Effects of fluid condition and material on surface damage in ultrasonic wet peening

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Abstract
Cavitation in solid-water mixtures generated by ultrasonic waves can be used to modify the topography of metallic surfaces. During ultrasonic irradiation two kinds of processes occur in the liquid: (a) material removal by bubble formation plus collapse and the resulting micro jets; (b) material removal by colliding or sliding of accelerated particles due to bubble formation plus collapse. Both processes allow the removal of burrs after micro milling. However high impact forces by bubble collapse often cause erosion pits on the surface which are detrimental to further processing.
The aim of this research was to avoid the creation of erosion pits on metal surfaces which often lead to increased surface roughness. Therefore these investigations focus on reducing this effect by the variation of material properties of the workpiece and fluid conditions. Distilled water or a solution of sodium chloride both mixed with alumina grains of a mean diameter of 25 µm were used. Additionally in case of distilled water the gas content was varied to change the intensity of the bubble collapse. Two different workpiece materials, a tempered low-alloyed tool steel and a precipitation-hardened steel were investigated. Flat samples as well as micro milled grooves have been exposed to ultrasonic waves in the alumina grain-water mixtures within a time period of 20 minutes.
The results show that the resulting surface topographies strongly depend on the hardness of the workpiece material used. With increasing material hardness the influence of cavitation on the surface roughness decreases. Furthermore it is demonstrated, that a reduction of amount, size and depth of erosion pits can be achieved by optimizing the fluid conditions namely gas content and density while deburring without shape errors or edge rounding is enabled effectively.

Keywords Ultrasonic cavitation, Micro deburring, Fine particle peening, Micro moulds

Introduction
Micro Powder Injection Moulding offers the production of metallic and ceramic 3D-micro parts [1]. To produce micro parts of steady high quality the moulds have to fulfil high requirements for surface quality to guarantee a successful demoulding and a high wear resistance [2]. Micro milling is considered as a suitable production process of tool steel micro moulds [3], but due to milling striations and burrs, super finishing processes are eligible to optimize the surface quality. As conventional superfinishing e.g. grinding or polishing cannot easily be applied at the range of size of micro moulds, new methods are required, which allow non contact machining. Therefore micro peening and ultrasonic wet peening were developed [4], whereby the properties of micro milled moulds can be improved regarding the micro powder injection process [5]. Similar to conventional shot peening, by micro peening as well as by ultrasonic wet peening high compressive residual stresses are achieved, which improve the wear behaviour [6, 7]. The effect on residual stresses is comparable at both processes, but micro peening has the disadvantage that plastic deformation like edge rounding and an increase in surface roughness can occur. In contrast the acceleration of abrasive particles by ultrasonic wet peening occurs not in a determined angle but in different directions, so that the impact angles of abrasives are distributed from 0° to 90°. Thereby plastic deformations and edge rounding are minimised, whilst wear of topography peaks like burrs is effected by the impinging abrasive particles.

Ultrasonic wet peening is distinguished by the unproblematic appliance to different mould geometries and by low cost. It also offers the further optimising of the achieved mould qualities, since the properties of abrasives and the processed material as well as the liquids used for generating cavitation play an important role for the effects on the surfaces.

Experimental Methods

The characterisations were carried out on specimens of two different materials. The first material was the low alloyed steel Toolox 44 (SSAB Oxelösund, Sweden) with a hardness of 434 HV 0.1 after quenching and tempering at 590 °C. The second material is Corrax (Uddeholm, Sweden), which is a high alloyed steel and can be precipitation-hardened. After aging for two hours at 525 °C, a hardness of 555 HV 0.1 is achieved. The chemical composition of the materials is shown in Tab. 1.

Table 1: Chemical composition of the investigated materials Toolox 44 and Corrax.

	C	Cr	Mo	Si	Mn	Ni	P	Al	V	S	W
Toolox 44	0.31	1.34	0.81	0.60	0.89	0.69	0.01	0.03	0.015	<0.01	0.01
Corrax	0.05	12.10	1.27	0.34	0.42	8.67	0.02	1.81	0.08	0.03	0.16

For generating cavitation in the blasting fluid an ultrasonic processor type "Hielscher UIP-500" with a sonotrode of a diameter of 40 mm was used. The excitation frequency was 20 kHz and the maximum acoustic power 500 W. The samples were placed at a distance of 1 mm to the sonotrode in a tank containing the fluid. For the blasting fluid suspensions of 5 mass-% of blasting abrasive alumina (Al_2O_3) with a diameter from 20–30 µm and different liquids were prepared (Figure 1). To agitate the suspension during processing a magnetic stirrer was used. Additionally disruptions of 0.2 s where executed to pulses of 0.8 s duration to guarantee the exchange of fluid. A cooling coil was used for maintaining a constant fluid temperature of 25 °C.
Three different liquids were used for the process of ultrasonic wet peening. Distilled water, boiled distilled water and a saturated solution of sodium chloride in distilled water with a density of 1.18 g/ml were used for the different suspensions.

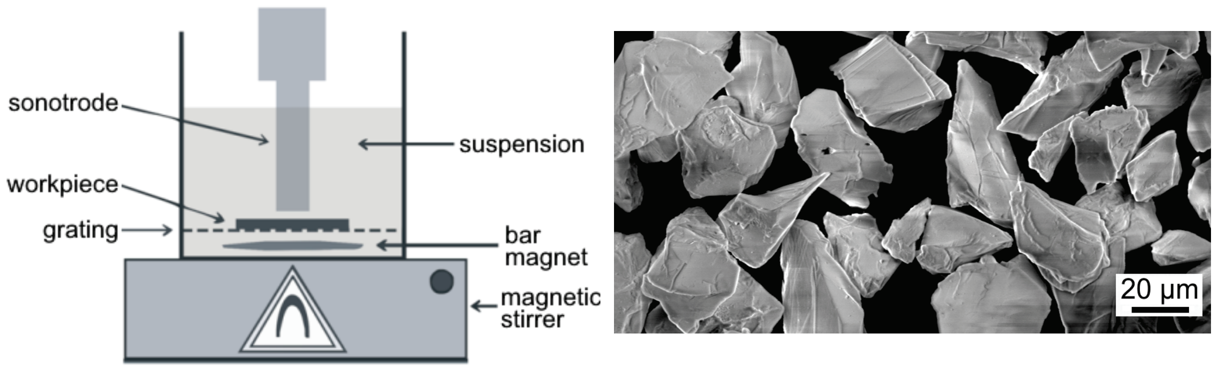

Figure 1: Ultrasonic wet peening: schematic view of the experimental setup (left) and blasting abrasive alumina (Al_2O_3, right).

The topography of the surfaces was measured by a confocal white light microscope "Nanofocus µSurf". To specify the surface roughness the average value R_a was computed after filtering and separating high- and low-frequency components with a cutoff wavelength of 250 µm. Cross-section profiles of the micro milled samples were made to evaluate the height of burrs.

Experimental Results

The development of surface quality was examined on polished workpieces of Toolox 44 and Corrax as well as on micro milled moulds of Toolox 44 to investigate the suitability of

ultrasonic wet peening process on the deburring of micro milled structures. The polished surfaces of Toolox 44 and Corrax had an initial average roughness R_a ~ 0.02 µm.
After ultrasonic wet peening of Toolox 44 damages of two distinguishable characteristics are found on the surfaces, which can be seen in Fig. 2. One kind of damage is impacts, which are distributed uniformly at the whole surface and the characteristic shape is polygonal. These impacts occurred after ultrasonic wet peening at both materials and in each fluid examined independent of processing time. The dimension of the damages is smaller than 2 µm and the depth is insignificant. A second kind of damages, namely pits, has a rounded shape and the depths range from about 0.1 µm up to more than 10 µm. These pits were found on samples made of Toolox 44 after processing in distilled and boiled water.

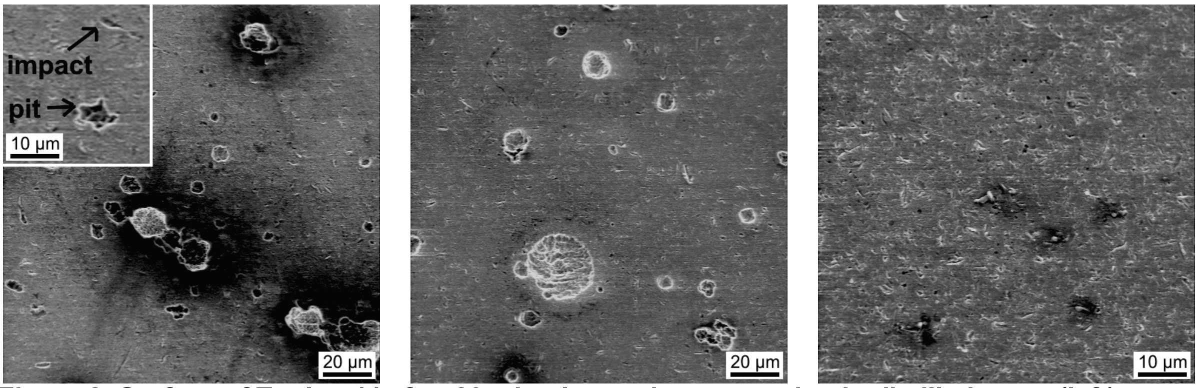

Figure 2: Surface of Toolox 44 after 20 min ultrasonic wet peening in distilled water (left), boiled distilled water (middle) and in sodium chloride solution (right).

To evaluate the development of the pits and their influence on the surface roughness, their number on an area of 0.6 mm^2 and their depth were determined. For the evaluation the depth was classified in logarithmic steps and frequency distributions of depth for the different classes were made (Fig. 3).

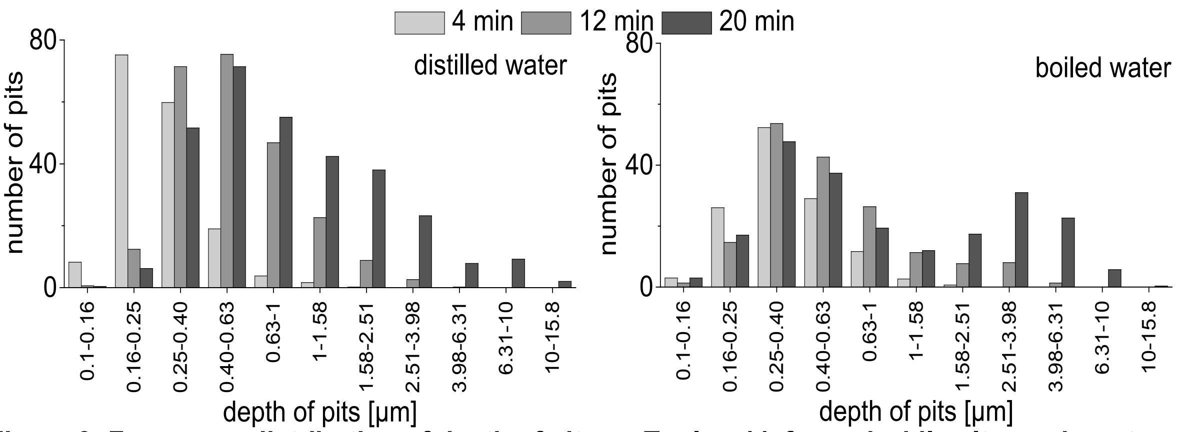

Figure 3: Frequency distribution of depth of pits on Toolox 44, formed while ultrasonic wet peening in distilled water (left) and boiled water (right).

For distilled water the number of pits increases with the duration of treatment from 168 after 4 min to 307 after 20 min. The distribution in Fig. 3 left shows, that the first pits occurring after 4 minutes have a most frequent depth from 0.16 – 0.25 µm. The maximum moves to increasing values of depth and also the depth itself is increasing. While at the beginning the depth are less than 1.6 µm, after the total time there are pits with a maximum depth of 12.9 µm found. Simultaneously the surface roughness increases from R_a ~ 0.02 µm to R_a ~ 0.16 µm (Fig. 4).
Similar results are found, if the surfaces were treated in boiled water (Fig. 3 right). In this case the number of pits also grows from 126 pits after 4 min to 213 pits after 20 min. In the

same way the maximum depth is increasing to 12.4 µm. The maximum of the first pits after 4 min occurs at a depth from 0.25 to 0.4 µm. At the same time the roughness increases from R_a ~ 0.02 µm to R_a ~ 0.11 µm (Fig. 4 left).

Using sodium chloride solution there are no pits found, the surface is affected by the polygonal formed impacts of low depth. The roughness is increasing to R_a ~ 0.04 µm, whereat a step after 12 min of 0.02 µm occurs. In this case there are sedimentations found on the surface, which could not be removed by ultrasonic cleaning. EDX-measurements showed that these particles contain sodium chloride, which was deposited at the surface from the fluid during ultrasonic wet peening.

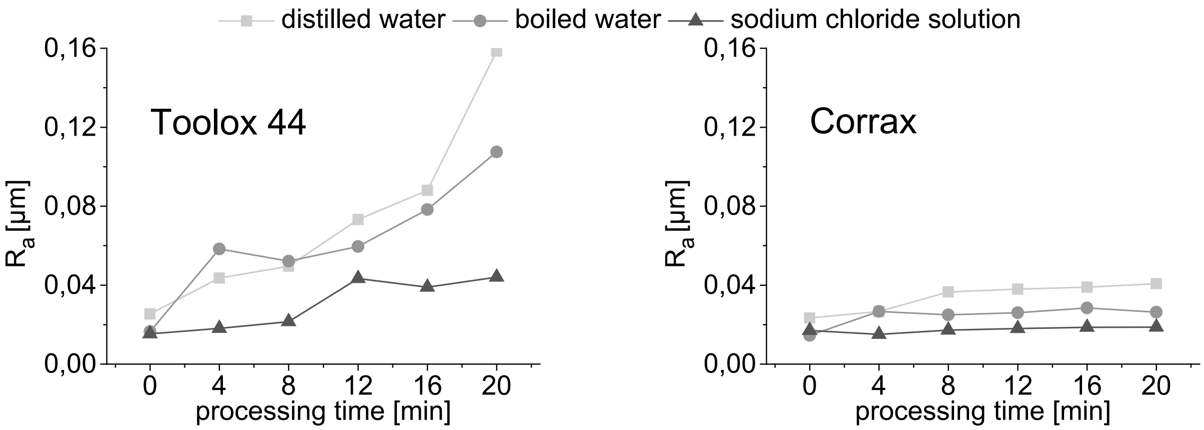

Figure 4: Development of surface roughness R_a of Toolox 44 (left) and Corrax (right) during processing time in different fluids.

The processed Corrax samples also show wedge-shaped impacts (Fig. 5). The rounded pits occurring at Toolox 44 in water are not found using the different fluids. The roughness is nearly constant, R_a is less than 0.04 µm in any case (Fig. 4 right).

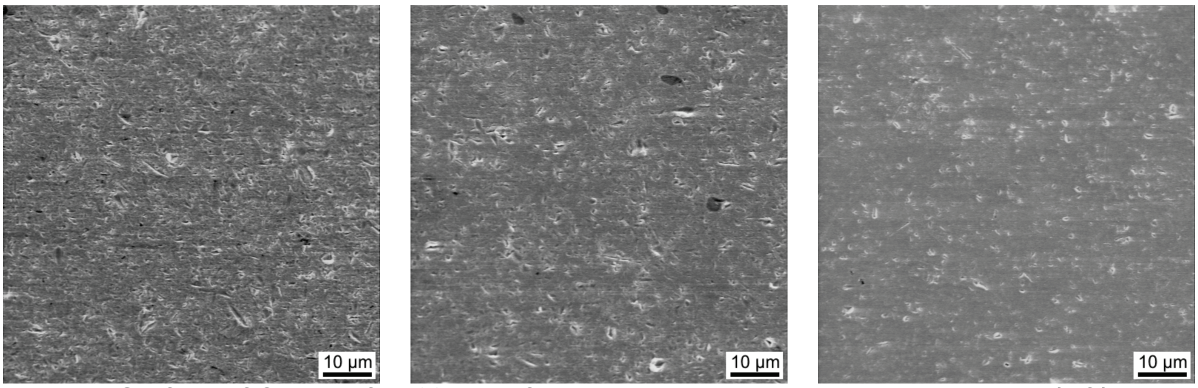

Figure 5: Surface of Corrax after 20 min of ultrasonic wet peening in distilled water (left), boiled distilled water (middle) and in sodium chloride solution (right).

Additionally the development of roughness and burrs of micro milled Toolox 44 moulds was observed during ultrasonic wet peening. The development of mould topography is shown in Fig.6. After micro milling (Fig. 6 a) burrs can be seen at the mould edges. At different locations at the ground of the machined mould an average low roughness of R_a ~ 0.02 µm was found, which fits the roughness of polished Toolox 44. The initial height of burrs of 10 µm is decreasing while processing to ~ 1 µm after 8 min (Fig. 7 left). In distilled water the fastest wear is observed. The SEM micrographs in Fig. 6 also show that within this time the burrs are removed. The change of the surfaces conforms to the polished surfaces: In distilled and boiled water pits occur (Fig. 6 b, c) and the roughness increases to R_a ~ 0.10 µm for distilled water respectively R_a ~ 0.09 µm for boiled water (Fig. 7 right). In sodium chloride solution there are no pits (Fig. 6 d) and the roughness after 20 min of processing is 0.07 µm.

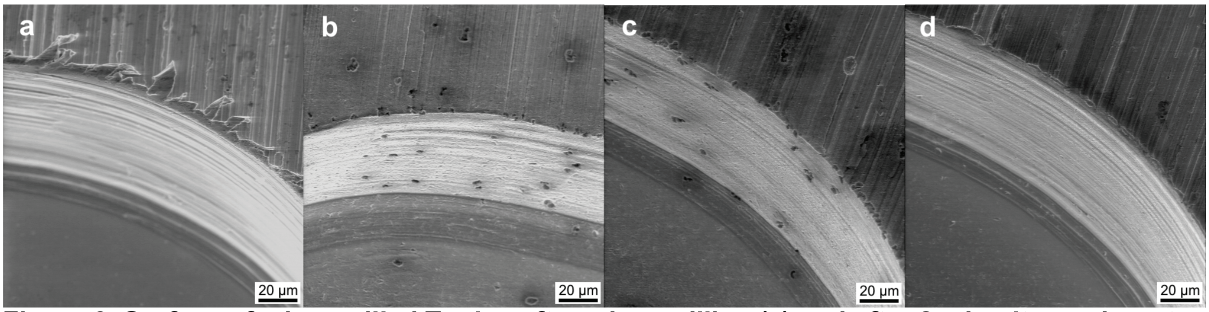

Figure 6: Surface of micro milled Toolox after micro milling (a) and after 8 min ultrasonic wet peening in distilled water (b), boiled distilled water (c) and in sodium chloride solution (d).

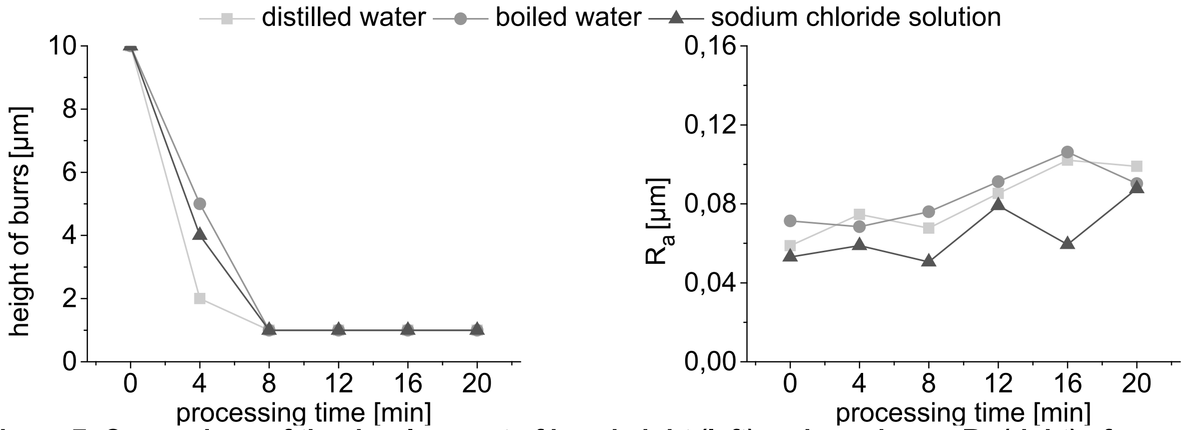

Figure 7: Comparison of the development of burr height (left) and roughness R_a (right) of micro milled Toolox 44 in different fluids.

Discussion

The damages of the different characteristics observed after ultrasonic wet peening are caused by different mechanisms that occur in the fluid while processing. The rounded pits are caused by the impact of cavitation bubbles near the surface and the resulting microjets leading to erosion of the surface. The second, wedge-shaped impacts result from abrasives colliding on the surface [7, 8]. Since bubbles form preferentially at the abrasive surfaces, the particles are accelerated by the collapse of cavitation bubbles and the resulting microjets.
Both processes account for the removal of burrs. Regarding the surface quality the pits due to direct bubble collapse are detrimental due to an increase of roughness. These pits only occur at Toolox 44 samples, the material with the smaller hardness. The frequency distributions of pits act similar in distilled and boiled distilled water. The appearance of pits of increasing depth during processing is caused by multiple cavitation erosion at the already eroded pits. This repeated erosion can be traced back to the topographical characteristics of the pits that act as nuclei to further occurrence of cavitation erosion. Additionally the number of pits increases with time as expected. The depth and the number of pits finally create the increase of roughness. Compared to distilled water, in boiled water less pits occur. This is due to the lower gas content, which results in less gas bubbles and thus less formation of cavitation bubbles. In contrast the maximum of single erosion pits, which are found after 4 min of processing is shifted to higher depths using boiled water. This effect is caused by higher microjet velocities due to the lower inside pressure of bubbles.
The lower gas content leads to less pits, but was not sufficient to avoid the occurrence of the erosion pits. Thus the effect of higher density of the liquid on the surface quality was examined. It is shown that by using saturated solution of sodium chloride in distilled water no pits are found and hence the roughness is constant and the surface quality is not degrading. The absence of erosion pits results from the higher density, whereby to slower bubble

collapses occur [9]. Therefore the sodium chloride solution is suited for processing of Toolox 44 by ultrasonic wet peening.
The examinations of Corrax show that all fluids are suited for processing because no pits occur in any fluid used and the surfaces are affected by the impacts caused by the alumina abrasives with constant surface roughness.
The development of micro milled moulds is proceeding similar to polished Toolox 44. It is found, that deburring of moulds is achieved in less than 8 min in all fluids examined, while sodium chloride solution produces the best results concerning surface quality due to absence of erosion pits. The disadvantage in this case is that with increasing processing time, sediments of sodium chloride remain on the surface, which are not easily removable.

Conclusion
The investigations show that the results of the achieved surface properties strongly depend on the material which is processed as well as on the choice of fluid used. Especially for surfaces of low hardness the fluid properties are a crucial factor for the received surface qualities. Due to unsuitable fluids detrimental cavitation erosion on the surfaces can occur. Reducing the gas content does not improve the surface roughness essentially. Contrarily a high density of fluid is capable to avoid detrimental effects on the surface and a constant surface quality is achieved. Choosing suitable materials and fluids, ultrasonic wet peening is capable as superfinishing process for deburring of micro milled moulds without degredation of surfaces. The removal of burrs is achieved by abrasives colliding to the surface. Further investigations will focus on replacing sodium chloride solution by other, not corrosive fluids of high density to further improvement of surface qualities without advancing corrosion or sedimentations on the surface.

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