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PRODUCTION PROCESS

Influence of XHV-adequate atmosphere on surface integrity

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Abstract

In aerospace engineering, high temperature alloys such as titanium are the preferred choice. However, machining of such materials remains a major challenge due to high process forces and process temperatures. Currently, machining is performed almost entirely in the presence of oxygen. This results in a process-inherent oxidation of the metal surface, which leads to higher tool wear during machining. By means of an oxygen-free machining undesirable oxidation reactions will be avoided and thus results in an extension of tool life. In addition, oxygen-free machining in an extreme high vacuum (XHV) adequate environment can influence the resulting workpiece surface and subsurface properties due to change in process forces and chip formation. In the present work, the influence of machining under air and XHV-adequate atmosphere is examined with regard to chip formation, workpiece surface topography and residual stresses. Significant differences can be seen in resulting surface integrity depending on the machining atmosphere.

Keywords Longitudinal turning · Oxygen-free atmosphere · Surface integrity

1 Introduction

In aerospace technology, titanium is one of the most frequently used materials [1]. This is due to the excellent mechanical properties of titanium, such as high mechanical strength combined with low density, which plays a key role in the aerospace industry in particular. In this context, the alloy Ti–6Al–4V is used in specific aerospace applications e.g. engine and airframe systems [2]. Despite these advantages, machining this material still proves to be a major challenge. A series of research works have therefore already been dealing with the investigation of the machining behaviour of titanium. Thereby, the high process forces, high process temperatures and unfavourable formed chips turned out to be the reasons for rapid tool wear and difficult machinability [3–7].

The chip formation mechanisms in titanium have already been studied in numerous research works [8–10]. Compared to many other materials, titanium is subject to serrated chip formation even at low cutting speeds during machining. This is due to the low thermal properties of titanium. During the machining of steel materials, different types of chip formation are found depending on the material properties and process parameters. These are divided into four categories: Flow chip, lamellar chip, serrated chip and discontinuous chip [8].

Currently, the machining of titanium in industry takes place almost solely in the presence of oxygen. Recent research results show that the absence of oxygen during machining can significantly reduce process forces and modify chip formation [11–13]. Denkena et al. investigated the tribochemical wear resistance of different coated carbide tools by varying the atmosphere during turning of Ti–6Al–4V. As a result, a reduction of tool wear and thus an extension of tool life up to 60% in an extreme high vacuum (XHV) adequate atmosphere could be proven [11]. These results are confirmed by the studies of Maier et al. [12]. They investigated tool wear during milling as a function of the ambient atmosphere. Here, a significant reduction of process forces was observed under XHV-adequate atmosphere. In addition, a change in chip formation is observed as a function of the atmosphere. Milling in an XHV-adequate atmosphere lead to a slight increase in chip curl radius as well as to a reduction in chip segmentation. As a cause for this, they specified the increased adhesion processes taking place under oxygen-free atmosphere, which leads to change

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in the rake angle and friction conditions [12]. Mercer and Hutchings performed pin-on-disc tests under variation of atmosphere. They attributed the differences in abrasion behaviour to the modification of the surface alloy composition by removal of interstitial elements e.g. primarily oxygen and nitrogen [14]. This follows in an increase of surface ductility and thereby can influence the chip formation during cutting in XHV-adequate atmosphere.

Surface and subsurface properties in particular have a significant influence on the application behaviour and lifetime of high-performance components [15–17]. The modified thermomechanical loads during oxygen-free machining are expected to change surface and subsurface properties compared to machining in ambient air. By adjusting the atmosphere in a targeted manner, surface reactions can therefore be induced that were previously not possible. Consequently, this leads to modified surface and subsurface properties compared to machining in air. Lee et al. exploited this effect to produce a hard protective layer of titanium nitride by gas nitriding of the workpiece surface. For this a multi-step process by heating the sample, maintaining the temperature for different time levels and supplying nitrogen under an oxygen-free atmosphere was conducted [18]. Due to the high reaction rate of titanium with oxygen, a reaction with nitrogen in air would not be possible. Susil et al. used the reactivity of carbon steel C15 with acetylene to harden the surface layer of the component during turning. By simultaneously adding nitrogen, they were able to suppress undesirable oxidation reactions [19].

Machining under an XHV-adequate atmosphere provides completely new potentials with regard to subsurface modification and lifetime optimization of high-performance components. In the present study the influence of XHV-adequate atmosphere during turning of Ti–6Al–4V on surface and subsurface properties compared to turning in air is being investigated for the first time.

2 Materials and methods

2.1 Material properties

In order to investigate the influence of XHV-adequate atmosphere on surface integrity, solid shafts of Ti–6Al–4V after longitudinal turning are studied. The chemical composition of this material is shown in Table 1. Generally titanium alloys are divided according to the phases involved in α, α + β and β-alloy. The α-phase is characterized by high corrosion resistance and high ductility, but has lower strength than the β-phase. The advantage of the β-phase is its higher temperature resistance, which enables the application in high temperature application like aircraft turbines. The alloying element aluminium, which is one of the alloys with the highest content with 5.5–6.75 wt.%, leads to a stabilization of the α-phase. The alloying element vanadium, as alloying element with second highest weight content, stabilizes the β-phase. Accordingly the Ti–6Al–4V alloy is characterized by α + β-phase. Due to the two-phase α + β-alloy composition, positive high-temperature properties are combined with high strength and creep resistance [1].

Thus, this alloy has a high tensile strength in the range of of $R_m = 900–1200$ MPa. Furthermore, this alloy is characterized by low values of thermal conductivity. The thermal conductivity depends on the temperature. While the thermal conductivity at room temperature is 6.6–6.8 W/mK, at a temperature of 800 °C increases it to 16.0–19.0 W/mK [1].

2.2 Machining

The aim of the present work is to investigate the influence of XHV-adequate atmosphere on surface integrity of Ti–6Al–4V alloy. For this purpose, in the first step, rotating bending shafts are produced from solid Ti–6Al–4V shafts with an initial diameter of 22 mm in the vertical turning machine of type CTV400 lathe of the company Gildemeister. The specimen geometry is shown in Fig. 1, top right. The turning experiments were carried out with a cutting speed of $v_c = 60$ m/min, a feed of $f = 0.1$ mm and a depth of cut of $a_p = 0.15$ mm under variation of the cutting atmosphere. PVD-coated indexable cemented carbide inserts of type DNMG150604 KCS10B with coating composition AlTiN of the company Kennametal were used for the turning process. The process parameters were selected according to process stability during turning of components clamped on one side and machined in vertical direction. With the process parameters chosen here, chatter vibrations could be avoided and a sufficiently good surface quality could be achieved, which is required for future fatigue life investigations. Furthermore all experiments were carried out dry without the use of cooling lubricant. For statistical verification, the test series for different atmospheres were repeated ten times. The experimental setup in the lathe for setting different atmospheres is shown in Fig. 1.

For creating an atmosphere adequate to XHV, the working chamber developed within the framework of subproject B03 in the CRC 1368 was used. The machining chamber is

Table 1 Chemical composition in wt.% of Grade 5 Ti–6Al–4V according to [8]

Al	C	Fe	N	O	V	H	Ti
5.5–6.75	0.1	0.3	0.05	0.2	3.5–4.5	0.015	Balance

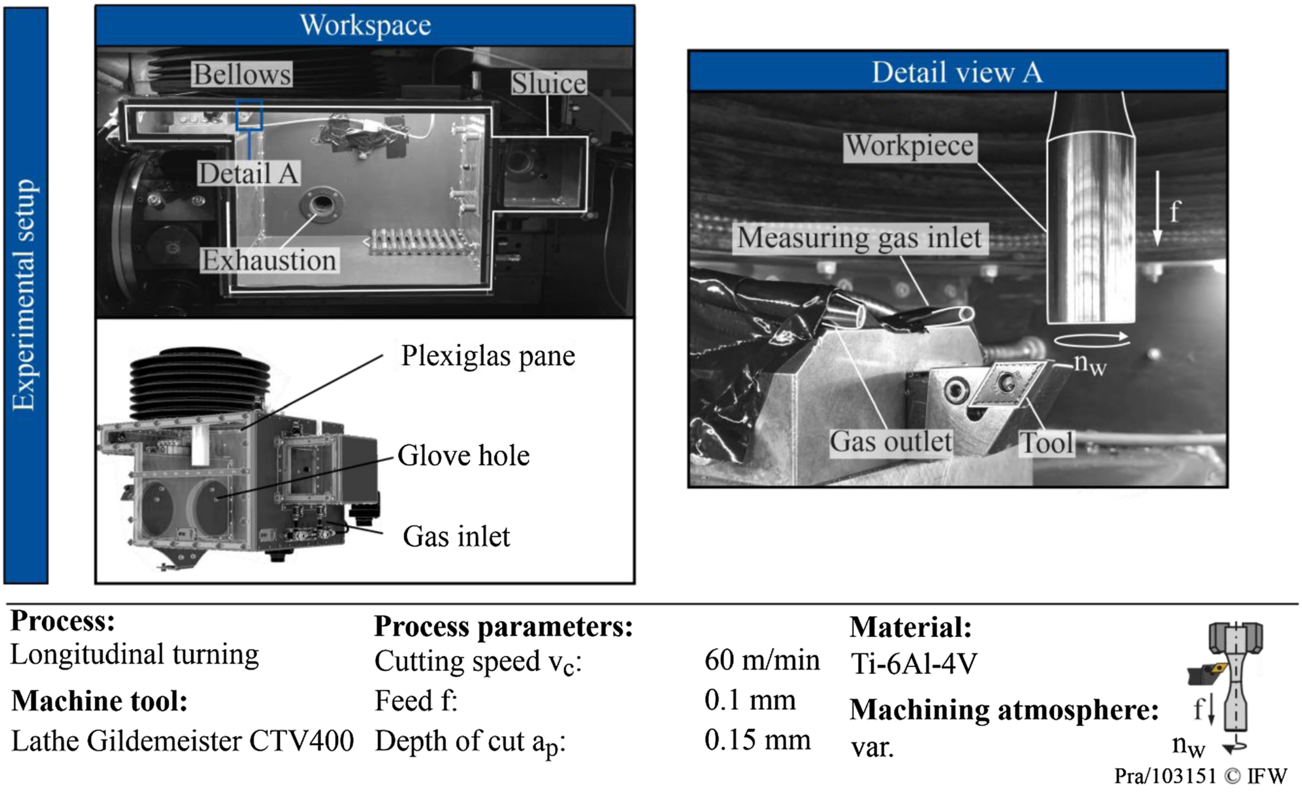


Fig. 1 Experimental setup in the CTV400 lathe

designed to be clamped to the tool revolver of the machine tool. The drive spindle can be moved in transverse direction and thus determines the cutting depth. The bellows located on the chamber allows the drive spindle to be separated from the ambient atmosphere while permitting the transverse motions required for the process. At the beginning, a flushing with argon 5.0 of high purity > 99.999% from Fa. Linde Gas & More was carried out. The XHV adequate atmosphere was then achieved by supplying an argon-silane gas mixture with 1.5% silan and 98.5% argon 5.0 from Fa. AIR LIQUIDE. The set atmosphere is checked with regard to the oxygen partial pressure by taking a sample gas by the measuring gas inlet. The extracted gas is fed to an oxygen partial pressure measuring device, thus enabling process monitoring of the oxygen partial pressure during machining. Integrated leak tight glove guides are provided for workpiece and tool changes during machining in XHV adequate atmosphere. After completion of the machining process, reaction products such as fine dust particles can be safely removed by an exhaust system installed at the back of the chamber.

2.3 Analytics

After the machining experiments the influence of XHV adequate atmosphere compared to air atmosphere is analysed with respect to chip formation, surface topography and residual stresses.

Micrographs of the chips produced in different cutting atmospheres were made to investigate chip formation. For this purpose the chips were electrically conductively embedded in a hot embedding medium WEM REM based on phenolic resin and graphite as filler from the Fa. Cloren. Subsequently, the embedded specimen was ground and polished. The specimen was then etched with a water-based etchant containing nitric acid, hydrochloric acid and hydrofluoric acid from Fa. Kroll. Finally, the micrographs were taken with the Leitz Aristomet optical microscope. In addition, stereomicroscopic images with the VHX 5000 digital reflected light microscope from Keyence-Corporation were carried out in order to analyse the chip shapes in dependence of the cutting atmosphere.

Surface measurements are used to examine the influence of cutting atmosphere on surface topography and roughness. The surface measurements were made with the Confovis DuoVario with TOOLinspect by the company Confovis GmbH. The measuring principle is based on confocal measurement. A 20 × magnification lens was used to capture surface topographies with required resolution in the micrometer range. An area of 6 mm × 2 mm was defined as measuring range. Surface topographies resulting from machining as a function of the ambient atmosphere are evaluated using the Abott-curve. With the Abbott-curve, the surface topography is not described by a single value, but irregularities in the surface such as changes in peak or valley areas are displayed graphically. To derive the Abbott-curve (also material contact ratio curve), sectional planes are plotted in defined increments starting at the highest point of the roughness peak down to the lowest point of the roughness depth. The intersected surface area is then determined for each cut plane position and plotted as a percentage of the total measured area. The so generated Abbott-Curve is then divided in three sections. Characteristic values that are related to the respective area are Spk (mean height of the peaks protruding from the roughness core profile), Sk (core roughness depth) and Svk (mean depth of the valleys protruding from the roughness core profile). Mr1 and Mr2 is the material ratio that limits the core area.

In addition, residual stress measurements are carried out on the components machined with different atmospheres. The residual stress measurements were performed on a two-circle diffractometer system GE XRD 3000 P. A copper tube with an applied high voltage of 40 kV and a current of 40 mA was used as the anode. The spot diameter was limited by a 2 mm point collimator. Measurements were made on the alpha titanium lattice plane hkl (213) using the $\sin^2\psi$-method. Here, the maximum information depth is $\tau_{max} = 5.1$ µm. The machined samples were measured in both circumferential and axial directions. Surface residual stresses were determined at different distances along the machined samples in air or under XHV-adequate atmosphere. Due to the reliability and reproducibility of the results already known from the state of the art as well as the higher measurement time required, two samples per atmosphere were investigated in each of the pre-investigations.

3 Results and discussion

3.1 Analysis of chip formation

During the turning process, the chips were collected and afterwards examined with regard to different chip formations depending on the ambient atmosphere. For this purpose, stereomicroscopic images as well as microsections of the chips produced under air and XHV adequate atmosphere were made. The results of the investigations are shown in Fig. 2.

With regard to the macroscopic chip shape, the chips produced in air and XHV adequate atmosphere differ significantly from each other. While the chips produced

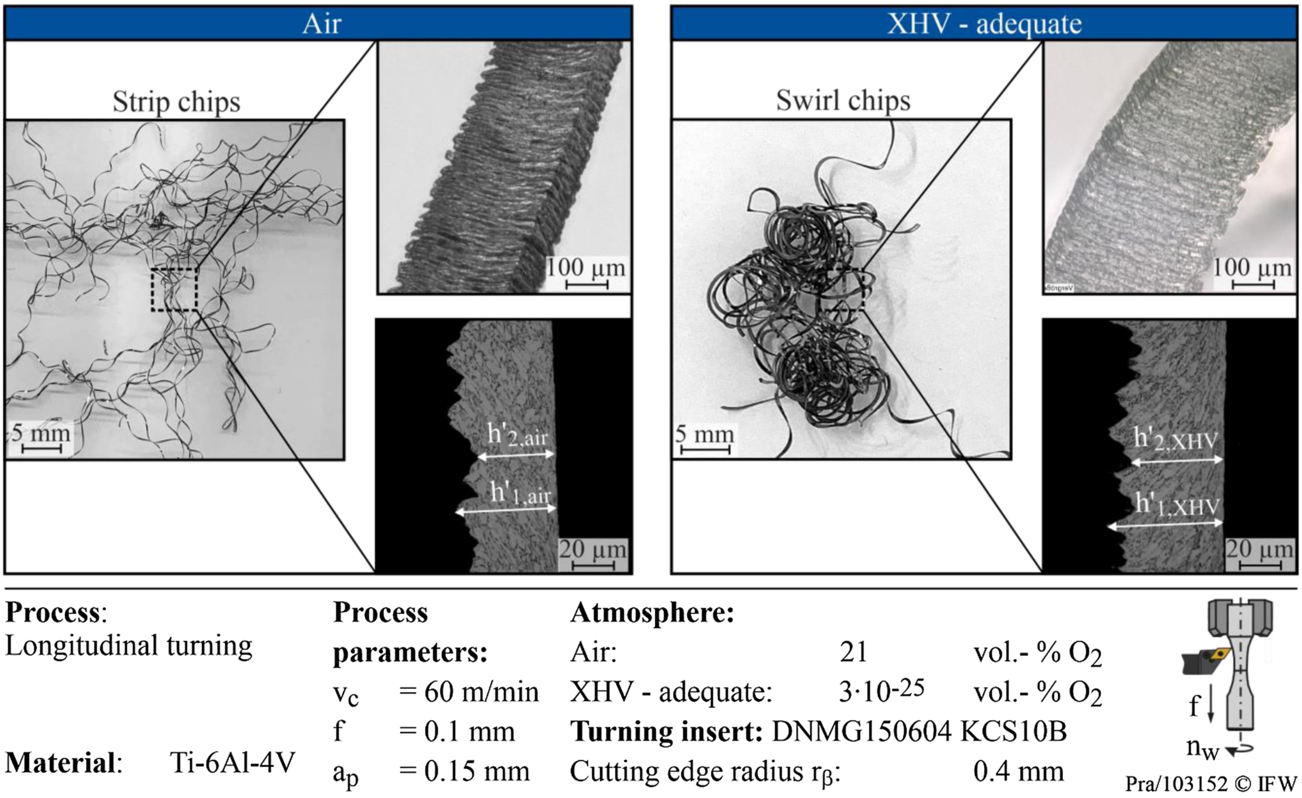


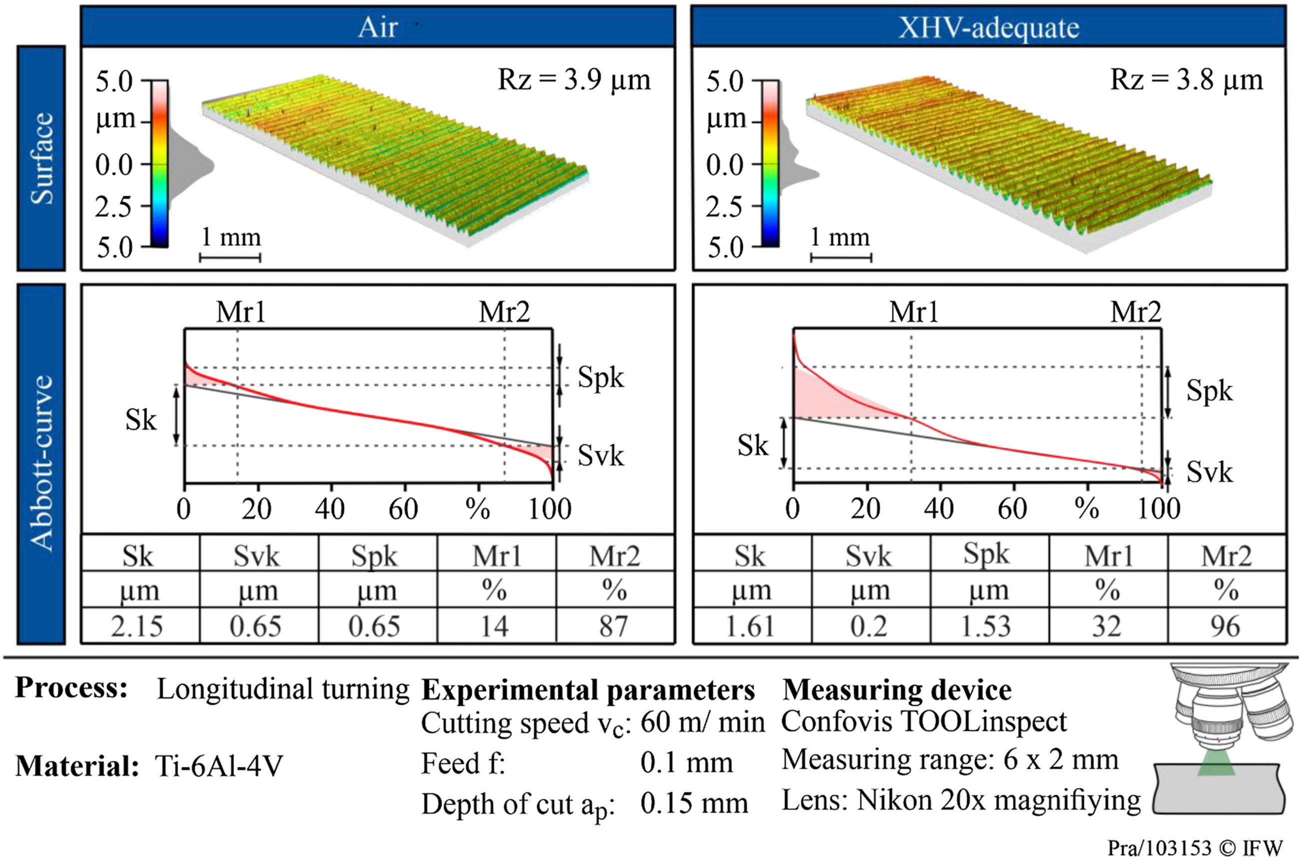
Fig. 2 Influence of machining atmosphere on chip formation

under air resemble lengthened strip chips, the chips produced under oxygen-free atmosphere are noticeably more compact and have a similar shape to swirl chips. With the aid of stereomicroscopic images and microsections, a difference in the microsectional chip shape can also be seen. The chip thickness of chips produced under air is with $h'_{mean} = 43.7$ µm smaller than compared to chips produced under XHV-adequate atmosphere with an average chip thickness of $h'_{mean} = 50.8$ µm. Accordingly, elongated strip chips are produced in air, while under an oxygen-free atmosphere they become more agglomerated due to greater chip thickness. In general, a change in chip formation is evident as a function of the ambient atmosphere during machining. The chip thickness increases, which indicates a change in chip formation mechanism. The material deformation in the chip also shows minor differences. However, to evaluate the effects of the ambient atmosphere on chip formation in more detail, further investigations are required with regard to shear angle, separation point at the cutting edge and chip flow rate. According to the studies of Meyer et al. [9] the cutting atmosphere influences the tendency to adhesion and thus affect chip formation. Accordingly, future investigations should also take into consider the effects of built-up edge formation as a function of the atmosphere in order to understand chip formation mechanisms.

3.2 Surface topography

For investigation of the influence of ambient atmosphere on surface topography, three dimensional surface measurements are evaluated with respect to roughness and Abbott-curve.

The results of the surface analysis are shown in Fig. 3. The averaged roughness depth Rz has a standard deviation of 0.37 µm under air and a standard deviation of 0.12 µm under XHV adequate atmosphere. While the averaged roughness depth Rz display nearly same values regardless of the ambient atmosphere, the produced surfaces differ significantly in the Abbott-curves. The core roughness Sk is 2.15 µm for machined surface in air. In XHV-adequate atmosphere, however, the core roughness is reduced by approx. 25%. Significant differences can also be seen in an increase of the reduced peak height and a reduction of the reduced valley height. Here, in oxygen-free machining, the peak area is significantly larger than the groove area compared to machining in air. The increase of the stochastic component of the surface roughness might be due to an increase of adhesion



Air

Sk	Svk	Spk	Mr1	Mr2
µm	µm	µm	%	%
2.15	0.65	0.65	14	87

XHV-adequate

Sk	Svk	Spk	Mr1	Mr2
µm	µm	µm	%	%
1.61	0.2	1.53	32	96

Process: Longitudinal turning

Material: Ti-6Al-4V

Experimental parameters
Cutting speed v_c: 60 m/ min
Feed f: 0.1 mm
Depth of cut a_p: 0.15 mm

Measuring device
Confovis TOOLinspect
Measuring range: 6 x 2 mm
Lens: Nikon 20x magnifiying

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Fig. 3 Influence of machining atmosphere on surface topography and its parameters phenomena. However, this occurs irregularly and randomly, whereby differences in chip formation have already been observed. Furthermore, the increase in the stochastic component may also be due to different reactivity of the α- and β-phases of the titanium alloy contained in the surface. Due to the avoidance of the formation of titanium oxide layer in XHV-adequate atmosphere, chemical reactions can take place which would not be possible in air. Future studies should therefore look more closely at the change in alloy composition in the surface as a function of the machining atmosphere.

3.3 Residual stress measurements

The results of the residual stress measurements are shown in Fig. 4. Specimens machined under air in particular show a high variation of the surface residual stresses in the circumferential direction $\sigma_\perp$ along the measuring positions. However, the other profiles also show slight fluctuations. In analogy to the observations made regarding the influence of the cutting atmosphere on chip formation and surface topography, differences are also found in the surface residual stresses. The fluctuation of residual stresses along the specimen is remarkable. The microstructure in the as-delivered condition consists primarily of the α-phase with grain size of 10–12 µm. During the alloy production, in places where grains of the α-phase and β-phase get in contact, the lamellar mixed α + β-phase is deposited. The variation of the surface residual stresses can be attributed to fluctuation of α- and α + β-phases of the titanium alloy in different measuring positions. The residual stress fluctuations seem to be reduced by the XHV-adequate atmosphere.

4 Summary and outlook

Surface and subsurface properties have a significant influence on service life and application behavior of high-performance components. How surface and subsurface properties change under variation of the ambient atmosphere has not been investigated so far. Therefore, in the present work, shafts made of Ti–6Al–4V are investigated under variation of the machining atmosphere (air and XHV-adequate) with respect to chip formation, surface topography and residual stresses.

Chip formation is significantly influenced by the cutting atmosphere. Here, machining in an oxygen-free atmosphere leads to an increase in chip thickness. At a cutting speed of

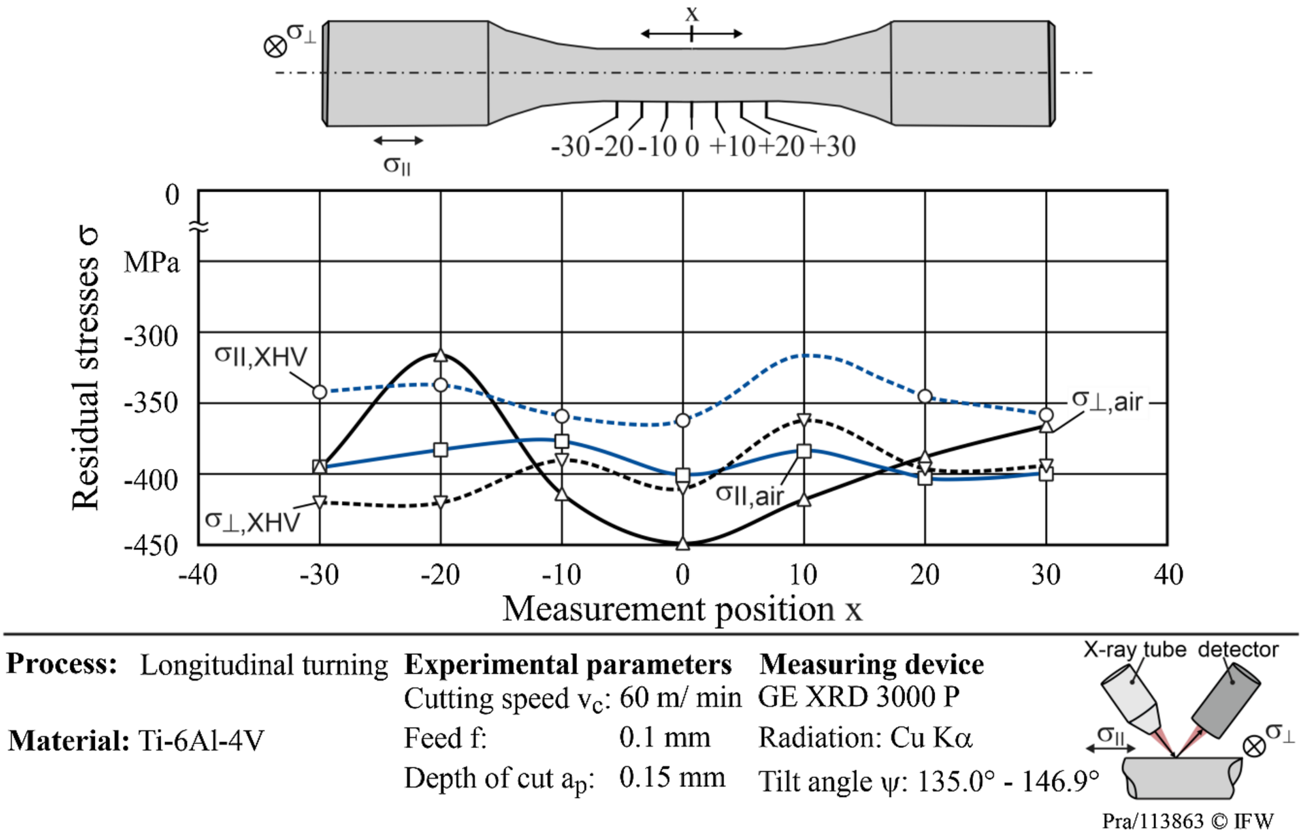

Fig. 4 Influence of machining atmosphere on surface residual stresses

$v_c = 60$ m/min, irregular chip formation is noticed for the investigated titanium alloy. Hence, a significant difference in terms of chip formation depending on the ambient atmosphere is evident. Further research is needed to understand the mechanisms underlying the observed effects. In further studies this is to be investigated in more detail.

A change in chip formation leads to a change in surface topography as well as residual stresses. In particular, the stochastic part of the surface topography is influenced by the ambient atmosphere. The peak area increases significantly under XHV-adequate atmosphere. This can be seen in the Abbott-curve. Differences can also be seen in surface residual stresses as a function of the ambient atmosphere.

In future investigations, the specimens produced under air and oxygen-free conditions will be examined in rotating bending tests with regard to fatigue life in dependency of the cutting atmosphere.

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