Influence of High-Speed Milling Process on Mechanical and Microstructural Properties of Ultrafine Grained Profiles Produced by Linear Flow Splitting

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(Received 29 September 2015; revised 2 December 2015; accepted 8 December 2015)

Abstract: The effects of milling parameters on the surface quality, microstructures and mechanical properties of machined parts with ultrafine grained (UFG) gradient microstructures are investigated. The effects of the cutting speed, feed per tooth, cutting tool geometry and cooling strategy are demonstrated. It has been found that the surface quality of machined grooves can be improved by increasing the cutting speed. However, cryogenic cooling with CO_2 exhibits no significant improvement of surface quality. Microstructure and hardness investigations revealed similar microstructure and hardness variations near the machined groove walls for both utilized tool geometries. Therefore, cryogenic cooling can decrease more far-ranging hardness reductions due to high process temperatures, especially in the UFG regions of the machined parts, whilst it cannot prevent the drop in hardness directly at the groove walls.

Key words: high-speed milling; ultrafine grained microstructure; linear flow splitting; hardness

CLC number: TG115 **Document code**: A **Article ID**: 1005-1120(2017)04-0349-07

0 Introduction

Due to resource scarcity, the demand for cost-effectiveness and increased product functionality, the companies are focused on the development of new production strategies which make use of synergetic effects and process induced enhanced material properties, especially in the field of aerospace, ship building and automotive applications[1-2]. In this context, manufacturing and processing of ultrafine grained (UFG) materials gain scientific and industrial importance in that UFG materials with average grain sizes less than 1 μm show high strength and good ductility in contrast to coarse grained (CG) metals and alloys. Among various processing methods for grain refinement, severe plastic deformation (SPD) technique provides the capability of producing bulk UFG materials for structural applications. The principle of SPD processes is based on the grain refinement by imposing very high strains on materials without any significant change in the overall dimensions of the workpiece[3-4]. However, most of SPD techniques are not competitive for large dimension applications and the massive forming process linear flow splitting was developed for continuous production of profiles out of sheet metal. Bifurcated profiles marked by a web and two flanges are produced by using a specific tooling system consisting of obtuse angled splitting rolls and supporting rolls[5].

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How to cite this article: Abele Eberhard, Müller Clemens, Turan Emrah, et al. Influence of high-speed milling process on mechanical and microstructural properties of ultrafine grained profiles produced by linear flow splitting[J]. Trans. Nanjing Univ. Aero. Astro., 2017,34(4):349-356.

http://dx.doi.org/10.16356/j.1005-1120.2017.04.349

UFG microstructures develop at the surface area of the split flanges due to high hydrostatic stresses in the processing zone. Detailed investigations of the microstructure revealed a process characteristic ultrafine grain size gradient perpendicular to the split surface resulting from the heterogeneous deformation within the process zone. This microstructure gradient is accompanied by a steep hardness gradient in flange thickness direction[6-7].

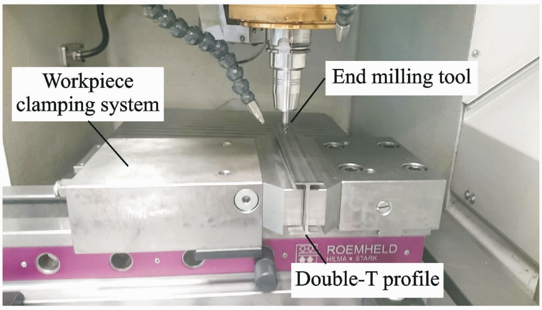
Manufacturing of multifunctional modules from linear flow split profiles requires the production of geometric elements as junctions by using the high-speed machining process. To avoid microstructural changes and the loss of hardness during the milling process, experimental investigation of the interaction between the cutting process and the microstructure is necessary. Therefore, the surface integrity and surface topography after machining of workpieces with different grain sizes are investigated. Symonova et al. observed that machining of pure UFG Ti caused a surface grain coarsening and surface softening due to temperature increase[8]. In a further investigation Rodrigues et al. studied the influence of the process parameters (cutting speed, feed per tooth) on the hardness and microstructure of low-carbon alloyed steel with ultrafine grains mainly at high-speed machining. In most of cutting conditions there was found to be little or no change in hardness and microstructure due to the milling of UFG steel. Consequently, the initial grain size of the workpiece can have a major effect on the surface properties of machined parts[9]. Investigations of the surface topography of milled UFG workpieces reveal an improved surface finish compared to machined CG materials even though the feed per tooth, and the cutting speed are increased[10-11].

Considering that the influence of UFG gradient microstructures of linear flow split profiles on the cutting process has not been investigated in detail yet, the aim of this work is to analyze the effects of high-speed milling process on mechanical and microstructural properties of UFG profiles.

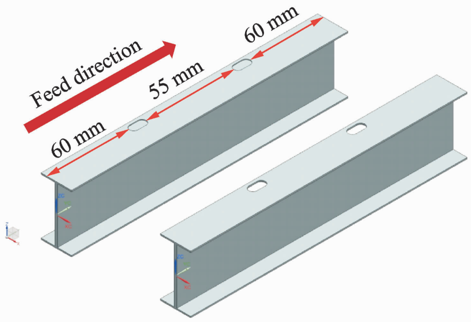
1 Experiments

1.1 Milling tests

The experiments were conducted on linear flow split profiles made from the high strength low alloy steel H480LA. The microstructure of the received sheet material consists of ferrite grains and evenly distributed small Fe$_3$C precipitates. The workpiece (Double-T profile) used in this investigation has a web thickness of 2 mm whereas the flanges have a thickness of approximately 1 mm. The experimental-set up of the milling operation and the position of the geometric elements on the workpiece are illustrated in Fig. 1. For the experiments, two 4-fluted end milling tools with a diameter of 6 mm and different helix angles 15° (A) and 50° (B) are used to identify the effect of the helix angle variation on the heat development and the quality of the machined geometric elements whereas the clearance angle ($\alpha = 8°$—$10°$), the rake angle ($\gamma = 9°$—$12°$)



(a) Experimental set-up



(b) Position of geometric elements on the workpiece

Fig. 1 Experimental set-up and position of geometric elements on the workpiece and the width of the cutting edge chamfer (0. 1 mm) are kept constant. To find out the correlation between heat development and microstructural evolution during the milling process, the cutting speed is increased from 150 m/min (conventional cutting) to 750 m/min (high-speed cutting). The feed rate per tooth (f_z) is varied from 0. 05 mm/z to 0. 1 mm/z while depths of cut of 0. 5 mm and 1. 0 mm are selected to analyze the groove (UFG) and slot milling (UFG plus CG). The radial depth of cut is kept constant at 6 mm. To avoid microstructural changes due to chemical attack, the workpieces were machined under dry conditions and also with the use of CO_2. The experiments were run on a 3-axis machining center of Roeders TEC (type: RHP 500) with a maximum spindle speed of 42 000 r/min (tool holder HSK 63A).

1. 2 Measurement methods

To assess the surface quality considering the tool geometry, the process parameter combinations and the cooling strategy, the surface roughness of the groove base in the middle of the geometric element was measured with a tactile surface measuring system MarSurf GD25 (measuring probe MFW-250) of the company Mahr. The microstructure was evaluated with a TESCAN MIRA 3 FEG high resolution scanning electron microscope with a four quadrant backscattered electron detector and an acceleration voltage of 15 kV. Hardness measurements were conducted on a FISHERSCOPE H100C micro hardness tester using a Vickers indenter and a load of 50 mN. To reduce scattering by increasing the applied load, the regions influenced by the milling process had to be broadened by cutting the milling edges under an angle of 8° to the feed direction with a cutting plane perpendicular to the splitting surface. The samples were then mounted, ground and polished with diamond suspensions.

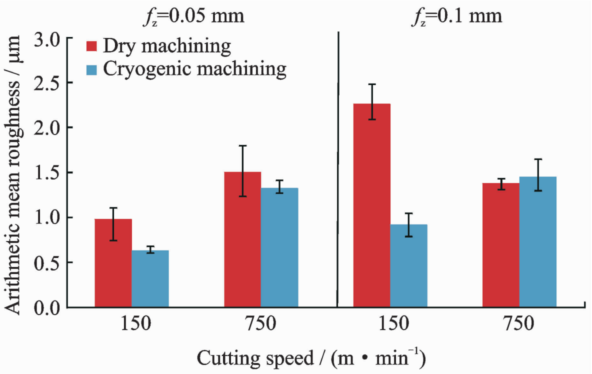
2 Results and Discussion

2. 1 Surface roughness

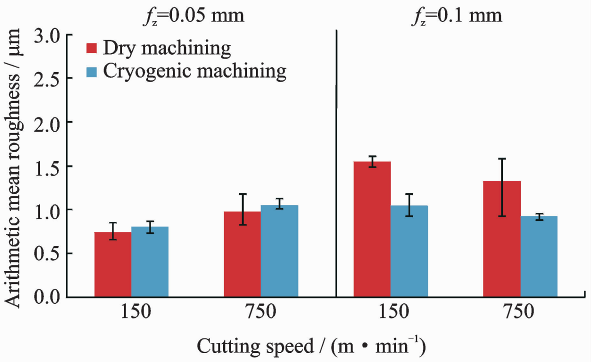
The roughness measurements of the machined linear flow split profiles with different helix angles confirm that an increasing helix angle leads to a better surface finish for all the process conditions due to the improved chip removal. The comparison of the roughness values of conventional and high-speed cutting (HSC) samples shows that the surface roughness decreases slightly by increasing cutting speed in the feed rate per tooth of 0. 1 mm/z. However, this effect is not observable in the minimum feed rate per tooth of 0. 05 mm/z. Moreover, it can be seen that increased cutting speeds result in enhanced roughness values and the reason for the poor surface quality may be the increased vibration amplitude of the workpiece during the milling of the thin-walled linear flow split profiles due to the influence of the feed rate per tooth on process damping. The investigations of the influence of different cooling strategies on surface quality reveal that a better surface finish can be reached by using cryogenic cooling whereas the positive effect of the cooling medium is stronger compared to dry machining in the range of conventional cutting (Fig. 2). Kaynak et al. traced the improvement of surface quality by cryogenic machining due to the reduced tool-wear, built-up-edge formation and process temperature[12]. The weak effect of cooling on the HSC-machined parts can be explained by the insufficient cooling of CO_2 (−60 °C) as the process temperature during HSC can reach up to 950 °C[13]. To improve cooling rates, the use of alternative cooling mediums e. g. liquid-nitrogen (N_2) is required.

2. 2 Microstructures

The flanges produced by the linear flow splitting process exhibit a characteristic marked microstructural gradient with a UFG microstructure near the split surface. The grains are highly elongated in the plane parallel to the surface, thus having a pancake structure (Figs. 3,4). With increasing distance to the split surface, the grain size increases whereas the grain aspect ratio decreases. The average pancake-thickness is 270 nm



(a) Geometry A



(b) Geometry B

Fig. 2 Surface roughness of the machined surfaces after dry and cryogenic milling with tool geometries A and B

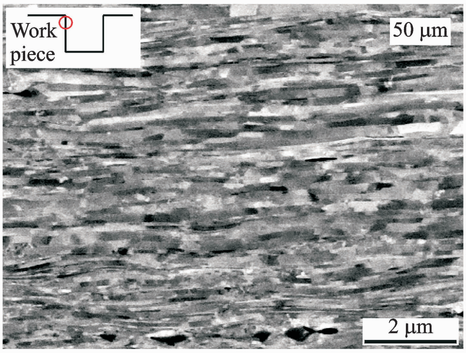


Fig. 3 Microstructure of flange in 50 μm beneath split surface

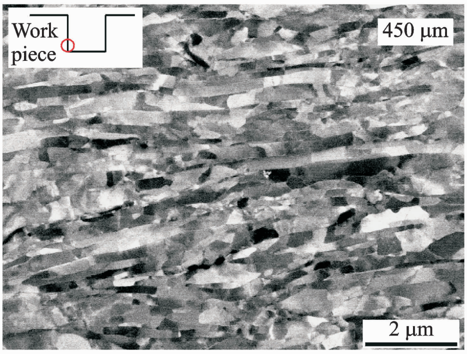


Fig. 4 Microstructure of flange in 450 μm beneath split surface

and 450 nm in 50 μm and 450 μm beneath the surface, respectively.

In the case of conventional cutting, there appears to be no significant influence of the milling process on the microstructure. The pancake thicknesses both in 50 μm and in 450 μm remain unchanged. The influence of the cutting process on the microstructure is more pronounced for the HSC samples. A uniform layer of mainly globular grains can be observed at the groove walls, which has not appeared on the utilized HSC parameters (Figs. 5—8). Within 2 to 3 μm of this thin layer, the average grain size is about 400 nm.

The samples milled with tool A (15° helix angle) exhibit further microstructure changes in the UFG region of the flanges under both dry and cryogenic conditions. Within roughly 2 to 8 μm from the groove wall, the pancake thickness is in-

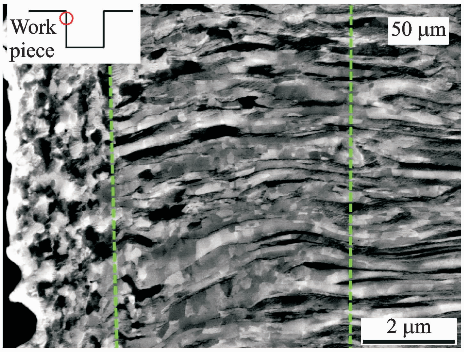


Fig. 5 Microstructure near groove wall in a depth of 50 μm beneath split surface of sample milled with tool A (15° helix angle) at cutting speed of v_c=750 m/min under cryogenic conditions

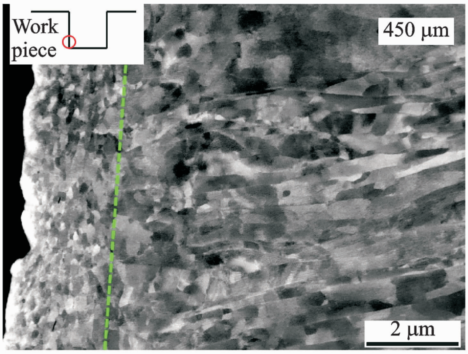


Fig. 6 Microstructure near groove wall in depth of 450 μm beneath split surface of sample milled with tool A (15° helix angle) at cutting speed of v_c=750 m/min under cryogenic conditions

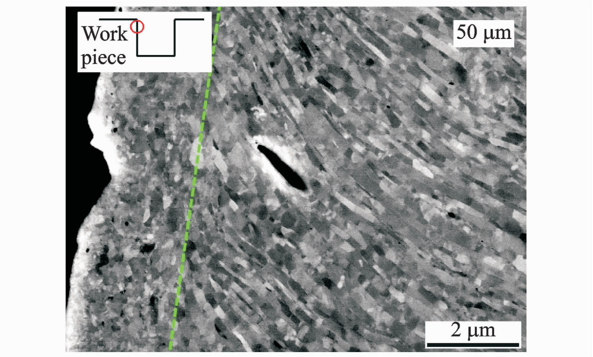


Fig. 7 Microstructure near groove wall in depth of 50 μm beneath split surface of sample milled with tool B (50° helix angle) at cutting speed of $v_c=$ 750 m/min under dry conditions

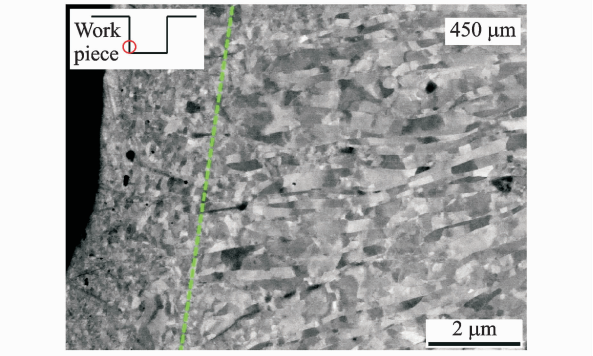


Fig. 8 Microstructure near groove wall in depth of 450 μm beneath split surface of sample milled with tool B (50° helix angle) at cutting speed of $v_c=$ 750 m/min under dry conditions

creased to an average of approximately 500 nm, which indicates the grain growth due to increased temperatures. With increasing distance to the groove wall, the grain size continuously decreases and reaches the level of the base material within 15 to 20 μm. In 450 μm beneath the split surface, the average grain size remains unchanged after the milling process, except for the thin layer of globular grains.

The samples machined with tool B (50° helix angle) show more far-ranging deformations near the top surface of the flanges. The grain orientations exhibit an up-drawing of near edge-material which leads to a more pronounced burr formation compared with tool A (Fig. 7). This deformation reduces with increasing depth beneath the split surface due to geometrical hindrance by the surrounding material (Fig. 8). Using CO_2 as a cryogenic cooling medium can reduce this up-drawing deformation both in magnitude and in range. In contrast to the samples milled with tool A, there appears to be no significant increase in pancake thickness in the microstructure adjacent to the fine grained globular layer.

2.3 Hardness

Since the microstructure investigations revealed a more pronounced influence of the milling process on the microstructure in the case of high-speed cutting, and the case for mechanical properties, i. e. , hardness can be assumed to be similar as well. Therefore, only the HSC samples were examined. The measured hardness distributions concur with the microstructure investigations. As the samples milled with tool A, a significant drop in hardness can be observed towards the milling edge under both dry and cryogenic milling conditions (Figs. 9, 10). In 50 μm beneath the surface of the UFG region, the hardness drops by 15% to a value of 380 HV compared with the level of 450 HV for the unaffected material. Cryogenic milling appears to decrease more far ranging hardness reductions, since the level of 450 HV cannot reach within a distance of 120 μm from the milling edge in case of dry machining, whereas the affected layer is only 20 μm for cryogenic conditions. The drop of hardness in 450 μm beneath the split surface is slightly lower than in the UFG region and the level of the base material is within 30 μm and 15 μm under dry and cryogenic milling conditions, respectively. This shows that the UFG region is more susceptible to increasing temperatures than the conventionally cold worked region.

The hardness measurements near the groove walls of the samples milled with tool B reveal a significant difference between dry and cryogenic millings (Figs. 11, 12). The hardness distributions of the sample milled under cryogenic conditions are very similar to those milled with tool A. The amount of hardness loss and the thickness of

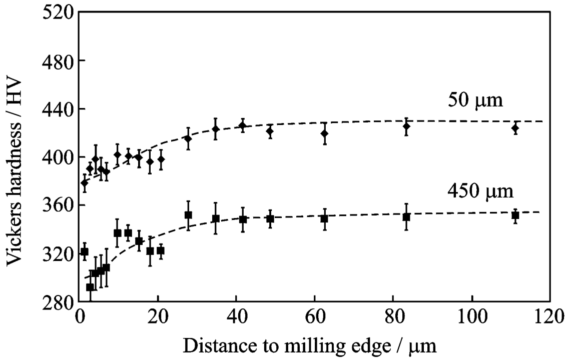


Fig. 9 Hardness distributions of the sample milled with tool A (15° helix angle) at cutting speed of $v_c = 750$ m/min under dry conditions, in depths of 50 μm and 450 μm beneath split surface

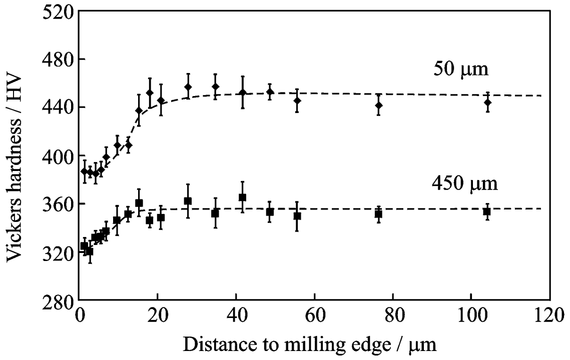


Fig. 10 Hardness distributions of the sample milled with tool A (15° helix angle) at cutting speed of $v_c = 750$ m/min under cryogenic conditions, in depths of 50 μm and 450 μm beneath split surface

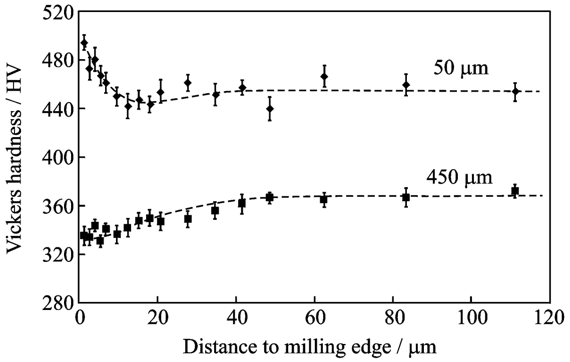


Fig. 11 Hardness distributions of sample milled with tool B (50° helix angle) at a cutting speed of $v_c = 750$ m/min and under dry conditions, in depths of 50 μm and 450 μm beneath split surface

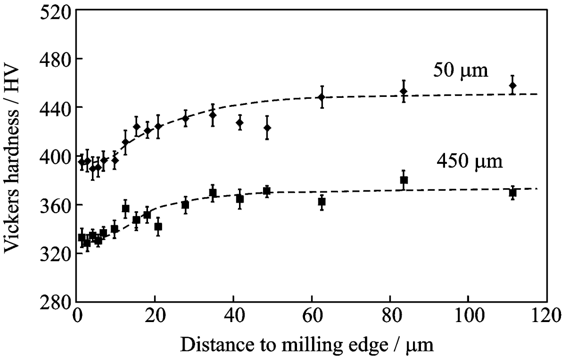


Fig. 12 Hardness distributions of sample milled with tool B (50° helix angle) at a cutting speed of $v_c = 750$ m/min and under cryogenic conditions, in depths of 50 μm and 450 μm beneath split surface

the affected layer agree very well. In contrast, milling under dry conditions with tool B appears to result in an increase in hardness at the milling edge in the UFG region. This might be attributed to adiabatic plastic deformation due to high strain rates within the plastically deformed near surface layers. To clarify this effect, further investigations are necessary.

3 Conclusions

Compared with conventional cutting, the HSC process has been found to generate surfaces with higher roughness values for a low feed rate per tooth of 0.05 mm whereas an increased feed rate per tooth of 0.1 mm causes lower roughness values of the HSC processed surfaces. Cryogenic cooling only had an improving effect on the roughness for conventional cutting at higher feed rate per tooth values. Moreover, an increased helix angle appears to generally deliver slightly better surface qualities with lower roughness values.

Hardness and microstructure investigations revealed a greater influence of HSC machining on the groove wall formation, compared with conventional cutting. Milling with a low helix angle of 15° results in a significant drop of 70 HV in hardness in the UFG regions. This drop in hardness is attributed to a thermo-mechanical process at the groove wall, which results in the formation of a uniform layer with a thickness of 2 to 3 μm and mainly globular grains with an average grain size of 400 nm. This layer can be observed for all process parameters and for both tool geometries. The thermal energy induced by the HSC process also causes recovery processes, especially in the UFG regions, which are more susceptible to increased temperatures. Recovery is visible in the form of grain growth for the samples machined with tool A, whereas for tool B only the hardness measurements revealed an influence of increased process temperatures. Cryogenic cooling has been found to reduce a more far-ranging decrease in hardness in UFG regions in the machining with tool A, but cannot prevent the significant drop in hardness within a near groove wall layer of 20 μm. In contrast to the reduction in hardness under most milling conditions, dry machining with a high helix angle of 50° leads to an increase in hardness at the groove wall. The increased hardness might be attributed to the plastic deformation in the near surface layers, but to identify the underlying mechanisms, further investigations are necessary.

Acknowledgments

This work is supported by the German Research Foundation (DFG). The authors thank the DFG for funding the subproject B3 and C5 of the Collaborative Research Center 666 "Integral sheet metal design with higher order bifurcations-Development, Production, Evaluation".

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(Executive Editor: Zhang Tong)