ULTRASONIC IMPACT TREATMENT FOR SURFACE HARDENING OF THE AERO-ENGINE MATERIAL IN718

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ABSTRACT

In order to satisfy stringent requirements regarding reliability, minimum weight, high performance, cost-effectiveness and long-term durability, the components of modern aircraft engines must tap the full potential of the materials used. For this reason, there has been a growing interest in work hardening processes applied to the surface layers of highly-stressed components with particular attention drawn towards the optimisation of established techniques such as shot peening and deep rolling as well as the development of new methods.

Such a new method is the ultrasonic impact treatment (UIT). UIT is predominantly used in the manual post-weld processing of steels. In addition to the intrinsic local and low loading treatment, UIT is cost-effective and easy to control such that it may be suitable for a wide range of applications. The objective of this work is to describe the potential of applying UIT to the high-strength nickel base alloy IN718. In order to characterise the hardened surface layer, surface roughness measurements and X-ray residual stress analyses were taken including experiments to evaluate the thermal stability of selected samples. The results obtained were compared to shot peened and deep rolled surfaces. It was discovered that the UIT technique produces deep surface layer work hardening. The hardening depths and surface roughnesses are similar to that obtained by deep rolling. Therefore all the specific advantages of UIT can be extended to the surface hardening of aero engine components.

KEYWORDS

Ultrasonic impact treatment, surface treatment, work hardening, residual stresses, IN718

INTRODUCTION

Highly-stressed components of modern aircraft engines must tap the full potential of the materials to improve product properties and reduce manufacturing costs. From this aspect, component surfaces and subsurface layers are of special interest, since they normally have maximum operating loads and therefore are the most likely source of potential failures. In this context, the material understanding of work hardened surface layers regarding their stability [V. Schulze, 2006; J. Hoffmeister, 2008] and crack initiation and propagation effects needs to be further developed. It will also be necessary to implement measuring setups that permit the non-destructive characterization of work hardened surface conditions on large complex-geometry components [e.g. R. Hessert, 2006] and to develop industrial measuring techniques for the non-destructive evaluation of work hardened subsurface layers [e.g. F. Yu, 2006]. Regarding product properties and manufacturing costs, it will be necessary to further develop manufacturing technologies that support the quality-oriented generation of work hardened surface layers. This can be achieved by optimization of the application area and the improvement of established techniques such as shot peening and deep rolling, or the development of new techniques like ultrasonic shot peening, or the combination of various techniques.

Formerly, ultrasonic impact treatment (UIT) was primarily used in the hand-held post-weld processing of predominantly steels [Y. Kudryavtsev, 2004; E.S. Statnikov, 2006]. In recent years, the technique has been finding increasingly wider use. Robot-based guidance of the working tool has achieved a high degree of reproducibility that enables predefined work hardening states on components or individual component areas in accordance with defined requirements. The technique is also recommended due to its high process stability and low operating costs. Very low initial loads are used to produce deep work hardening with a low surface roughness, and given certain conditions, a nano-crystalline layer may form on the component surface [Y.S. Pyoun, 2003]. The technique accordingly opens up applications that are impossible to achieve using conventional work hardening techniques or techniques that are substantially less cost-effective.

The objective of this work is to describe the potential of applying UIT to high-strength IN718 engine material. In the course of the work, the process parameters are varied and comparison is made with conventional shot peening and deep rolling processes for an exemplary estimation of the thermal stability of the resulting work hardening.

EXPERIMENTAL DETAILS

The laboratory set-up shown in Figure 1 was designed and built to consistently reproduce UIT on samples. The ultrasonic equipment components are a high-frequency 250 W generator, a transducer and a titanium sonotrode. The system has an operating frequency of 24 kHz and a maximum vibration amplitude of 55 µm. The tip of the sonotrode is fitted with a tungsten carbide hemisphere that is used as the working tool. The tool acts as an oscillating indenter plastically deforming the workpiece surface with each impact. The initial load is set and maintained pneumatically. To cover the surface area, the specimen is moved in a meandering course under the locally fixed tool. The movements are produced by two computer-controlled perpendicular linear axes with an accuracy of 0.01 mm.

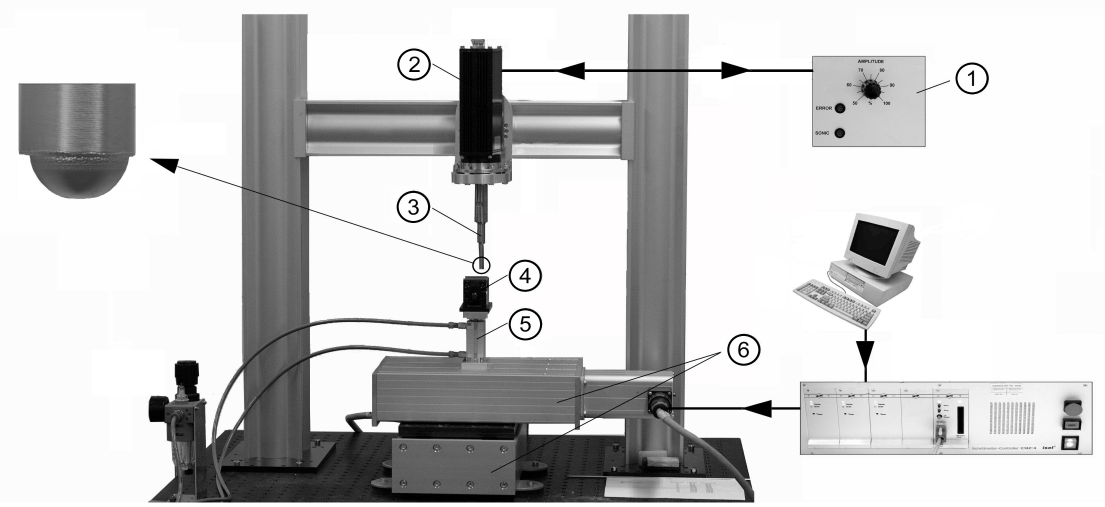

Figure 1: Laboratory set-up for the UIT of samples. 1 = high-frequency generator, 2 = transducer, 3 = sonotrode, 4 = sample holder, 5 = pneumatic cylinder, 6 = motor controlled x/y-axes.

The investigations were done on precipitation hardened IN718 samples sized 40 x 55 x 10 mm³. The samples were finish ground in their longitudinal direction. Subsequently, a 40 x 55 mm² surface of each sample was subdivided into four areas which were work-hardened by UIT, shot peening and deep rolling. The processing direction during work hardening coincided with the grinding direction. The different work hardening procedures and the corresponding process parameters are given in Table 1. During the UIT, the tool diameter, initial load and amplitude were varied, while the feed velocity and the lateral feed (overlap) were kept constant. The process parameters during shot peening and deep rolling were each selected to achieve strong and weak surface work hardening. After surface work hardening, some of the samples were heat treated for 100 h at 600 °C in vacuum. Residual surface stresses were determined by means of X-ray diffraction. Using Mn Kα radiation the {311} lattice planes at $2\theta = 151^\circ$ were measured in accordance with the $\sin^2 \psi$ method. Therefore the X-ray elastic constants $E^{\{311\}} = 191$ GPa and $\nu^{\{311\}} = 0.29$ were used. The depth distributions of the residual stresses were determined by successive electrochemical surface removal and subsequent X-ray measurements. The size of the locally removed area was small compared to the sample size, so that the resultant redistribution of stresses could be ignored. Apart from macrosopic residual stresses, the full width at half maximum (FWHM) values of the X–ray diffraction peaks were also recorded; they indicate microstructural changes in the material and can therefore be a measure of surface work hardening. Determination of surface roughness was made in processing and transverse direction using a mechanical sensor.

Variant	Tool-∅ [mm]	Initial Load [N]	Amplitude [µm]	Overlap [%]	Feed [m/min]
UIT1	6	40	55	50	0.11
UIT2	6	80	55	50	0.11
UIT3	6	80	23	50	0.11
UIT4	3	80	55	50	0.11

Variant	Shot-∅ [mm]	Air Pressure [bar]	Nozzle Angle [°]	Overlap [%]	Intensity [mm A]
SP1	0.35	1.0	80	100	0.12
SP2	0.79	1.5	80	100	0.33

Variant	Tool-∅ [mm]	Load [bar]	Feed [m/min]	Overlap [%]	
DR1	6	80	0.6	60	
DR2	13	250	0.6	60	

Table 1: Work hardening options and their characteristic process parameters in UIT, shot peening (SP) and deep rolling (DR).

RESULTS

As expected, following the finish grinding, some minor change in the surface layer resulted, with maximum compressive residual stresses of about –325 MPa on the surface and at a depth of about 25 µm. Shown in Figure 2 are the depth distributions of the residual stresses and the FWHM-values in the processing and transverse direction for the UIT variant UIT2. In both measurement directions compressive residual stress depth distributions are obtained, their absolute values increase from the processing to the transverse direction in the near-surface area. It becomes apparent that UIT can also result in the formation of maximum compressive residual stresses below the surface typically found after shot peening, depending on the effects of Hertzian pressure. The residual stress profiles exhibit another increase within immediate proximity of the surface, which is also noted after deep rolling. This near-surface residual stresses are attributed to friction and slip processes [B. Scholtes, 1990]. The results below only correspond to the work hardening effects transverse to the processing direction. Figure 2 also clearly illustrates the effect of the tool diameter, initial load and amplitude on the UIT variants. As the initial load grows from UIT1 to UIT2 and the amplitude increases from UIT3 to UIT2, the thickness of the compressive residual stress affected surface layer grows. The 6 mm to 3 mm reduction in tool diameter from UIT2 to UIT4 increases primarily the absolute values of compressive residual stress in the near-surface area and shifts the compressive residual stress maximum to the surface. Starting from the value of the untreated material, the FWHM-values increase continuously towards the surface. As the initial load and amplitude increase, and more importantly as the tool diameter decreases, deeper work hardening and increasing near-surface stress values are noted.

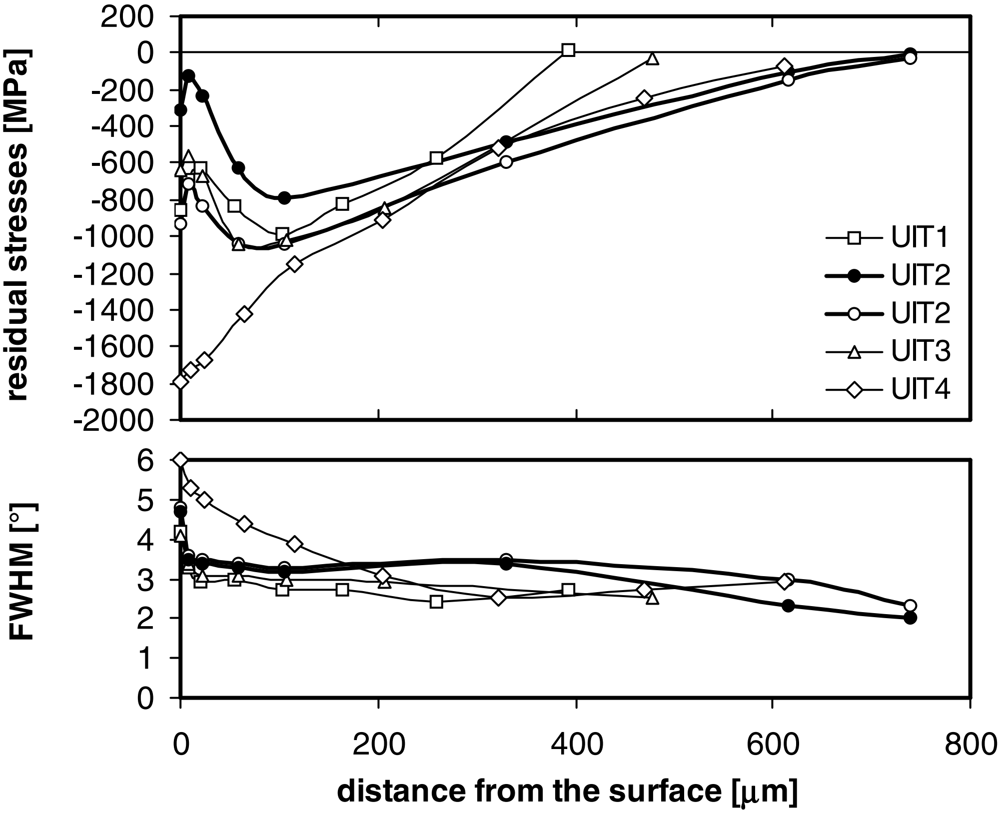

Figure 2: Depth distributions of residual stresses and FWHM-values in the processing (close symbol) and transverse (open symbol) direction of UIT variant UIT2 and effects of tool diameter, initial load and amplitude during UIT in transverse direction.

The data in Figure 3 compares the various work hardening processes UIT, shot peening and deep rolling regarding strong (UIT2, SP2, DR2) and weak (UIT1, SP1, DR1) surface layer work hardening. It becomes apparent that UIT produces thicker compressive residual stress affected surface layers than shot peening. Moreover the surface layer thicknesses obtained by UIT are larger than after weak deep rolling, even if for deep rolling, the initial loads are distinctly greater than for UIT. The use of optimized tool designs and ultrasonic set-ups of greater power will certainly increase the depth effect after UIT. The FWHM-values, too, are continuously growing, starting from the value of the untreated material, toward the surface. It becomes apparent that after shot peening, the values are a maximum near the surface and that on the heavily deep rolled variant DR2 the near-surface effect is greatest with a plateau region under the surface.

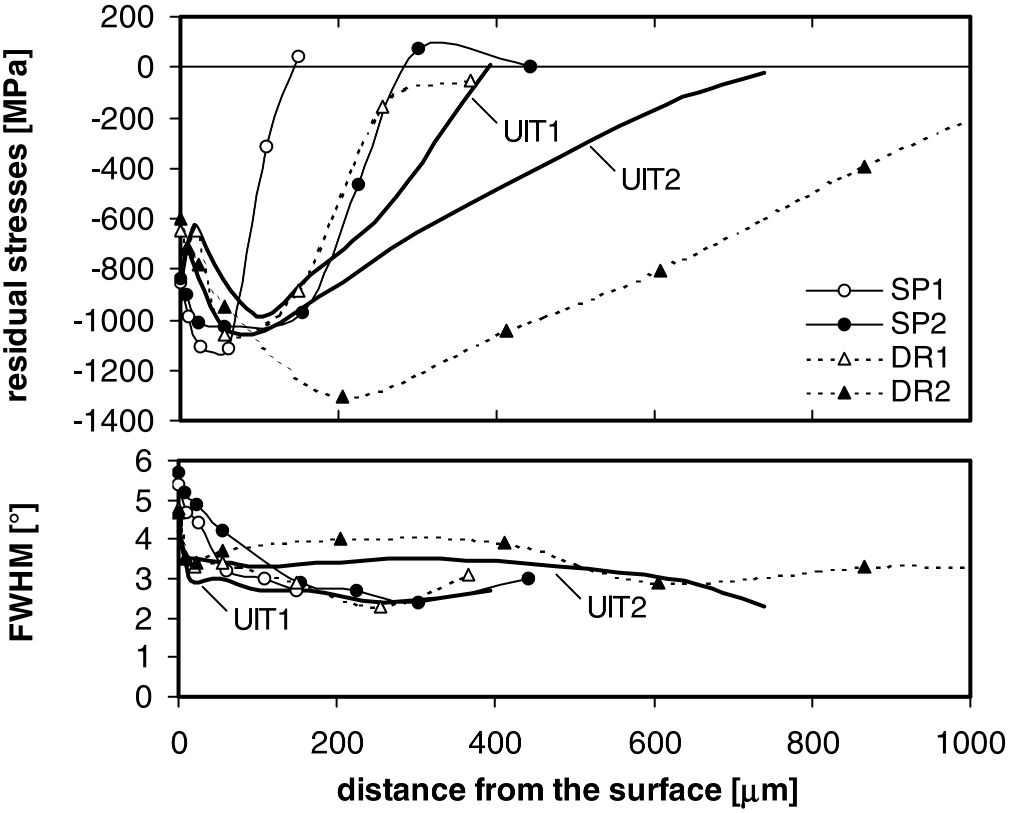

Figure 3: Comparison of depth distributions of residual stresses and FWHM-values in transverse direction after UIT (variants UIT1, UIT2), shot peening (variants SP1, SP2) and deep rolling (variants DR1, DR2).

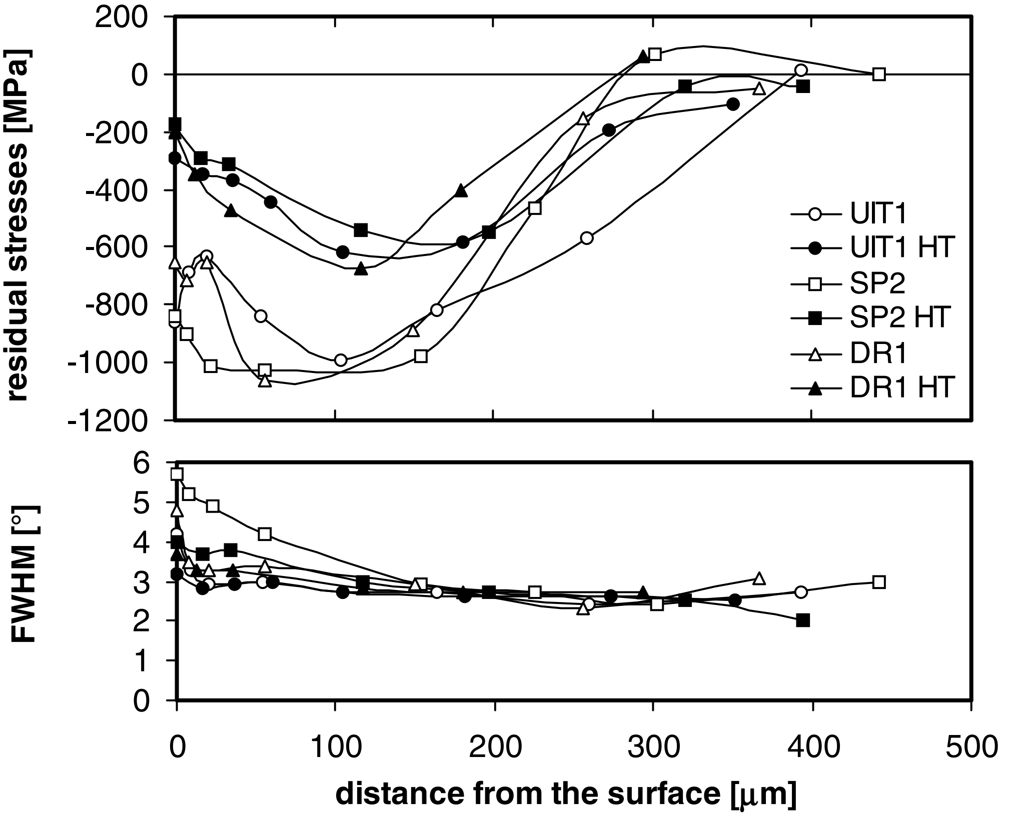

Figure 4: Depth distributions of residual stresses and FWHM-values in transverse direction of UIT variant UIT1, shot peening variant SP2 and deep rolling variant DR1, each before and after heat treatment (HT) 100 h at 600 °C in vacuum.

Variant	R_z [µm]		
	‖	⊥	Average
ground	1.37	4.57	2.97
UIT1	0.35	1.39	0.87
UIT2	0.31	1.32	0.81
UIT3	0.45	1.47	0.96
UIT4	1.00	7.44	4.22
SP1	6.04	5.43	5.74
SP2	14.01	13.98	14.00
DR1	0.73	1.83	1.28
DR2	0.41	1.51	0.96

Table 2: Surface roughnesses R_z after grinding and after various surface hardening treatments.

The associated surface roughnesses are listed in Table 2. While after UIT and deep rolling, surface roughnesses are similar, the roughness values are distinctly greater after shot peening. After UIT and deep rolling, owing to the accompanying surface grooving, the surface roughness is invariably less pronounced in the processing direction than in vertical direction. A comparison of the various work hardening techniques regarding the thermal stability of similar residual stress depth distributions is made in Figure 4. After heat treatment, the initial compressive residual stresses are reduced to almost the same residual stress depth distributions, regardless of the work hardening technique used. On all variants, heat treatment reduced the near-surface FWHM-values, reflecting a reduction in surface work hardening. Some minor differences are still noted among the various techniques.

CONCLUSION

Comparing the work hardened surface layers with those generated by shot peening and deep rolling, the results show that by UIT, essentially deeper compressive residual stress conditions can be produced than by shot peening, with an appreciably less pronounced surface roughness. Deep rolling produces surface roughness comparable with results obtained by UIT, but requires distinctly higher initial loads to generate a deep work hardening layer. The thermal stability of all three work hardening techniques seems to be similar. Therefore UIT is recommended for the treatment of thin-walled components while keeping surface roughness low. UIT is an innovative technology providing great development potential for improving the cost situation and workpiece quality in the manufacture and repair of high-strength components.

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