2 mm. A higher depth of cut would remove the workpiece volume cooled down by the cryogenic cooling and less martensite would be formed in the workpiece surface layer.

2.2. Workpiece material

The workpiece material is the metastable austenitic steel AISI 347 in solution-annealed state (no martensite content). This material exhibits a high susceptibility to austenite-martensite transformation due to its chemical composition (Table 1). Each alloying element influences the austenite stability. Additionally, if the deformation-temperature exceeds a critical value no phase transformation can take place. For this purpose, the M_{d30}-temperture allows a characterization of this thermal barrier [6] and is calculated according to the empirical equation of Angel [11] to 319 K with an uncertainty of ± 1.1 K.

Table 1. Chemical composition of investigated steel AISI 347 in weight-%.

C	N	Cr	Ni	Nb	Mn	Mo
0.024	0.019	17.29	9.25	0.41	1.55	0.19

2.3. Measurement technology

The process forces are measured with a piezoelectric three component dynamometer. The mechanical loads are characterized by means of the effective passive force F_p’ calculated according to [12]. For the cutting conditions in this study, F_p’ is composed by nearly the complete passive force and about a quarter of the feed force. Additionally, the stress distribution in the workpiece surface layer is determined as a result of equivalent stress hypothesis due to the Hertzian stress [12]. The workpiece temperature is measured using an infrared high-speed thermography-system with a frame rate of 328 Hz. As the contact zone itself cannot be monitored, the maximum surface temperatures below the reflection zone after a ¾ rotation along the feed travel are recorded and their average value per cut is calculated. The emissivity is determined for each feed. To evaluate the resulting workpiece quality, the surface roughness is measured by a mobile stylus instrument. A magnetic sensor is used to detect the martensite fraction in a fast and non-destructive way. An averaging value in vol.-% of the content of α’-martensite, formed in the measured volume part with a penetration depth between 2-3 mm [13], is determined via the sensor. The measurement of