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Grit Blasting for Removal of Recast Layer from EDM Process on Inconel 718 Shaft: An Evaluation of Surface Integrity

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The heat generated during EDM melts the work material and thereby allows large amounts to be removed, but an unfavorable surface of a recast layer (RCL) will also be created. This layer has entirely different properties compared to the bulk. Hence, it is of great interest to efficiently remove this layer and to verify that it has been removed. The main objective of this work has been to study the efficiency of grit blasting for removal of RCL on an EDM aero space shaft. Additionally, x-ray fluorescence (XRF) has been evaluated as a nondestructive measurement to determine RCL presence. The results show that the grit-blasting processing parameters have strong influence on the ability to remove RCL and at the same time introduce beneficial compressive stresses even after short exposure time. Longer exposure will remove the RCL from the surface but also increase the risk that a larger amount of the blasting medium will get stuck into the surface. This investigation shows that a short exposure time in combination with a short grit-blasting nozzle distance is the most preferable process setting. It was further found that handheld XRF equipment can be used as a nondestructive measurement in order to evaluate the amount of RCL present on an EDM surface. This was realized by analyzing the residual elements from the EDM wire.

Keywords aerospace, EDM, Inconel 718, residual stress, shot blasting, surface integrity, XRF

1. Introduction

In aerospace engine applications, structural parts often have large and complex geometries. Figure 1 presents an overview of an aircraft turbo fan engine. Many parts of the engine are made of heat-resistant nickel-based alloys such as Inconel 718. Machining of these alloys can be difficult and time-consuming due to their specific properties such as work hardening. The yellow circle indicates the type of component that this investigation is related to, namely a large shaft section in the fan structure.

A machining concept that sometimes can be very competitive for removal of large amounts of material quickly is electric discharge machining (EDM). This method utilizes the heat generated by the discharge from two electrodes, one of which is the part to be machined. The other electrode could either be a so-called die sink, which is a single tool that can generate holes and engravings, or a wire that can cut larger sections of the material.

The heat generated from the EDM wire (W-EDM) melts the material. Hence, the generated surface will contain an unfavorable recast layer (RCL). This recast layer can further be divided into three sub-layers according to Kumar (Ref 1), who defines a spattered surface layer, a recast layer (white layer) and a heat-affected zone. The recast layer is generated by the melting and fast quenching of the material which alters the metallurgical state and becomes hard and brittle. The underlying heat-affected layer has not been subjected to melting, only heating (Ref 1). However, there are large differences in RCL depending on which type of work material that is processed by EDM. For steel, this layer becomes hard and brittle which cause microcracking of the surface layer (Ref 2, 3) with a typical thickness of the RCL of 10-20 μm. According to the literature, the RCL of Inconel 718 does not show any microcracks but voids and hollow channels instead, which is believed to be due to the low carbon content of Inconel 718 (Ref 4). The thickness of the RCL for Inconel 718 is also thinner, typically less than 10 μm. Depending on process parameters, this layer could either appear as a discontinuous and non-uniform layer or a continuous thin layer (Ref 4).

There are several research papers investigating the surface integrity after EDM where the surface has been measured by means of microhardness, residual stresses, amount of microcracks and how the surface chemistry has been affected by the process. However, most of these papers concern conventional tool steels. Only a few concern surface integrity for more advanced materials, such as the nickel-based Inconel 718. Newton et al. (Ref 5) showed an investigation of how the main W-EDM process parameters affect the characteristics of the recast layer formation when processing Inconel 718. It was shown that the RCL was typically 5-9 μm thick and that surface roughness mainly was affected by the EDM energy per spark. It was further shown that both Cu and Zn from the wire migrated from the wire electrode to the work piece.

In the study by Li et al. (Ref 4), the surface integrity of the RCL was investigated where a W-EDM surface of Inconel 718 was evaluated in terms of surface roughness, microhardness and chemical composition by energy-dispersive spectroscopy

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(EDS) analysis. The results showed a strong influence on the surface structure and roughness depending on discharge energy. It was also shown that the RCL had a much lower microhardness compared to the bulk indicating a thermal degradation regardless of discharge energy.

In order for a W-EDM processed surface to be used in the application addressed in the present paper the RCL first needs to be removed by some sort of post-process. The method proposed and evaluated in this paper is grit blasting.

Even though grit blasting is a well-established method no prior published results have been found where the influence of this process upon a material like Inconel 718 has been explored. There are, however, published results regarding shot peening where the influence of shot media, exposure time and distance to work piece has been investigated (Ref 6). Also to be mentioned is a work by Cai et al. (Ref 7) where an XRD method was presented to determine the precipitation kinetics of γ'' on shot peened Inconel 718 samples.

The only published study that is somewhat related to removal of RCL was presented by Wang et al. (Ref 8) who evaluated a method to remove the RCL by means of etching in combination with a mechanical grinding. The etching was performed with phosphoric acid coupled with hydrochloric acid in order to soften the RCL and thus allow it to be removed by grinding the surface.

Grit blasting could be a more environmentally acceptable alternative to etching for post-processing an EDM processed surface. However, in order to qualify grit blasting as a post-process for EDM, the effects of the process parameters on the work piece with respect to surface integrity need to be fully understood, which has been the main objective with this investigation. A secondary objective was to investigate if chemical analysis of the surface can be used in order to qualify whether the surface is free from RCL or not.

2. Experimental Set Up

In this investigation, the surface integrity of EDM surfaces that were grit blasted, using different grit-blasting parameters, was evaluated (Fig. 2).

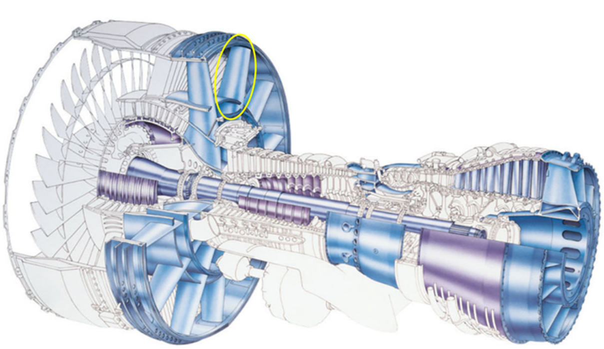

Fig. 1 Overview of an aircraft turbofan engine. Yellow circle indicates a typical component relevant for this investigation

The material of the shaft was Inconel 718 which has the chemical specification according to Table 1.

The grit blast operation was performed in a robot cell where the EDM machined shaft was mounted on a turntable and the blast nozzle held by a robot in order to achieve a fully repeatable setup. The robot motion during the blast operation was single axis only, parallel to the shaft, whereas the attack of the stream of blast media was perpendicular to the shaft during all of the tests (Fig. 3). The grit medium used for these tests was aluminum oxide with a grit size of 60 µm and a 4-bar pressure of the media.

The grit-blasting operation was performed with different process parameters in terms of number of passes (equivalent to exposure time) and nozzle distance (ND) which represents the distance between grit-blasting nozzle and the surface. Exposure time was varied between 2 and 40 s (exp) and the nozzle distance between 25 and 100 mm.

Areas in between the test positions, dark shaded in Fig. 2, were masked during the grit blasting and were used as reference surfaces representing the state after EDM processing.

The EDM method used on this sample was a wire EDM, wire brand name bedra megacut® plus. This wire was composed of CuZn36 material with a so-called gamma-messing coating and had diameter of 0.25 mm.

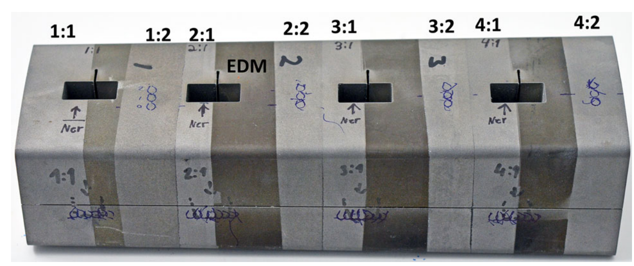

Fig. 2 Overview of the test sample, Inconel 718 shaft, showing the different grit-blasting positions

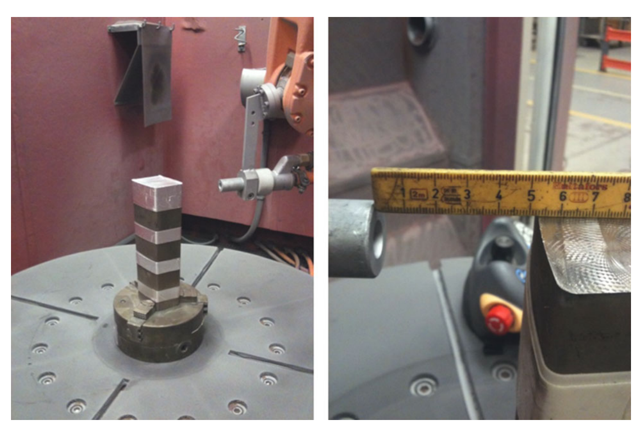

Fig. 3 Overview of the test setup. To the left the Inconel 718 shaft on the turn table just before the blast operation is to commence is shown. To the right the measured nozzle distance is shown

Table 1 Chemical specification of Inconel 718

Ni, %	Cr, %	Fe, %	Nb, %	Mo, %	Ti, %	Al, %	Co, %	C, %	Mn, %	Si, %	P and S, %	B, %	Cu, %
50-55	17-21	Bal.	4.75-5.5	2.8-3.3	0.65-1.15	0.2-0.8	< 1.0	< 0.08	< 0.35	< 0.35	< 0.015	< 0.006	< 0.3

3. Analysis and Evaluation

The different analyses have been performed either to evaluate how the grit blasting has affected the material or to find a way to evaluate the RCL by means of nondestructive testing. Surface integrity of the samples has been evaluated using scanning electron microscope (SEM), energy-dispersive spectroscopy (EDS), residual stress measurement with x-ray diffraction, chemical analysis of the surface with x-ray fluorescence (XRF) and evaluation of the RCL with optical microscopy.

The grit-blasting erosion depth was measured using the optical measurement and analysis equipment MikroCad from GFM. This equipment utilizes phase fringe projection consisting of parallel stripes which are projected onto the object surface, and their perspective deformation is recorded by a camera.

The grit-blasting erosion depth was measured over the different steps between EDM surface and the different blasting positions 1:1-4:2. Measurements were performed at a spot of 19 × 19 mm for each position. The results were filtered and adjusted by form removal and performing a least square fit on the measured data. Finally, from the 1236 profiles across the step, an averaged profile was calculated and the step height was measured as the height between the levelled areas. The measurement height accuracy for this method is typically ±1 µm. The different analysis steps for this evaluation are presented in Fig. 4-6.

Residual stress measurements were preformed with x-ray diffraction which is a well-established method to measure residual stresses at the surfaces as well as below the surface. The measurements were performed with a Stresstech G2R XStress 3000 diffractometer equipped with a Mn x-ray tube (λ:0.21031 nm). The modified $\sin^2\psi$ method was used with 5 psi angles (45°⋯−45°) measuring the 151.88° diffraction peak. The residual stress was calculated assuming elastic strain theory according to Hook's law using 196.6 MPa as Young's modulus and 0.29 in Poisson's ratio. Measurements of residual stress profiles were performed with layer removal where successive material removal is performed by electro polishing. The electro polishing was done with Struers Movipol and electrolyte A2.

A Jeol 6610LV SEM equipped with a Brucker XFlash 5010 EDS detector was used for chemical analysis of the surfaces. An EDS detector measures the electron interaction with the sample and generates energy spectrums that can be translated into chemical information. EDS is mainly used as a qualitative measurement to identify the chemical elements that are present on the sample surface. The chemical analysis of the surfaces was performed by EDS mapping which generates colored images of the distribution of the different chemical elements present on the surface.

The chemical content on the surface has also been measured with a handheld Thermo Scientific Niton XL3t GOLDD + x-ray florescence (XRF) equipment. This equipment utilizes the characteristic secondary x-rays that emit from a sample surface which is exposed with high-energy x-rays in order to determine the chemical content. This specific version of the equipment has an expanded range for detecting elements which includes Mg, Al, Si, P and S. The results from the chemical analysis with XRF are average values from three measurements at

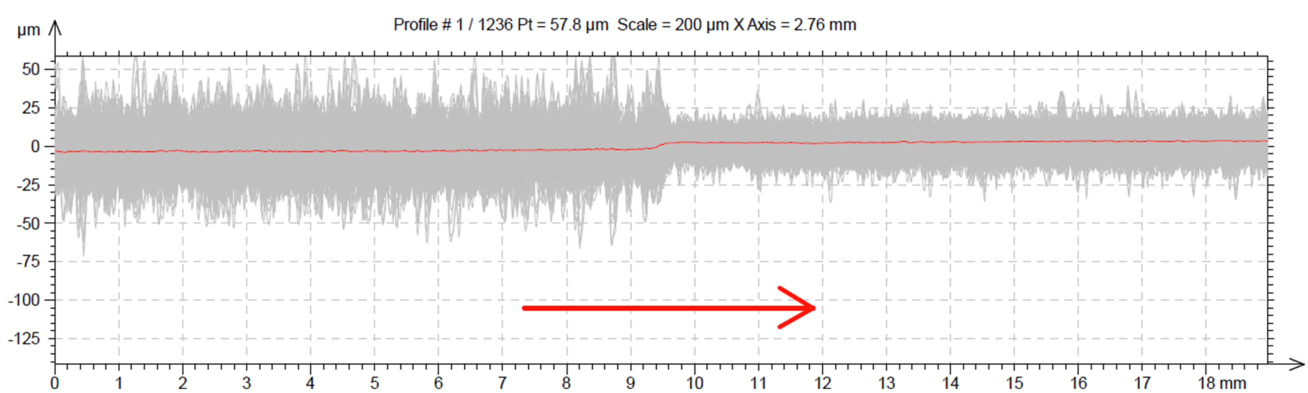

Fig. 4 Raw data from the erosion depth analysis

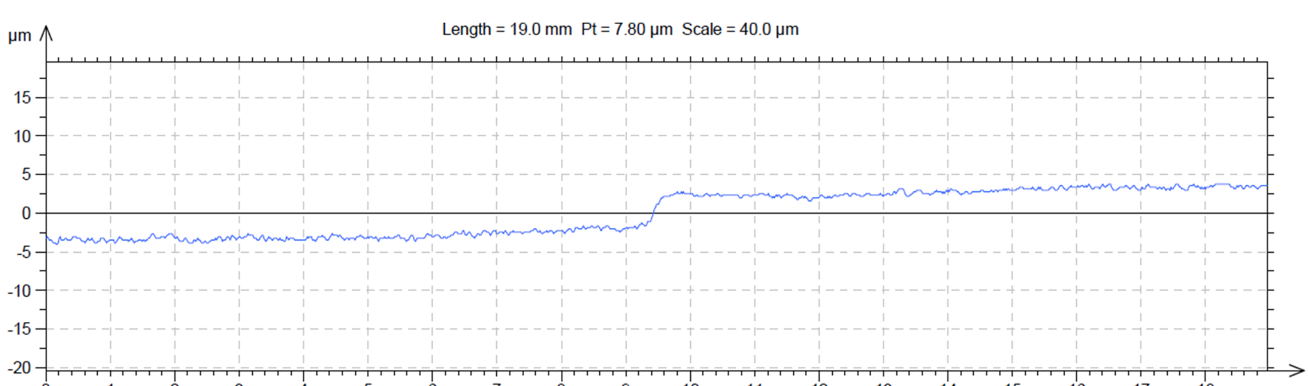

Fig. 5 Filtered and adjusted data

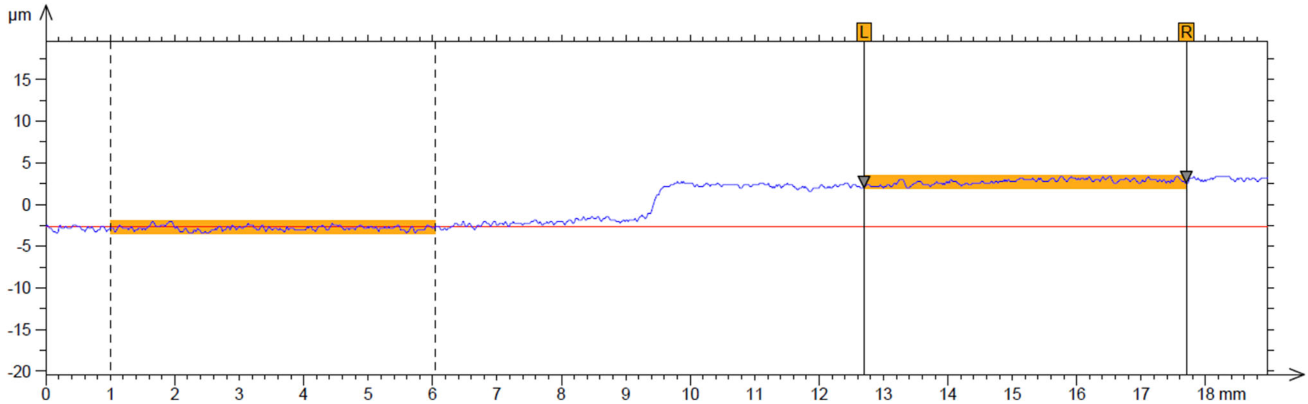

Fig. 6 Erosion depth calculated by use of two collimation lines

Table 2 Results from erosion depth measurements

	Shot-blasting parameters				
Surface marking	**No. of pass**	**Nozzle distance, mm**	**Blasting exposure time, s**	**Material removal (Max), µm**	**Material removal (Mean), µm**
1:2	×1 pass	100	2	1.0	0.1
2:2		100	4	3.6	2.7
3:2		100	8	7.6	6.9
2:1	×5 pass	100	10	6.2	5.6
3:1		100	20	8.4	7.9
4:1		100	40	18.6	17.4
4:2	×5 pass	25	40	12.8	12.2
1:1	×5 pass	50	40	13.8	13.2

different locations for each of the individual grit-blasting positions.

The microstructure was evaluated on polished and etched samples. The etching was performed with Kalling's solution in 30-60 s.

4. Experimental Results

4.1 Erosion Depth and Surface Topography

The results from the surface profile measurements show that the erosion from the grit blasting increases with increasing exposure time. It was also observed that blasting with longest nozzle distance and longest exposure time has resulted in the largest amount of erosion. Further, a masking effect could be seen close to the step which has resulted in a pit. Hence, the evaluation of step height was performed at a position 3-4 mm from the actual step. The results from the erosion depth measurements are summarized in Table 2.

4.2 Residual Stresses

The surface residual stress measurements were performed at different grit-blasting positions on the front side of the shaft according to Fig. 2. The results show that the blasting operation has a strong influence on the residual stresses according to Fig. 7. The stress state is predominantly compressive to a magnitude of (−)500-(−)800 MPa which is a great difference from the tensile stresses of approximately 200 MPa which was measured for the reference EDM surfaces.

In Fig. 8, residual stress profiles for the grit-blasted surfaces with the same nozzle distance of 100 mm are presented. The residual stress profile measurements were performed with layer removal on the top side of the shaft according to Fig. 2. These results show that all profiles have the typical behavior from a grit-blasting process with high compressive stresses in the surface and a maximal compressive stress located 5-20 µm below the surface. The surface stresses, the maximal compressive stress and the penetration depth increase with increasing exposure time for most of the samples except for the 40 exp sample which does not follow this trend. Even the short 2 s grit-blasting exposure has resulted in a rather deep residual stress profile. A further increase in exposure time, comparing the 2 and 4 exp samples, shows further increase of 200 MPa of the compressive stresses to a depth of 100 µm. The residual stress profiles for grit blasting more than 4 s are quite similar even though 10- and 20-s exposures seem to have a somewhat higher compressive stresses close to the surface compared to the other positions. The profile for 20-s exposure has the deepest impact according to Fig. 8. The reference EDM surface shows high tensile stresses deep inside the surface.

The residual stress profiles from blasting position 4:2, 1:1 and 4:1 show the influence of the nozzle distance and is presented in Fig. 9. These results indicate that the shortest ND, 25 mm, generates the highest compressive stress both in terms of magnitude of the stresses and affected depth below the surface. Even at depths below 300 µm, this profile shows a compressive stress of −400 MPa. The profiles for ND 50 and

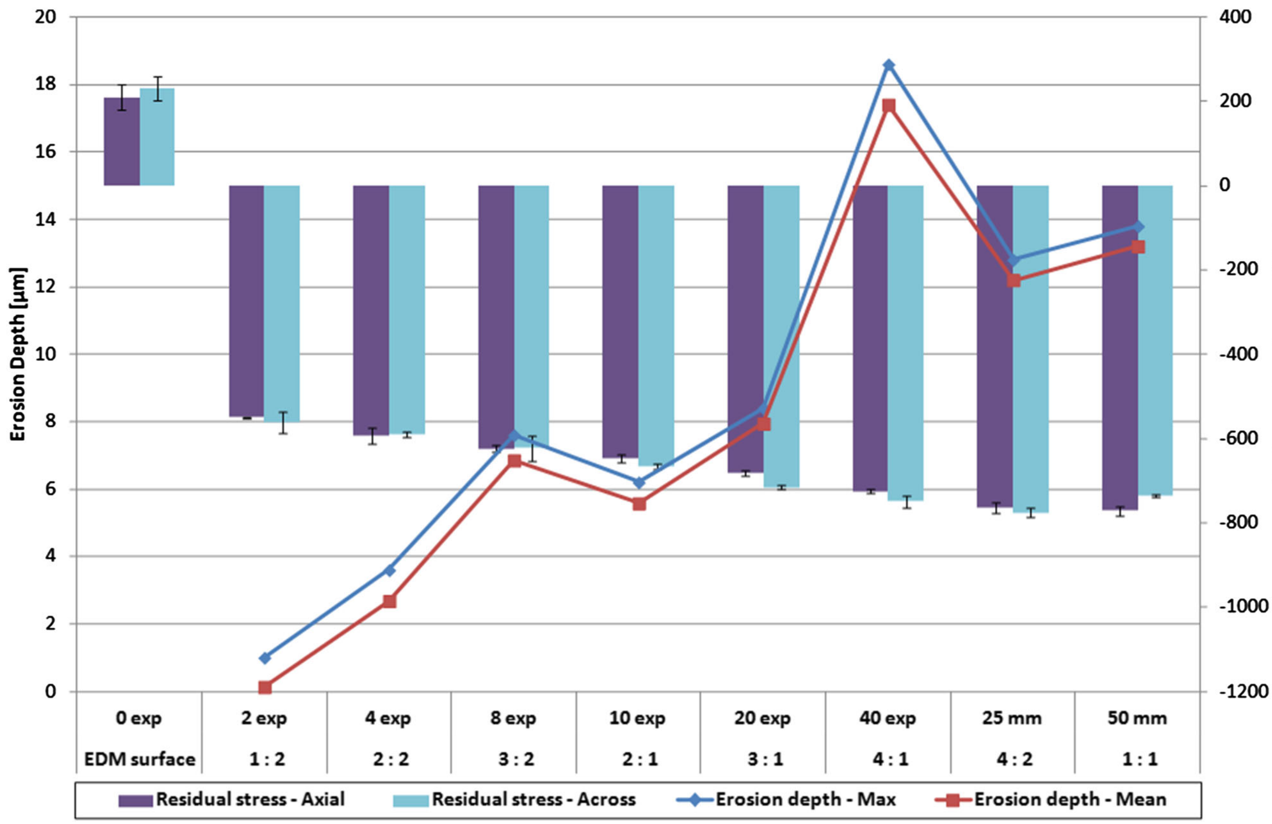

Fig. 7 Results of the erosion depth and surface residual stress measurements at the different blasting positions compared to the erosion measurement data. The error bars represent the standard deviations for the two residual stress measurements

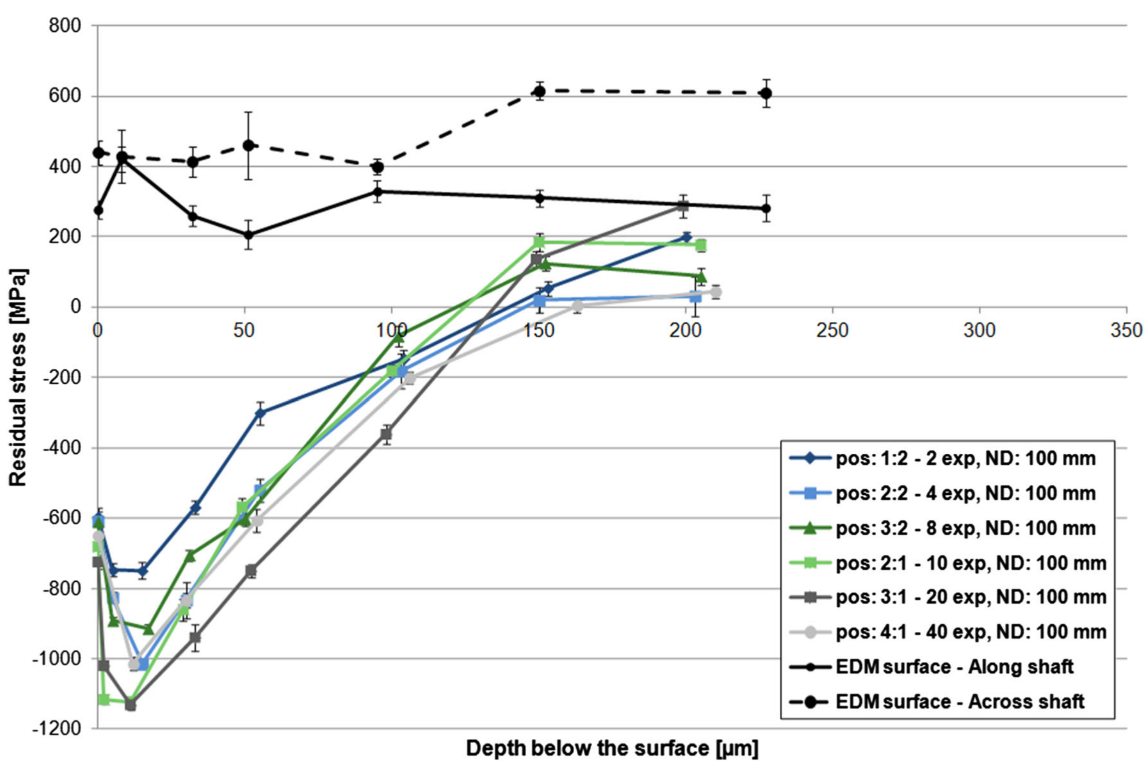

Fig. 8 Results of the residual stress profile measurements at position 1:2, 2:2, 3:2 which differs in terms of exposure time in direction across the sample. The error bars represent the deviations of the diffraction peak curve fitting

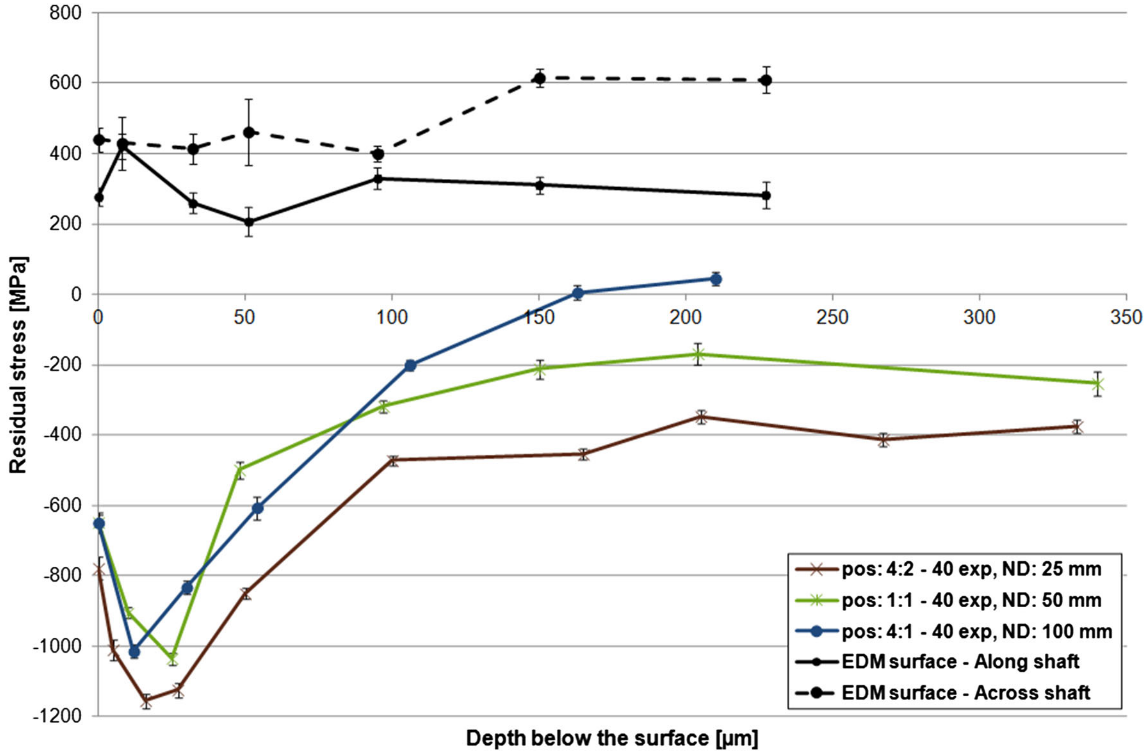

Fig. 9 Results of the residual stress profile measurements at position 4:2, 1:1 and 4:1 which differ in terms of nozzle distance (ND) in direction across the sample. The error bars represent the deviations of the diffraction peak curve fitting

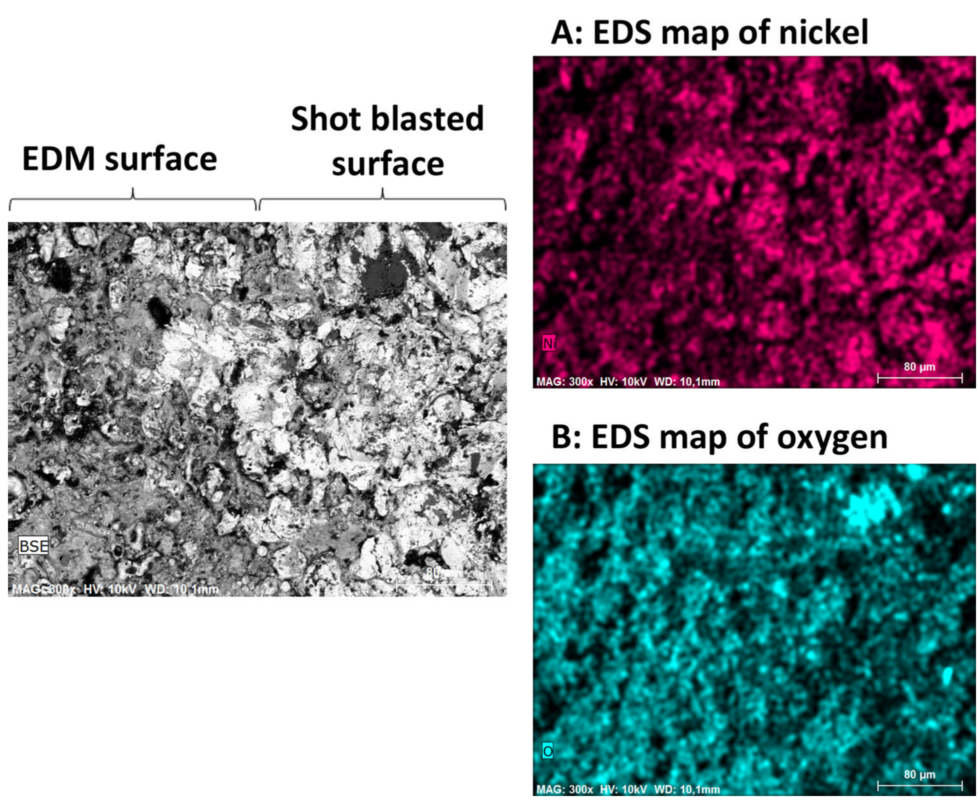

Fig. 10 EDS mapped surface in 300× magnification at the blasted step between masked and grit blast surface for sample 1:1 where (a) EDS map of nickel in purple color and (b) oxygen content in the green-colored surface

100 mm are quite similar to a depth of 100 μm. Below this depth ND 100 mm approaches a tensile stress, while the residual stress profile for ND 50 mm instead approaches a compressive stress of −200 MPa even at depths below 300 μm.

4.3 Surface Chemistry: EDS Mapping

The surfaces of the different blasting positions were further inspected by means of SEM and EDS mapping of the chemical content of the surface. These results imply that the EDM surface has a higher amount of oxygen and a lower amount of nickel, while the blasted surfaces show less surface oxides which could be seen in Fig. 10, whereas the more intense colored areas contain higher amounts of the elements oxygen and nickel.

In Fig. 11, the Zn content is illustrated in green color showing that the EDM surfaces have a much higher Zn content compared to the grit-blasted surfaces. It could further be seen that the Zn content decreases with increasing grit-blasting exposure time. Both zinc and copper are possible residue elements from the EDM wire that can indicate presence of RCL. These pictures also show that the grit-blasted positions with longer exposure times (3:2 and 4:2) have a lower amount of Zn. It could further be observed that both sample 3:2 and 4:2 are similar, indicating that longer exposure times than 8 exp have less influence on the presence of Zn.

Similar EDS maps were derived for copper, but comparing those images no clear difference could be observed.

4.4 Surface Chemistry: XRF Surface Analysis

The XRF results show that both Zn and Cu content decreases with increasing blasting exposure time and increased erosion depth according to Fig. 12. It can further be seen that the variation in the measurements of the EDM surface is large compared to the grit-blasted positions. Independently of the nozzle distance, long exposure times result in low contents of Zn and Cu. Figure 13 shows how the measurements of Ni and Cr differ for the different positions. The error bars represent the standard deviation for the three measurements that were performed on different locations on the grit-blasted surface for each individual sample position. However, for the elements Ni and Cr, the error bars are rather large for all sample positions which shows that the nickel and chromium content varies quite much in the analyzed surfaces. Therefore, it might be difficult to use the Ni and Cr content as an indicator of RCL removal. The nozzle distance shows some influence indicating a somewhat lower Ni content for the shorter ND.

4.5 Evaluation of the RCL by Microscopy

Evaluation of the recast layer was done on polished and etched cross sections of the shaft at positions at the steps between blasted and masked surface. The evaluation was done

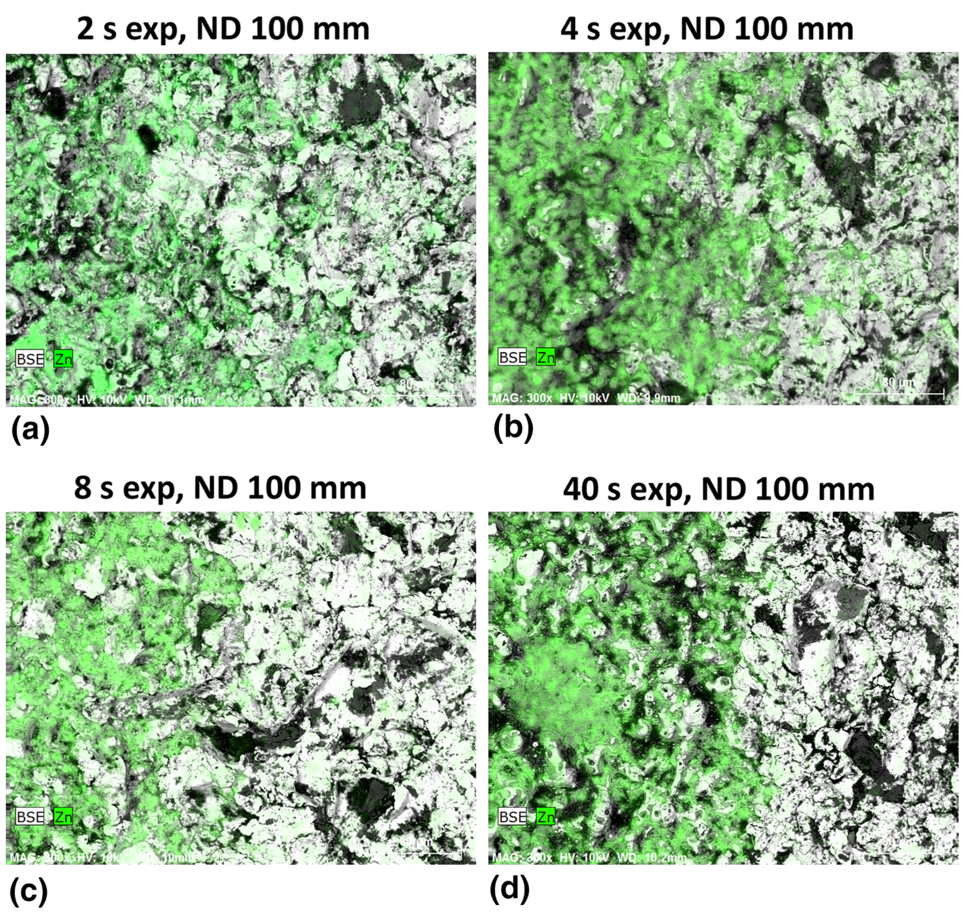

Fig. 11 EDS maps in 300x magnification of Zn content visualized in green at the blasting step between a masked and grit-blasted surfaces. (a) sample 1:2 with 2exp/ND 100 mm, (b) sample 2:2 with 4 exp/ND 100 mm, (c) sample 3:2 with 8 exp/ND 100 mm and (d) sample 4:2 with 40 exp/ND 25 mm

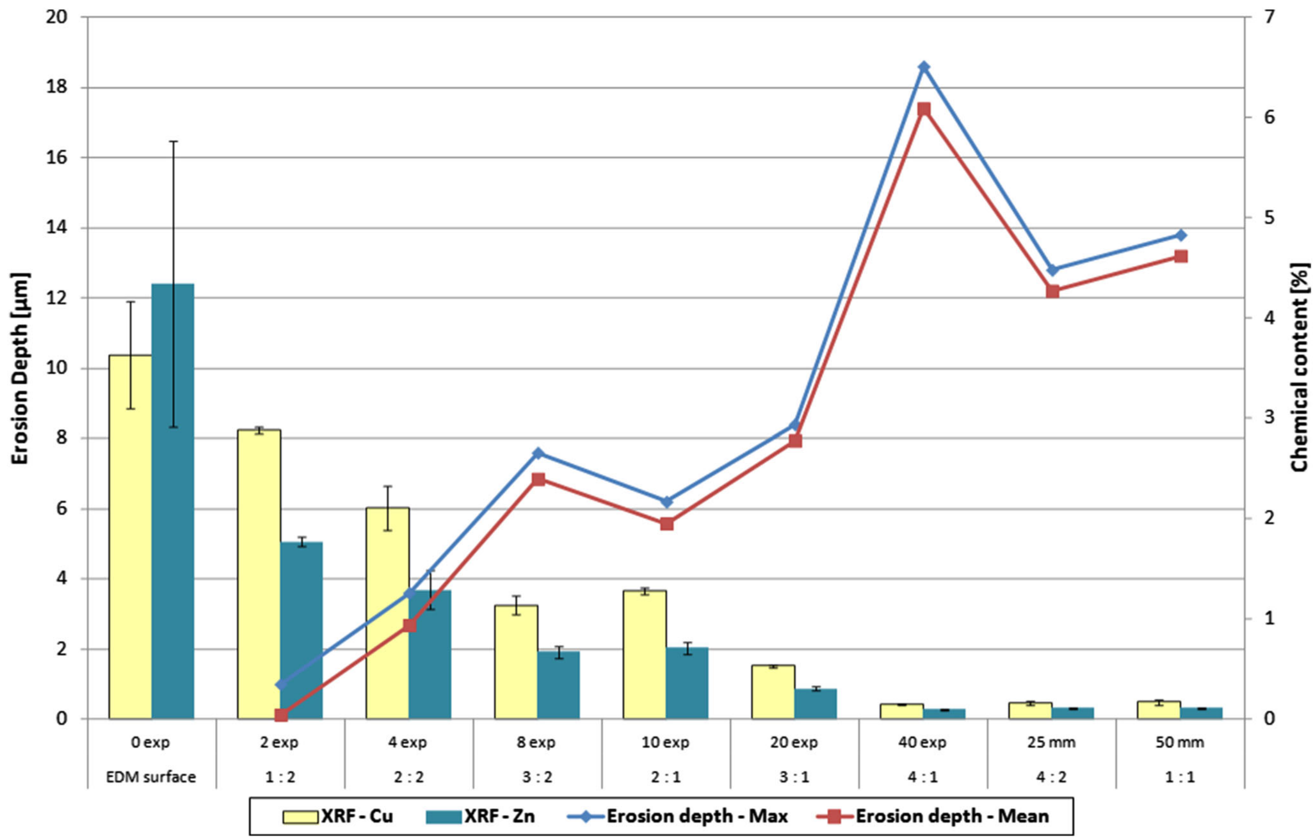

Fig. 12 Results of erosion depth and XRF chemical data measurements of Zn and Cu for the different blasting positions. The error bars represent the standard deviations for the three XRF measurements

at four positions for each individual blasting position, and representative micrographs in x1250 magnification are presented in Fig. 14. Recast layer could be detected on all EDM surfaces, but the amount differs a lot for the different locations. The RCL on the EDM surfaces is not continuous but instead appear as islands of RCL that typically only has an extension of less than 5 µm. The lower right images illustrate the appearance of the RCL which show a flake-like material that appears brighter in respect to the underlying bulk material.

RCL could only be observed for blasting position 1:2 and 3:2 where the later has only a minor amount embedded into the surface as a consequence of the grit blasting, see Fig. 14. All other samples show no traces of the RCL but differ instead regarding different amount of deformation of the outer surface. Some of the samples show relatively deep pits of erosion from the grit blasting.

5. Discussion

Although EDM is an efficient method for processing difficult materials to complex geometries the mechanical properties of the processed surfaces are often disadvantageous compared to other existing processing methods. Results presented by Navas where EDM was compared to grinding and hard turning of an AISI O1 tool steel showed that EDM was the most detrimental process (Ref 9). It has further been implied in several papers that the EDM of Inconel 718 generates a surface RCL that appears white when etching which is of different microstructure than the core (Ref 4, 5). This white layer is highly unwanted for functional and operating surfaces since the material properties might differ substantially compared to the bulk material. However, there has only been very limited work previously done regarding removal of this RCL with a method such as grit blasting even though the general opinion is that this is a well-established technique. In this study, the intension is to fill this gap of knowledge.

This study shows that grit blasting might be an efficient method for removal of the RCL and as an added value the surface will be plastically deformed into a compressive residual stress state. This compressive stress state is beneficial since it increases the fatigue strength of the material (Ref 10, 11).

The results reported in this paper show that the grit-blasting process has a strong influence on the surface characteristics for all of the investigated sample surfaces, even after a very short grit-blasting exposure time. The investigated surface topography, degree of deformation in microstructure and residual stress state have significantly been affected by the grit-blasting process. The results show that a long exposure time will remove the RCL from the surface, but this will also increase the risk that a larger amount of the blasting medium will get stuck into the blasted surface.

The typical residual stress profile from the related post-process shot peening is a rather high compressive surface stress state that increases somewhat more a few micrometers below the surface. This is an effect of the Hertz's compression which, due to the impact, has a maximal plastic deformation that occurs below the surface (Ref 12). Typically, such results have been reported for different types of steel in the literature (Ref

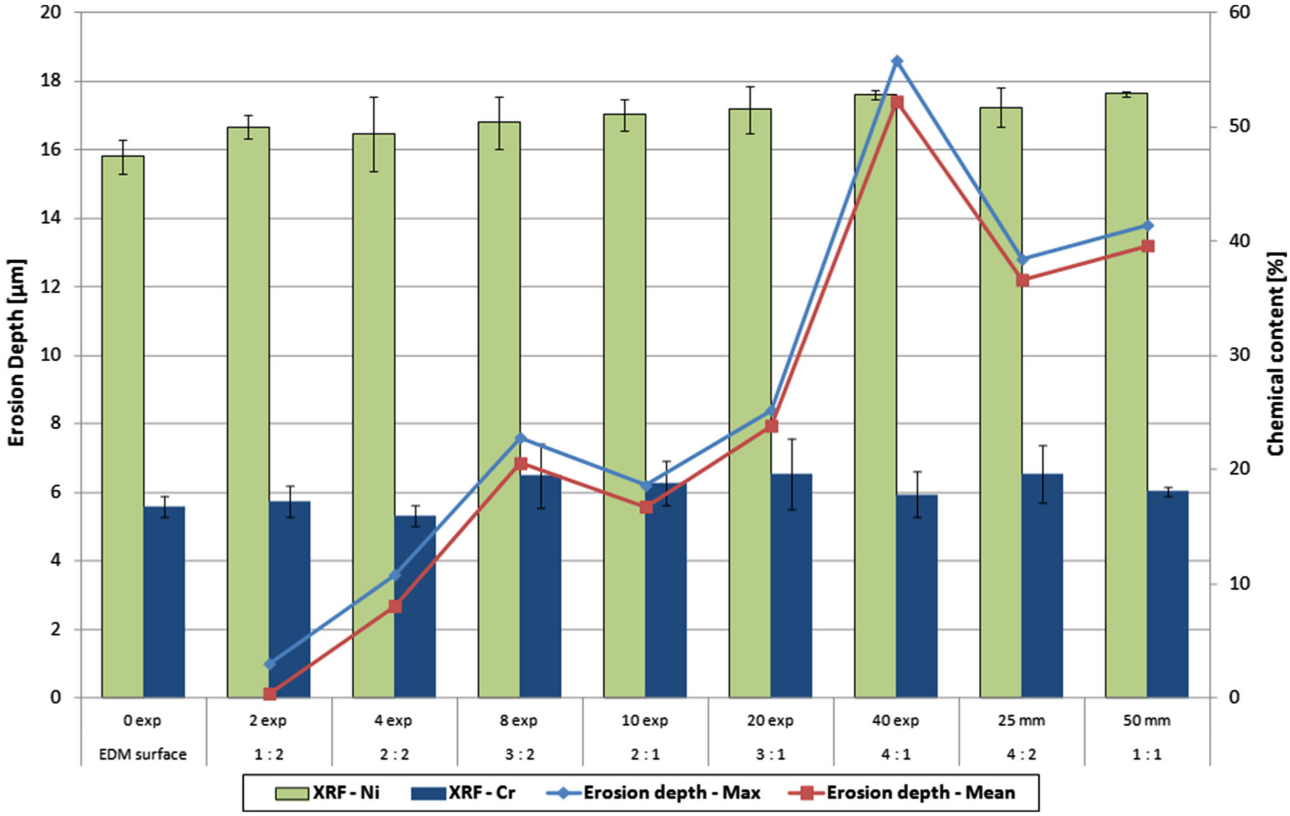

Fig. 13 Results of erosion depth and XRF chemical data measurements for Ni for the different blasting positions. The error bars represent the standard deviations for the three XRF measurements

11-14). In contrast, the residual stress measurements for the investigated grit-blasted Inconel shaft show an expected profile, but these profiles have a much higher maximal stress magnitude and a much lower penetration depth compared to other results, such as the results reported by Cai et al. (Ref 7) where the same super alloy was studied.

From these results, it could further be concluded that the exposure time has less influence and for longer exposure times than 4 s only minor increase in the compressive stresses could be observed. Though, for the shortest exposure time, 2 s, a relatively high compressive stress has been generated in the surface. There is, however, an irregular trend to be observed where 10- and 20-s exposures show a much higher compressive residual stress just below the surface compared to 40-s exposure. The reason for this need to be further investigated with a more thorough analysis of the microstructure.

The residual stress measurements further show that the nozzle distance has a somewhat stronger influence on both de maximal compressive stress and the penetration depth. For both the sample with short nozzle distance of 25 mm and the sample grit blasted with 50 mm ND, the residual stress state in the sample approaches a compressive residual stress compared to the profile for the reference EDM position which instead approaches a tensile stress deeper inside the sample. The relative high tensile stress state measured for the EDM position is surprisingly high, and it is believed to be a result of the cooling during the casting of the shaft rather than an effect of the EDM process which is only affecting the outermost surface.

The examination of the microstructure revealed that the degree of deformation also increased with decreased nozzle distance. This might also be an argument to use a shorter nozzle distance in order to retain maximal compressive stress in the surface. These analyses show how important it is to evaluate the surface characteristics when optimizing a RCL removal process. Both the residual stress state and the degree of deformation will have great influence on mechanical properties of the final surface. On the one hand, a high and rather deep compressive residual stress is preferable from a fatigue resistance perspective, but on the other hand a short nozzle distance will increase the deformation and risk of embedding unwanted grit-blasting medium particles in the surface. The investigation of the microstructure concludes that a rather short exposure time, 4 s, generates a surface that appears to be free from RCL in light optical microscopy.

Additionally, it was found that one possible way of evaluating presence of RCL could be by performing chemical surface analysis using EDS. The analysis showed that there exist traces of the EDM wire electrode by means of zinc and copper in the EDM surface, which also was reported by Williams and Rajurkar (Ref 15). EDS mapping of the interface between the EDM surface and grit-blasted surface illustrates very well that the amount of primarily Zn differs, but difference in O and Al could also be detected. The difference was especially significant when comparing the EDM surface with the sample that was grit blasted with longer exposure times. Further, unwanted grit-blasting particles were detected in the surface. This could be seen as the darker areas in the images in Fig. 11. These images show that all blasted surfaces contain some amount of the Al particles that got stuck into the surface during the blasting operation, but increased exposure time will probably increase the amount of particles that get stuck in the surface. EDS analysis in SEM showed that it was possible to

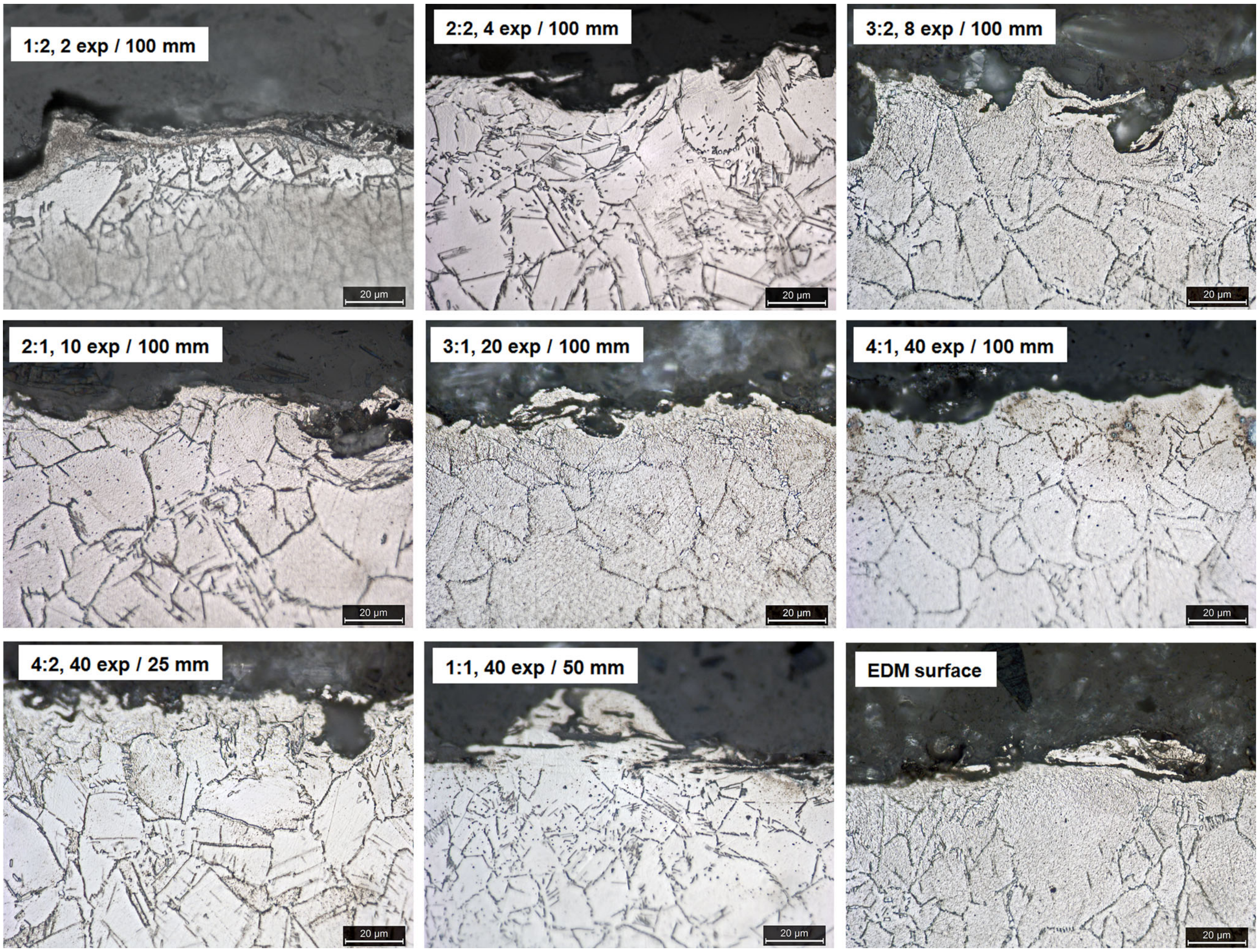

Fig. 14 Illustrative micrographs at 1250x magnification showing the microstructure of the grit-blasted surface for different grit-blasting parameters

detect a difference, but this type of analysis is time-consuming and not suitable if large surfaces are to be evaluated.

A nondestructive alternative to EDS was evaluated by means of hand held XRF equipment which has the advantage of measuring directly on the surface and without necessitating a vacuum environment. This equipment was selected to evaluate the surface chemistry since it is fast, nondestructive and is a mobile equipment that could be used for in-line process control. However, XRF does have some detection limitations regarding lighter elements due to both instrumentation and the low x-ray yields from lighter elements. Therefore, it is often difficult to quantify lighter elements than sodium. Even though the material Inconel 718 contains several alloying elements according to Table 1 it is only carbon and boron that cannot be quantified by the XRF measurement. All other elements can be quantified with good accuracy. Both carbon and boron represent very low amounts in the chemical composition of Inconel 718. Hence, the error of not detecting these elements will only have a marginal impact on the final quantitative results.

The selected strategy regarding how to evaluate the RCL with the XRF equipment is to analyze the surface regarding the copper and zinc content. The results showed that it is possible to detect and quantify the presence of residue from the EDM wire, even though the amounts are fairly low. The Cu and Zn content in the EDM surface is approximately 3.6 ± 0.5 and $4.3 \pm 1.4\%$, respectively. While for a grit-blasted surface, these amounts drop to $2.9 \pm 0.03\%$ Cu and $1.8 \pm 0.05\%$ Zn after only 2 s exposure time. These amounts decrease even further with increased exposure time, and the longest exposure times show the lowest amount of these residues, indicating that the RCL is almost completely removed. In addition, the results show that the variation of the measured amounts also decreases, respectively. This indicates that XRF can be a suitable method to be used since it is fast and seems to be a reliable measurement in order to determine whether the surface is free from RCL or not.

6. Conclusions

- The results show that grit blasting is a possible method to be used in order to remove RCL after EDM processing. The grit-blasting parameters blasting time and nozzle distance have great influence on the resulting surface integrity generating a RCL-free surface with high compressive residual stresses after exposure times greater than 4 s.
- Grit-blasting time only has a minor influence on the residual stress profile for exposure times longer than 4 s.

- Penetration depth and amplitude of the compressive stresses increase with shorter nozzle distance.
- Residue of the EDM wire has been detected on the EDM surface that could be used in order to determine presence of RCL.
- XRF measurements of the surface can be used as a nondestructive method for evaluation of whether RCL is still present on the sample surface after grit blasting.

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