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Local structure of metallic chips examined by X-ray microdiffraction

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ABSTRACT

Nickel-base alloys are used in high-temperature applications whenever steels or titanium alloys cannot be applied anymore. This class of alloys is furthermore used in low-temperature applications in the oil or gas industry in case the corrosion resistance of stainless steels in related liquid media is not sufficient and titanium alloys would be too expensive. Nickel-base alloys, however, due to their high strength and toughness can be machined only at low cutting speeds as otherwise poor surface quality and enhanced tool wear is observed. From all aspects influencing the machinability, the chip formation mechanism is the key factor and only a thorough understanding of this mechanism can lead to an optimisation of the cutting process.

In the current study, a detailed microstructure and phase analysis of Alloy 625 chips produced in an orthogonal cutting process at conventional cutting speeds is presented. Utilising hard monochromatic X-rays focused down to micrometre size, microstructural differences between distinct structural units of the chips, namely, the segments and shear bands, are investigated. Scanning cross sections of the chips with this small beam allowed us to determine misorientation between the segments and shear bands crystal lattices which as we found are not changing abruptly but continuously, with an absolute difference up to 10°.

1. Introduction

Nickel-base alloys are preferably used in high-temperature applications whenever steels (due to drop in mechanical properties at elevated temperature) or titanium alloys (due to insufficient oxidation resistance above 550 °C) cannot be applied anymore. In aerospace engine applications or in stationary gas turbines, excellent mechanical properties are needed at temperatures above 600 °C in combination with corrosion and oxidation resistance [1,2].

Due to its excellent corrosion resistance, the class of Ni–Cr–Mo alloys like Alloy 625 with the chemical composition Ni (bal), Cr 20–23%, Fe < 5%, Si < 0.5%, Mn < 0.5%, Mo 8–10%, Ti < 0.4%, Co < 1%, Nb + Ta:3.15–4.15%, and Al < 0.4% (all numbers in wt.%) is not only applied in stationary gas or turbines for exhaust or piping systems. It is furthermore applied in low-temperature applications in the oil or gas industry wherever the corrosion resistance of steels in liquid media is not sufficient anymore and titanium is too expensive [3].

During the component manufacturing of related Alloy 625 products (e.g. turbine housings) in any application, up to 50% of the forged semi-finished parts have to be removed by different machining operations as during welding or brazing microstructural transformations might occur leading to increased notch-sensitivity of the parts or the transformation of γ''- to δ-phase [4,5]. Due to the high strength and toughness of Alloy 625 only low cutting speeds can be applied during metal cutting operations as otherwise poor surface quality and enhanced tool wear is observed. In addition, the cutting process has to be interrupted as often as it is necessary to remove the long chips from the process zone. Automation especially of turning or drilling operations is therefore almost impossible. The following suggestions are given for machining of Alloy 718 (an alloy similar to Alloy 625 with respect to machinability) regarding the cutting speed: turning operations <80 m/min, drilling operations between 3 m/min and 5 m/min [6].

From all aspects influencing the machinability, the chip-formation process is the key factor and only a thorough understanding of this mechanism can lead to an optimisation of the cutting process. The chip formation process can be described as follows: At the beginning of the cutting action, the material is dammed in front of the tool and the plastic deformation is concentrated in a narrow zone, the primary shear zone, leading from the tool tip to the upper surface of the workpiece. Most of the energy used for the plastic

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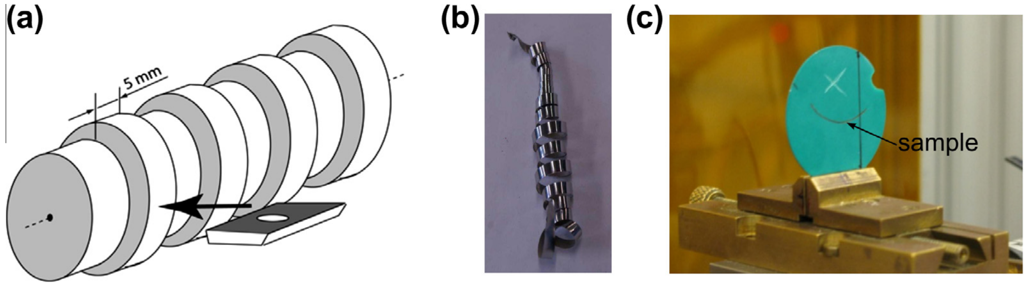

Fig. 1. (a) Sketch of the orthogonal cutting experiment carried out on a CNC lathe; (b) chip coming from the orthogonal cutting experiment; and (c) experimental set-up for the X-ray microdiffraction experiments.

deformation is transformed into heat in the primary shear zone. The rate of heat dissipation into the surrounding material strongly depends of the material properties (e.g. heat conductivity and flow curves) and the cutting parameters (e.g. the cutting speed, cutting depth and feed rate). In case the heat can dissipate quickly, the material is deformed homogeneously leading to the formation of a continuous chip with constant chip's thickness. The cutting force remains almost constant as well. If the heat cannot dissipate quickly into the material surrounding the primary shear zone, the material locally softens and the deformation therefore localises. In the end, the material is deformed in a narrow zone of a few micrometres (the so-called adiabatic shear band, the width of the shear band in the investigated alloy lies between 2 μm and 20 μm) which leads to the formation of segmented, saw-tooth like chips [7,8]. The (local) temperature in the shear bands can easily reach 1000 °C [9,10].

In the current study, a detailed microstructure and phase analysis of chips produced in an orthogonal cutting process at conventional cutting speeds are presented. These results were used to verify related finite element simulations as presented in [11].

2. Material, cutting experiments and sample preparation

Alloy 625 is a nonmagnetic, corrosion and oxidation resistant, nickel-based alloy. Its outstanding strength and toughness in the temperature range from cryogenic to 1093 °C are derived primarily from the solid solution hardening effects of the refractory metals, niobium and molybdenum, in a nickel–chromium matrix [12]. In addition, particle strengthening by means of γ''-phase (Ni_3Nb) is possible. The alloy has excellent fatigue strength and stress-corrosion cracking resistance to chloride ions. Some typical applications for Alloy 625 therefore include heat shields, furnace hardware, gas turbine engine ducting, combustion liners and spray bars, chemical plant hardware, and special seawater applications [7,13].

The material used in our study has been produced by Outokumpu VDM (Alloy 625, brand name: Nicofer® 6020 hMO) following the specifications UNS NO6625 Grade 1, 2.4856 and ASTM B 446-03. The chemical composition was: Ni:balance, Cr:22.10%, Mo:9.10%, Nb:3.43%, Fe:4.73%, Ti:0.33%, Al:0.21%, Mn:0.11%, Si:0.10%, Co:0.08%, C:0.03%, Ta:0.01%, S:0.001%, and P:0.006%. The alloy has been processed by forging from diameter approx. 200 mm to a final diameter of 80 mm at 1080 °C followed by the heat treatment 975 °C/0.45 h/WQ (grade 1, soft annealed). During component manufacturing, the material is often machined in the soft annealed state [14].

Orthogonal cutting experiments at Alloy 625 using conventional cutting speeds (20 m/min < v_c < 200 m/min) and different cutting depths (0.05 mm < a_p < 0.15 mm) have been carried out in an earlier study. The experiments have been performed on a computer-numerically controlled (CNC) lathe [8]. The sep-up of the experiment is shown in Fig. 1a. Alloy 625 bars of approx. 78 mm have been sectioned into rings of a 5 mm width and a depth of approx. 3 mm. The width of the tool was much larger than the width of cut so that edge effects were minimised. The rings have been removed by moving the tool in radial direction towards the bar's centre. To keep the cutting speed constant, the rotational speed has been continuously increased during the experiment. The cut has been stopped after a length of cut of approx. 500 mm was reached. Standard TiN-coated cemented carbide cutting inserts, SECO CNMA 120408 – TK2000, have been used for the cutting experiments as the rake angle of these tools is 0°, the clearance angle is 5°. The tools have been changed after each cutting operation to exclude wear effects.

The resulting chips as shown in Fig. 1b have been analysed in cross section to study the chip geometry and microstructural features. At low cutting speeds (up to 80 m/min) and low cutting depths (0.05 mm < a_p < 0.10 mm) continuous chips were obtained. At intermediate cutting speeds and cutting depths (80 m/min < v_c < 120 m/min, 0.10 < a_p < 0.15 mm) chips formed showing areas with chip segmentation and areas in which the chips had a constant thickness, the so-called transition cutting speed regime. Above a cutting speed of v_c = 120 m/min fully segmented chips were formed if $a_p \geqslant$ 0.10 mm [15].

In the present study, selected fully segmented chips produced at v_c = 160 m/min and a_p = 0.1 mm have been investigated by micro-X-ray diffraction, to perform detailed phase and microstructure studies. As the sample preparation can introduce residual stresses in the material, special care has been taken during the sample preparation: first, an approx. 20 mm long piece from the middle part of the chip was cut with a metal scissors and embedded in IsoFast thermosetting resin (Struers GmbH) at a pressure of 28 MPa and a temperature of 170 °C in a SimpliMet 1000 automatic mounting press. The chip in the mount was positioned in such way that axis of chip width was parallel to the mount main axis and chip cross-section was visible from one side. This has been controlled by stereo microscopy at a magnification of about 10. In the second step, the sample has been ground and polished from both sides to a final thickness of 0.5 mm. This was necessary, to (1) remove the chips' edges to allow the analyses of the chips' centre region and (2) to remove possible residual stresses coming from the scissors-cut. The last operation was chemical etching of the two free surfaces. The thin disc containing the cross section of the chip has finally been mounted into a bench vice and positioned in the X-ray path of P07 (PETRA III at HASYLAB, DESY, Germany) beamline. The experimental set-up is shown in Fig. 1c.

As the sample was analysed in transmission, it had to be ensured that the segments were straight in the direction of the beam. Otherwise, a detailed shear band analyses would not have been possible. The sample investigated at beamline P07 has afterwards been metallographically analysed in the three dimensions. To do so, small amounts of the sample were removed by grinding and polishing and ten cross sections have been analysed, see Fig. 2. The part of the chip that has been analysed by hard X-ray microdiffraction (red line in Fig. 2) was regular and the segments were sufficiently straight. This can be explained by the use of an orthogonal cutting operation.

3. Instrument used for microdiffraction experiment

To determine the structure orientation and possible phase transformations in the shear bands a hard X-ray micro-diffraction experiment was performed at beamline P07 [16] at PETRA III (positron storage ring operating at energy 6 GeV with beam current 100 mA) [17]. During the experiment, monochromatic synchrotron radiation of energy 80.09 keV (λ = 0.01548 nm) was used. The beam of photons was focused by compound refractive lenses down to a spot size of 2.2 μm × 34 μm. The specimen was scanned shot-by-shot along a straight path (red line marked in Fig. 2) of to-

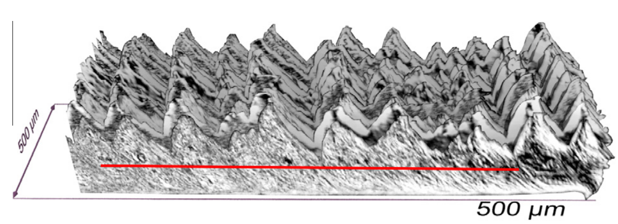

Fig. 2. Three-dimensional view (ten cross sections) of the Alloy 625 chip investigated by microdiffraction. The segments and the shear band in the investigated region (red line) are straight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)