

# Effects of the surface treatment on the measured diffraction peak width of Inconel 718

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## Abstract

Macroscopic and microscopic residual stresses can be determined by the X-ray diffraction technique. The macroscopic residual stresses can be derived from the shift of the diffraction peak position. The diffraction peak widths are a measure for the microscopic residual stresses and are often directly correlated with the amount of cold work in a material. Thereby, aspects like for example the strain rate or the stress state by which the cold work was induced are not taken into account in the correlation. Nevertheless, the induced dislocation structure depends on these parameters. For example, there are different dislocation structures after shot peening (high strain rates during the process in the treated material) and deep rolling (lower strain rates during the process in the treated material). So the strain rate during a deformation process affects the dislocation structure and hence has also an effect on the diffraction peak width.

In order to find out the influence of strain rate on the diffraction peak width, specific compressive deformations with different strain rates were performed on Inconel 718 specimens. After mechanical loading the specimens were cut in the middle. The new surfaces were electro polished and afterwards the X-ray diffraction peaks of the {311}-planes were measured. The full widths at half maximum (FWHM) of the  $K_{\alpha 1}$ -interference lines were determined. These FWHM were correlated to the plastic strains and the different strain rates. The correlations found will be shown and discussed in this paper.

**Keywords:** Inconel 718, nickel base alloy, cold work, FWHM, micro residual stresses

## Introduction

Macroscopic residual stresses can be derived from the shift of the diffraction peak position by the X-Ray diffraction technique. The diffraction peak widths of the interference lines are also a measure of the microscopic residual stresses present in the material. Therefore Prev y [1] proposed an equation to link the cold work and the full width at half maximum (FWHM) of the interference line directly. Prev y used this equation for different processes such as shot peening, gravity peening, laser shock peening and low plasticity burnishing [2]. Thereby aspects such as the strain rate or the stress state are assumed to have negligible effect. However, these can also influence the induced dislocation structure. In this paper the influence of strain rate on the development of the FWHM-values is investigated.

## Methods

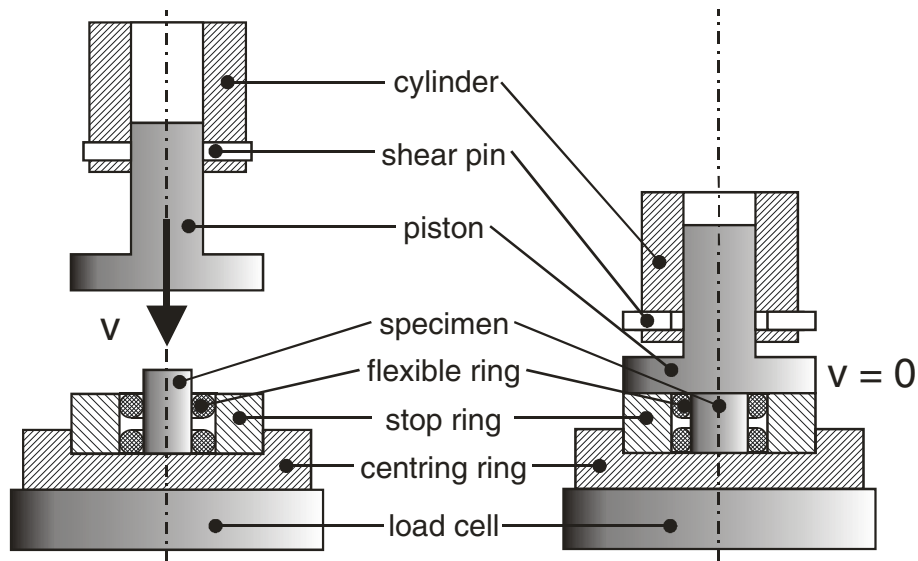
The investigations were carried out on age hardened cylindrical Inconel 718 (IN718) samples. The diameter of the cylinders was 4 mm and the length 10 mm.

In order to find out the influence of strain rate on the FWHM-values, these cylinders were loaded with diverse discontinued compression tests. Different specimens were isothermally loaded at room temperature (RT) to different total strains between 0 % and 25 %. Two different total strain rates  $\dot{\epsilon}_t$  were applied ( $10^{-4}$  1/s and 1000 1/s).

The experiments with the lower strain rate ( $\dot{\epsilon}_t = 10^{-4}$  1/s) were performed under controlled total strain rate in a tensile testing machine.

The tests with the high total strain rate ( $\dot{\epsilon}_t = 1000$  1/s) were performed in a high-speed testing machine (Zwick HTM 5020). This machine allows loading a specimen with maximum piston speed of 20 m/s both in tension and compression. For this machine a special device was built to test the specimen up to a specified total strain. Figure 1 shows a schematic diagram.

The testing device is accelerated at velocity  $v$  from the piston of the machine. The piston of the device impacts on the cylindrical specimen. The specimen is deformed until the piston of the device impacts on the stop ring. Then the force escalates and the shear pin is cut. Afterwards the piston of the device can move freely in the cylinder while the piston of the machine is decelerated by the end-of-stroke damper. During the total testing the force is measured by a piezoelectric load cell.



**Figure 1:** Schematic diagram of the testing device for high strain rate experiments

The lengths of the specimens before ( $l_{before}$ ) and after ( $l_{after}$ ) the experiments were measured and the plastic strain was identified as:

$$\epsilon_p = \frac{l_{before} - l_{after}}{l_{before}} \quad (1)$$

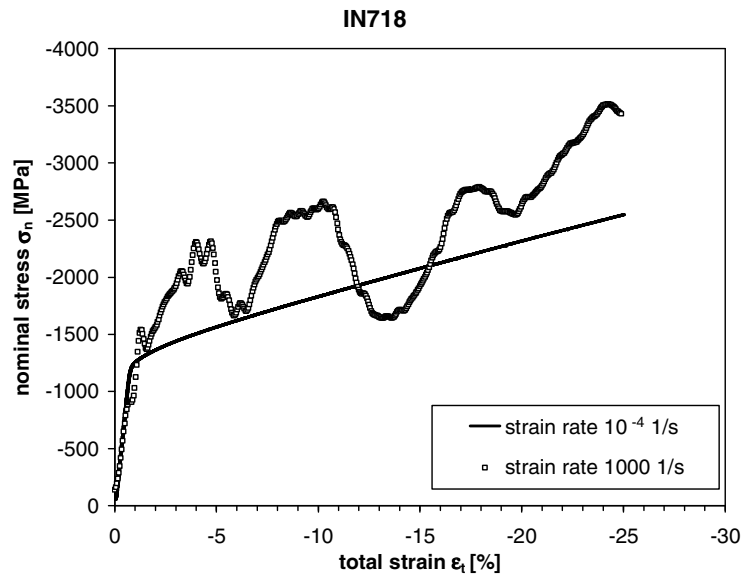
The specimens were cut in the middle across the longitudinal axis and the new surface was electro polished to remove the hardening introduced during cutting. Afterwards the FWHM-values were measured in the middle of the specimens on the electro polished surface by the X-ray diffraction at the  $\{311\}$ -interference using  $\text{Cu-K}\alpha$ -radiation with three different inclinations  $\psi = -5^\circ, 0^\circ, 5^\circ$ . The spot diameter of the incident X-ray beam was 1 mm. The secondary slit was a slot with breadth of 2 mm. The  $\text{K}\alpha$ -doublet was separated to determine the width of the stronger  $\text{K}\alpha_1$  peak using the Rachinger correction. The three FWHM-values for the three different  $\psi$  inclinations in each specimen were averaged.

To correlate the measured results with the technically relevant FWHM-values, different samples were shot peened with Almen intensities of 0.1 mmA and 0.25 mmA. Afterwards the FWHM of the shot peened surfaces were measured.

## Experimental Results

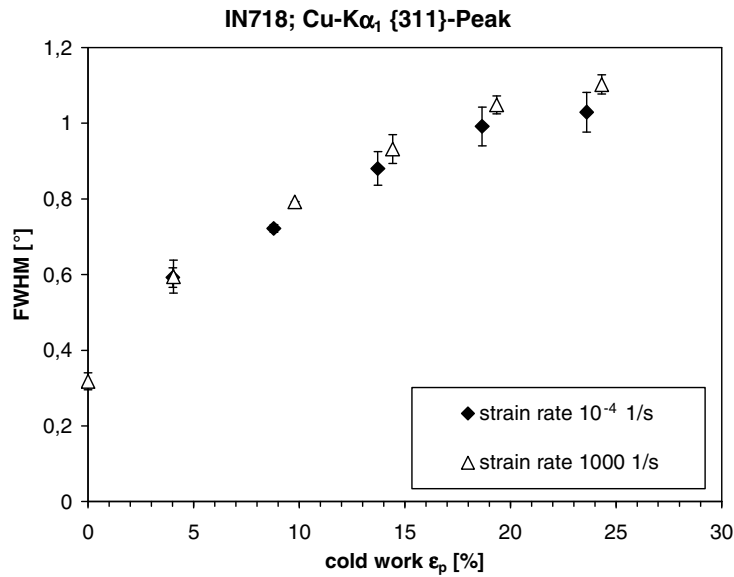
A typical measured compressive stress strain curve for each of the two different total strain rates ( $\dot{\epsilon}_t = 10^{-4}$  1/s and 1000 1/s) is shown in Figure 2. The experiments were stopped at a total strain  $\epsilon_t = 25$  %.

Comparing the two stress strain curves it can be seen that the stress strain curve with the high strain rate shows oscillations. This is due to the impact of the measurement setup and is a common result. It can also be seen that the curve for ( $\dot{\epsilon}_t = 1000$  1/s) shows a higher stress level than the other curve ( $\dot{\epsilon}_t = 10^{-4}$  1/s).



**Figure 2:** Typical measured compressive stress strain curves for the two different total strain rates ( $\dot{\epsilon}_t = 10^{-4}$  1/s and 1000 1/s) for IN718

The measured FWHM after the different loadings are shown in Figure 3. The FWHM increase with the applied plastic strain  $\epsilon_p$ . It can also be seen that the FWHM of the experiments with the higher strain rate ( $\dot{\epsilon}_t = 1000$  1/s) are on a higher level than the one with the low strain rate ( $\dot{\epsilon}_t = 10^{-4}$  1/s). This trend could also be observed at other experiments.



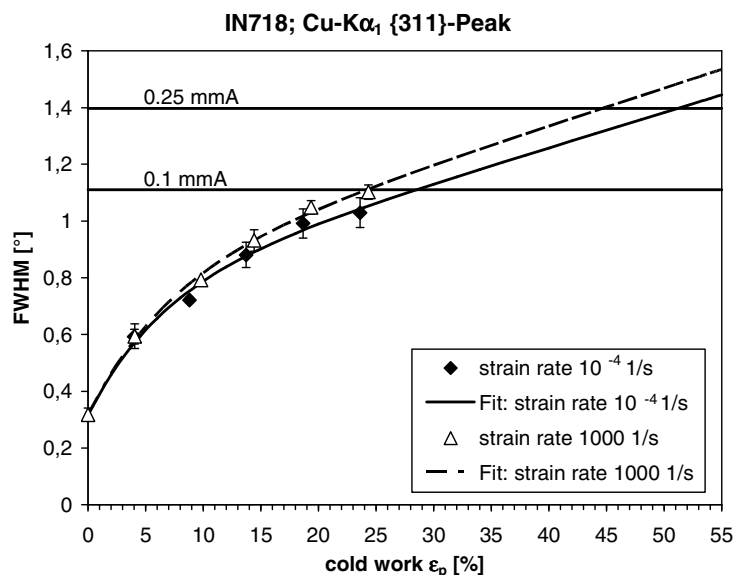
**Figure 3:** FWHM-values measured after different loadings for IN718

### Discussion

Prevý suggested an equation to correlate the cold work (plastic strain  $\epsilon_p$ ) with the FWHM [1]:

$$FWHM = A(1 - \exp(-B \cdot \epsilon_p)) + C \cdot \epsilon_p + D \quad (2)$$

Where A, B, C and D are fitting parameters. With this equation the results are shown in Figure 3 are fitted with a least-square algorithm. For the different strain rates different fitting parameters are used. This result is shown in Figure 4.

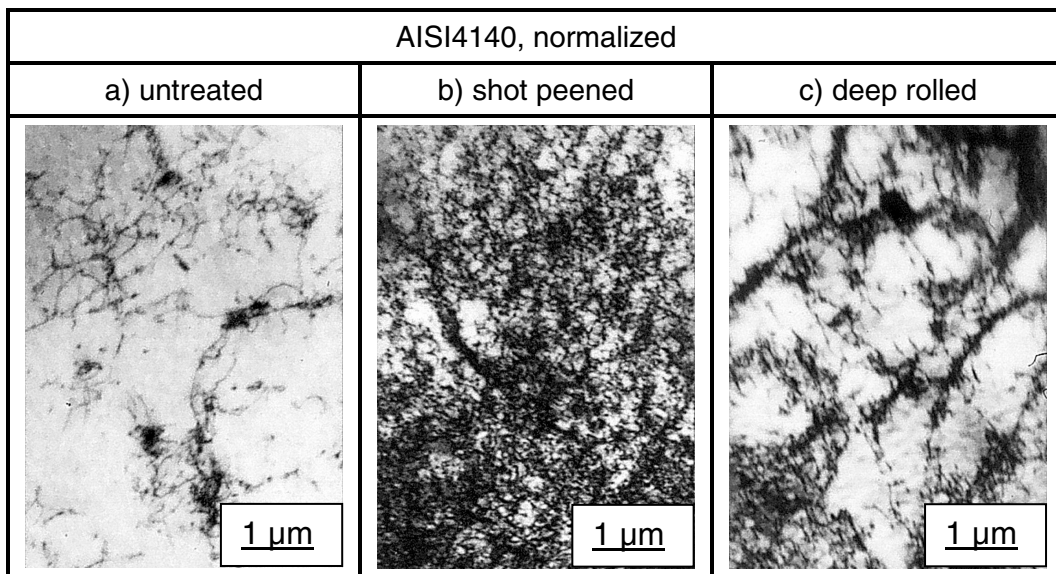


**Figure 4:** FWHM-values measured after shot peening and different loadings and for the different strain rates fitted with equation (2) and the FWHM-values of the shot peened samples for IN718

The fits show the same tendency as already implied: FWHM of the experiments with the high strain rate are higher than the experiments with the low strain rate. This can be explained by

the strain rate effects. At low strain rates the dislocations have a lot of time to annihilate and to order in new arrangements like subgrain boundaries. At high strain rates the dislocation movements are handicapped because of obstruction of the cross slip of screw dislocations which leads to more planar dislocation structures. On the one hand this causes a hardening of the material (cf. Figure 2) on the other hand the developed dislocation structures are different. The dislocations have no time to arrange and to annihilate at the shorter time of the cold work and more dislocations are left in the material [3].

This phenomenon can be already observed by a transmission electron micrograph of untreated, shot peened and deep rolled AISI4140 specimens (cf. Figure 5) [4] and should be transferable to IN718 in spite of the different microstructures. It can be seen that the microstructure of a shot peened and a deep rolled specimen is completely different. The specimen after shot peening (high strain rates during the impact of the shots) shows a lot of unsystematic dislocations in comparison with the untreated specimen. This dislocation structure is typical for deformation with high strain rates. The deep rolled specimen is also work hardened but with a lower strain rate. In contrast to the shot peened specimen there are few dislocations and this dislocation are ordered in subgrain boundaries.



**Figure 5:** Transmission electron micrographs at surface distance of 0.08 mm in a untreated (a), a shotpeened (b) and a deep rolled (c) normalized AISI4140 specimen [4]

Because the dislocations have no time to arrange and annihilate there are more dislocations after deformation at high than at low strain rates. So the measured FWHM at same cold work and higher strain rate are higher.

In Figure 4 the two FWHM-values of the shot peened specimens (Almen intensity of 0.1 mmA and 0.25 mmA) are also shown. For the two specimens there are significant differences between the correlated cold work according to equation (2) for the high and the low strain rates. For the specimen with the Almen intensity of 0.1 mmA, the equation for the low strain rate produces a cold work of  $\epsilon_p = 28.5 \%$ , while for the for the high strain rates, it produces a cold work of 24.5 %. This corresponds to a deviation of 16 %. For the specimen with the higher Almen intensity (0.25 mmA) the fits of the equation (2) for different strain rates must be strongly extrapolated. The equation for the low strain rates predicts a cold work  $\epsilon_p = 51 \%$ , for the high strain rates 44.5 %. This corresponds to a deviation of 14 %.

## Conclusion

It could be shown that the strain rate influences the full width at half maximum (FWHM) of the X-ray diffraction peak. So the FWHM can not directly be correlated with the cold work. As an

example, the emerging differences in two shot peened specimens were estimated. The deviation to the equation predicted by Prev y [1] for the two estimated strain rates ( $\dot{\epsilon}_t = 10^{-4}$  1/s and  $10^3$  1/s) was about 15 %. So the equation of Prev y can be used to predict a range of cold work as function of FWHM. Nevertheless the exact value of cold work as function of FWHM is dependent on the process which produces the cold work and respectively the strain rate.

## References

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