THE IMPACT OF DAMAGE IN INCONEL 718 ON HARDNESS MEASURED BY THE VICKERS METHOD

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Abstract

To prevent failure of machine components it is necessary to measure material damage generated in a component throughout its entire lifetime. Damage can be quantified by means of damage parameters. This paper considers the usefulness of hardness measurements to evaluate damage parameter in Inconel 718. Vickers hardness tests were performed on a specimen with a variable cross section area after tensile testing. The specimen's geometry enabled the evaluation of damage parameter in respect of hardness measurements made on one individual specimen.

Keywords: Damage parameter, Vickers hardness, Inconel 718, Tensile test.

INTRODUCTION

To avoid material failure engineers use damage numerical models [1] e.g. the Gurson–Tvergaard–Needleman model (GTN), and the Jonson-Cook and Lemaitre models [2]. These models refer to microscopical damage in the material structure related to the plastic deformation of the material caused by macroscopically applied stress. These structural changes in the deformed material affect its mechanical properties and have a great impact on the safety and life prediction of the working component. Quantitative evaluation of material damage can be done using the damage parameter. According to the model proposed by Katchanov isotropic damage can be described as a reduction of the specimen's cross section area, which is related to the presence of microvoids in the material. The damage parameter can be then defined as a scalar and expressed by the equation [3]:

$$D = \frac{S_D}{S} \tag{1}$$

Where S is the surface of the representative volume element (RVE) cross section, S_D is damaged surface of RVE cross section.

The scalar damage parameter (D) can be evaluated in many ways by means of material properties sensitive to plastic deformation of the material. One such property is hardness.

The hardness test is one of the easiest and most widely used mechanical tests used for evaluating the properties of metals. Hardness can be described as the resistance of the material to permanent deformation caused by an indenter which is pressed into the material with a specified force. According to Lemaitre, for isotropic and kinematic hardening the yield stress in damaged material is formulated as [3]:

$$\sigma_s = (\sigma_y + X + R) \cdot (1 - D) \tag{2}$$

Where σ_y is yield strength, X is back stress, R is stress due to isotropic hardening.

In the same work [3], Lemaitre presents the conclusion that the hardness of a material can be expressed as the linear function σ_s:

$$H = k' \cdot \sigma_s \tag{3}$$

Hardness in any region of damaged material will be expressed as:

$$H = k' \cdot (\sigma_y + X + R) \cdot (1 - D) \tag{4}$$

According to Equation (4) the damage parameter in respect of material hardness (D_H) can be expressed as:

$$D_H = 1 - \frac{H}{H^*} \tag{5}$$

Where H^* is a hypothetical reference hardness of the tested material that has been plastically deformed without any damage.

METHODOLOGY

Hardness tests were performed on plastically deformed specimens in order to verify Equation (5).

Arrangements prior to Hardness Test

For the tests, Inconel 718 was used. It is a Nickel-based alloy (Table 1) used for heat resistant components such as compressor blades in a jet engine.

Table 1. Chemical composition of Inconel 718 selected for tests

Chemical elements [wt. %]						
Ni	Cr	Nb	Mo	Ti	Al	Fe
50.0-55.0	17.0-21.0	4.75-5.50	2.8-3.3	0.65-1.15	0.20-0.80	Balance

The specimen for the tensile test was prepared from the annealed rolled sheet. Metallography inspection shows that the material's structure consists of equiaxial grains and carbides particles (Figure 1).
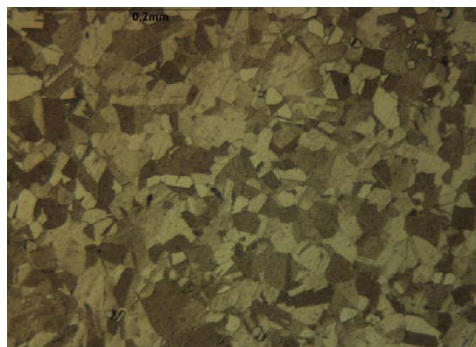

Figure 1. Structure of tested Inconel 718

Tensile test was conducted on a specimen with a variable cross-section area (Figure 2) [4] in a MTS testing machine (model MTS 318.10) with a force transducer (Made: MTS model no. 661.20F-03). The specimen's geometry is responsible for continuous deformation after the tensile test, ranging from plastic strain associated with yield strength to plastic strain associated with ultimate strength.
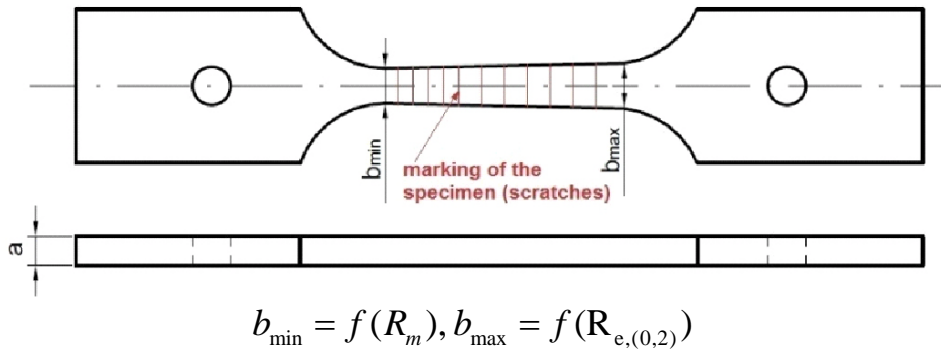
$$b_{\min} = f(R_m), b_{\max} = f(R_{e,(0,2)})$$

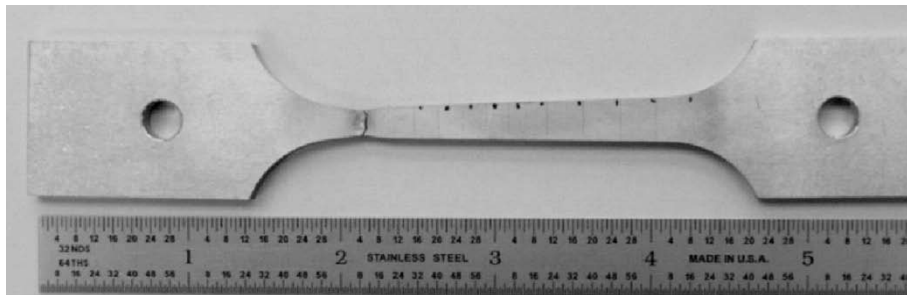**Figure 2. Specimen geometry used for tests**

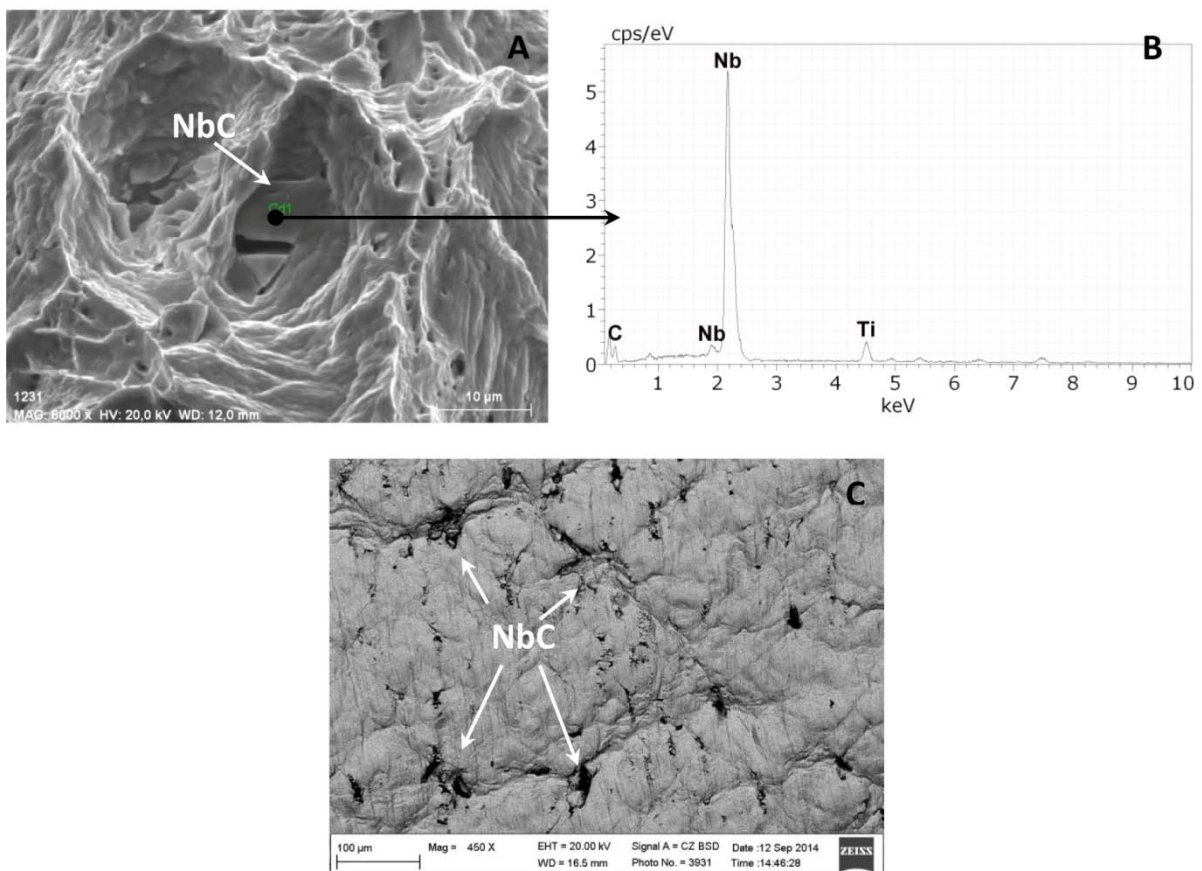**Figure 3. Specimen after tensile test**

**Figure 4. SEM inspection of the specimen after tensile test. SEM-SE image shows
the fracture surface with carbides at the bottom of the dimple (A).
EDX spectrum shows chemical composition of carbides (B).
SEM-BSE image shows cracked carbides in the specimen's surface near the fracture (C).**

After the tensile test, the specimen (Figure 3) was inspected in a scanning electron microscope (SEM) (Made: CARL ZEISS model no. 25MA). The fracture's surface was ductile-type with dimple structure (Figure 4A).

There were cracked particles in the bottom of the dimple. Energy-dispersive X-ray spectroscopy (EDX) using a BRÜKER detector (model no. X Flash Detector 5010 125 eV) was performed to determine the composition of these particles. The results showed that these particles consisted of Niobium (Nb), Carbon (C) and Titanium (Ti) (Figure 4B). It seems that the NbC primary carbides are quite often present in Inconel 718. As these NbC carbides are not aligned with the crystal structure of the matrix, they worsen mechanical properties of Inconel 718 [5].

Carbides of the same type were found in the specimen's surface (Figure 4C). They were cracked, detached from the matrix and in consequence created cavities in the material. The intensity of cracks and detachment were increasing with an increasing degree of plastic deformation. This type of damage occurs simultaneously with the plastic deformation of the matrix.

This type of damage is called Ductile Plastic Damage [6] and the failure mechanism can be associated with the forming and growth of the fracture's free surface on cracked NbC carbides and their debonding from the matrix.

For these reasons, it was assumed that D can be expressed by Equation (1) and DH can be evaluated according to Equation (5).

Hardness Test

After the SEM inspection, a piece of the material was cut out from the specimen reduction area (Figure 5). It was then ground and polished to prevent the deformed and damaged specimen's surface from affecting the hardness value. Hardness tests were conducted in selected areas in the specimen's width-height cross section in the tensile direction.
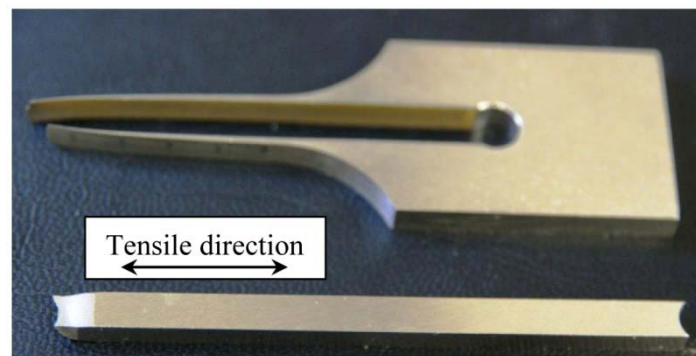

Figure 5. Specimen after tensile test prepared for hardness test

Hardness measurements were performed on a Vickers hardness test machine (Made: INNOVATEST, model no. NEXUS 4000). The measurement procedure was specified with respect to ASTM E384 [7]. 5 indentations were done in each selected area. Average hardness values calculated for each set of indentations (calculated from Equation (6)) were used for further investigation.

$$HV = \frac{F}{A} \approx \frac{1.8544F}{\sim d^2} \tag{6}$$

where *F*- is force applied to the intender, *A*- is area of indentation, and *d* is average length of the indentation's diagonals.

The parameters of the test are presented in Table2. The force used has been chosen such as to achieve an indentation size corresponding to the representative volume element (RVE) (Figure 6). Also, for force equal to or greater than 10 kgf, the measured hardness value depended on the force applied to a small extent only (Figure 7). Prior to the tests, the measurements were made on the hardness reference test block 336.6HV10. Deviation from the reference value was lesser than 1.5%.

Table 2. Parameters of hardness test and measured value of hardness reference block

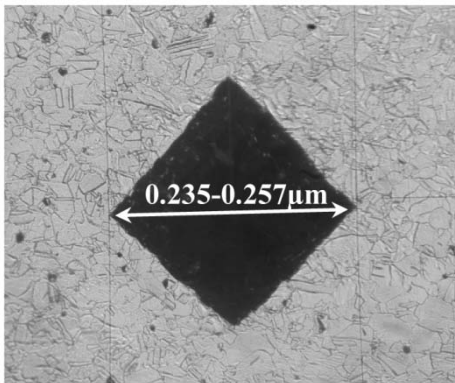| Force [kgf]	DWEL TIME [s]	MAGNIFICATION [x]	MEASUREMENT ON HARDNESS REFERENCE TEST BLOCK 336.6HV10 [HV10]
10	10	20	332.3

Figure 6. Indentation in tested Inconel 718 depends on the material's structure
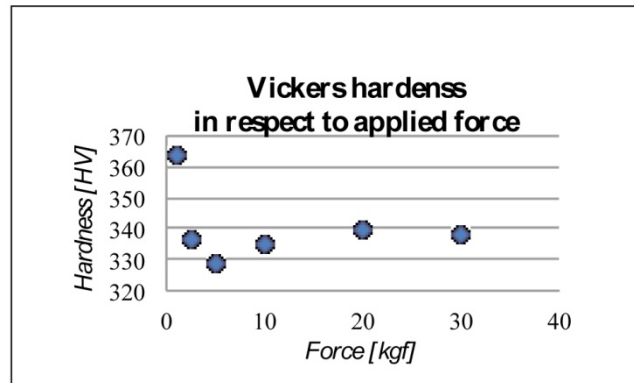

Figure 7. Hardness in relation to applied force

RESULTS AND DISCUSSION

The measurement results show that the average hardness value of the tested inconel 718 increases with increasing its plastic deformation (Figure 8). This is associated with strain hardening of the deformed material.
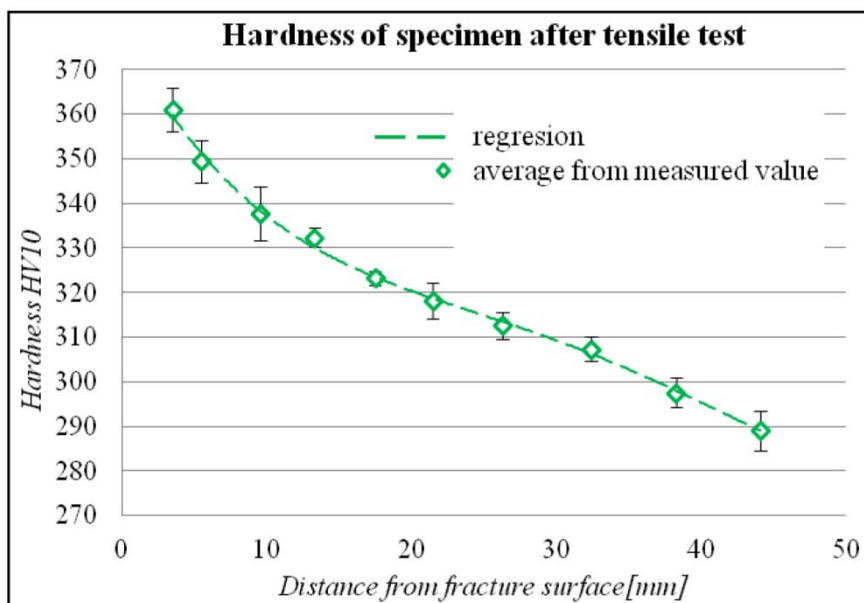

Figure 8. Hardness values for the specimen after tensile test

To evaluate the damage parameter from Equation (5), reference hardness (H^*) has to be found. It was done using the tensile test data based on the procedures described in [8]. According to the assumption contained in this paper it can be stated that:

$$\frac{HV^*}{\tilde{\sigma}_p} = \frac{C_H \cdot (\tilde{\varepsilon}_p)^n}{C_R \cdot (\tilde{\varepsilon}_p)^n} = a \qquad (7)$$

Where C_H, C_R and a are the material parameters, $\tilde{\sigma}_p$ is hardening stress, $\tilde{\varepsilon}_p$ is the plastic component of true strain, n is the material constant known as the strain hardening exponent.

It was assumed that for small plastic strain the material's damage is negligible. It means that:

$$HV^* = HV \qquad (8)$$

Combining Equation (7) and (8) the equation for C_H can be expressed as:

$$C_H = a \cdot C_R \qquad (9)$$

The parameter C_R and a can be found from the hardening stress- true strain curve determined from the tensile test data. After that the reference hardness of the tested material can be found from the equation:

$$HV^* = C_H \cdot (\tilde{\varepsilon}_p)^n \qquad (10)$$

In a specimen with a variable cross section area, hardening stress in function of true strain was determined only for the reference sections. These were marked on the specimen's surface prior to performing the tensile test. Assuming that the volume of the material doesn't change the plastic component of true strain in the reference sections, ($\tilde{\varepsilon}_{p_i}$) was calculated from the relation:

$$\tilde{\varepsilon}_{p_i} = -(\ln \frac{a_i}{a_{i_o}} + \ln \frac{b_i}{b_{i_o}}) \qquad (11)$$

Where a_i, b_i are the specimen's width and thickness respectively in the reference sections after the tensile test; a_{i0}, b_{i0} are width and thickness in the reference sections before the tensile test.

Hardening stress in the reference regions ($\tilde{\sigma}_{p_i}$) was calculated from the relation:

$$\tilde{\sigma}_{p_i} = \frac{F_{max}}{a_i \cdot b_i} - \sigma_y \qquad (12)$$

Where F_{max} is maximum load applied to the specimen during the tensile test, and σ_y is yield strength.

Power regression for the determined hardening stress-true strain values was done (Figure 9). The parameters n and C_R were found from the regression curve equation (Figure 10). It means that calculation for H* can be performed now.

Hardness wasn't measured at the same places where reference hardness was calculated. Therefore, the approximation of the specimen's hardness value was done.

After that D_H can be specified (Figure 11). The results show that the relation between D_H value and the measured hardness value fits well to linear regression.
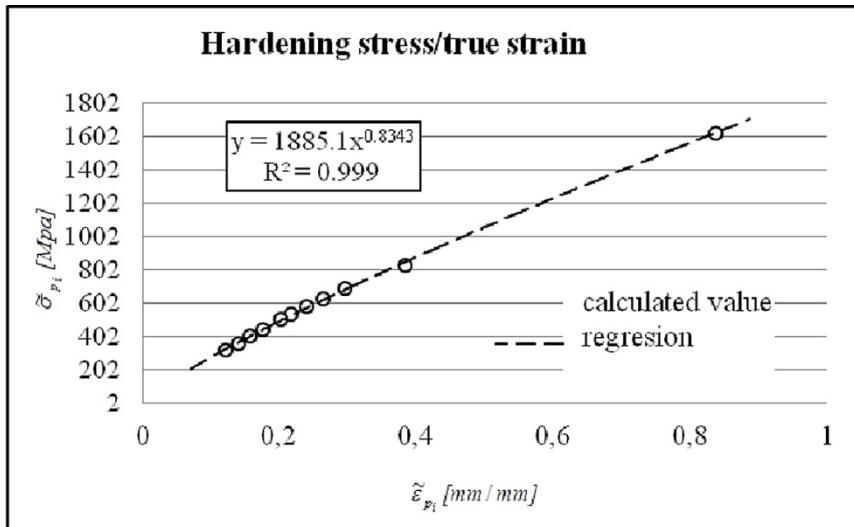
***Figure 9. Hardening stress in function of the plastic component of the true strain curve
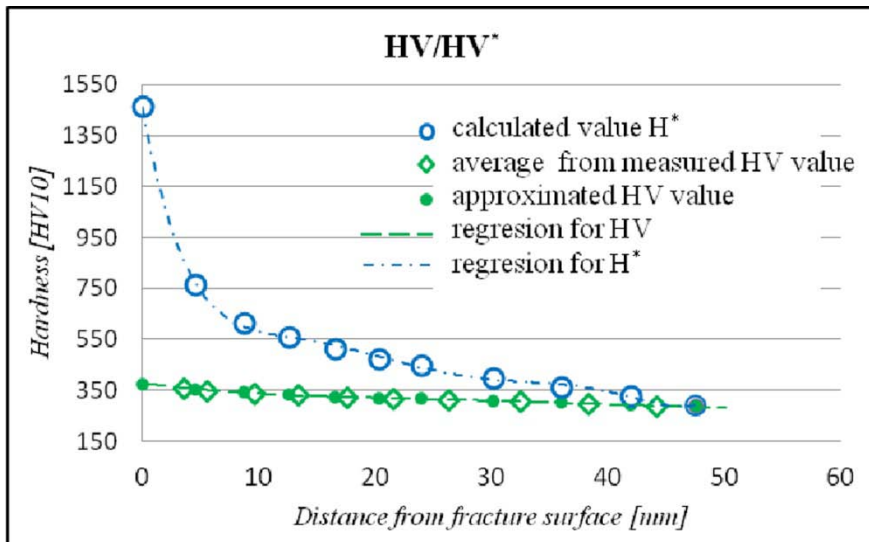for the specimen after tensile test***

Figure 10. Hardness and reference hardness for tested Inconel 718
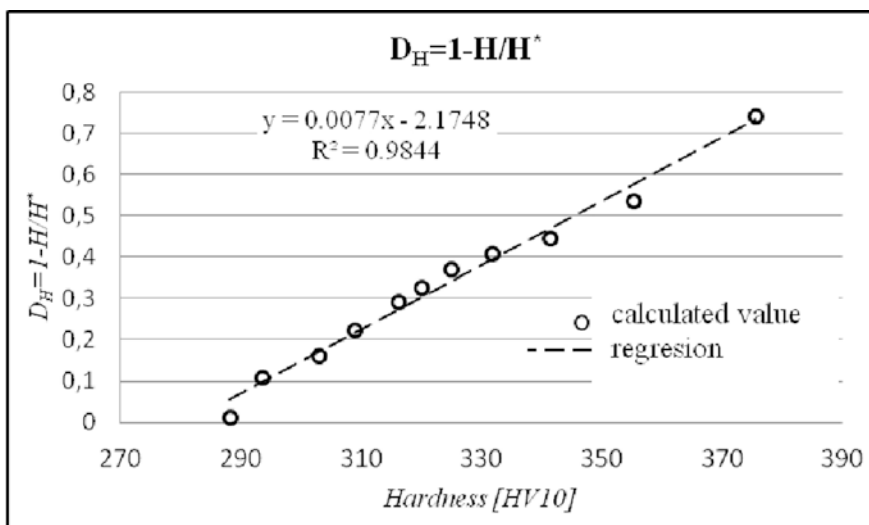

Figure 11. Damage parameter in relation to material hardness

One disadvantage of evaluating the damage parameter based on hardness measurement is that hardness is not the material constant. It means that the value of D_H will be dependent on a test method used. A more independent value of the damage parameter can be calculated based on the plastic strain value (D_ε). It is possible to verify D_H by comparing values of D_H and D_ε.

Correlation between D_ε and D_H

The damage parameter expressed by strains was defined by Jonson [9]. For the tensile test, D_ε can be described by the equation:

$$D_\varepsilon = \frac{\varepsilon_p}{\varepsilon_p^f} \tag{13}$$

Where ε_p is a variable value of equivalent plastic strain which occurs during tensile test, and ε_p^f is strain equivalent to fracture.

Values obtained for ε_p can range from 0 to ε_p^f. To evaluate the damage parameter defined by Equation (15) it was assumed that strain ε_p^f is approximately equal to maximal strain which occurs in the neck of the fractured specimen. The Value of ε_p in specimen reference sections (ε_{p_i}) was calculated from the relation (Fig. 12):

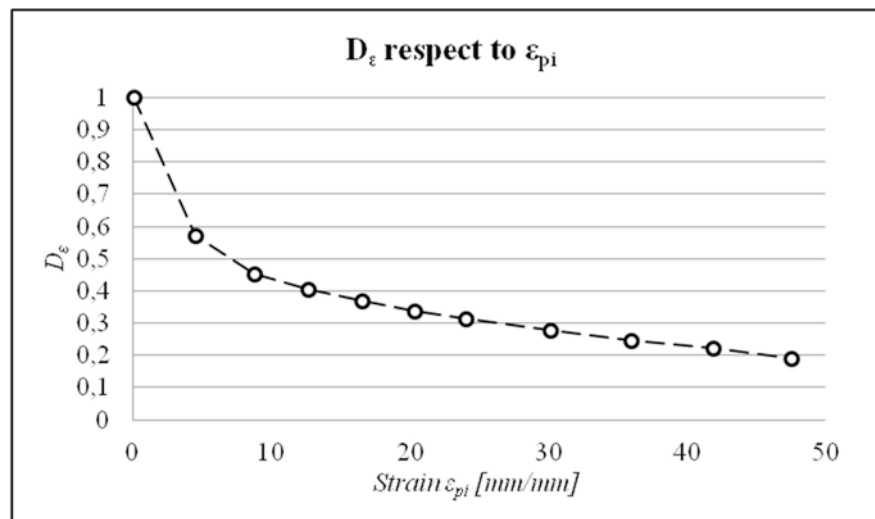$$\varepsilon_{p_i} = -(\frac{a_i - a_0}{a_0} + \frac{b_i - b_0}{b_0}) \tag{14}$$

Figure 12. D_ε in relation to ε_{pi}

As shown in Figure 13 the damage parameter calculated in relation to hardness doesn't match the damage parameter calculated with respect to tensile strain of the tested material.
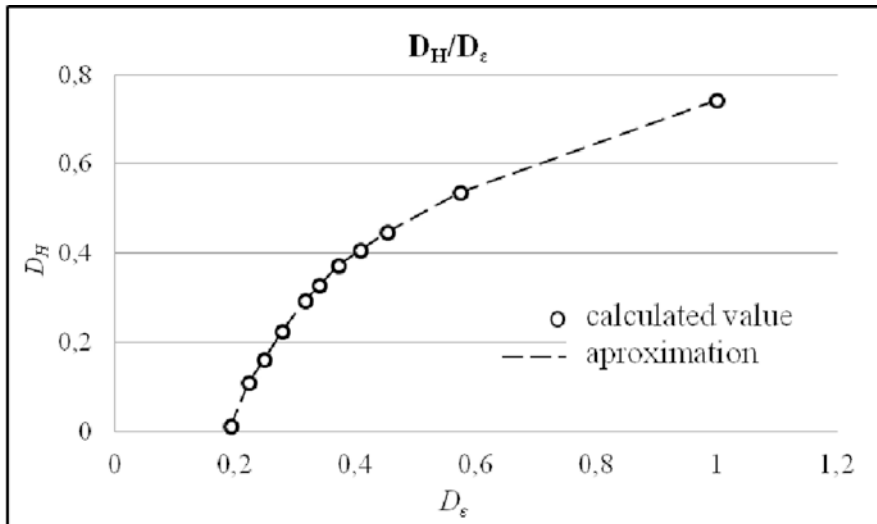
Figure 13. Correlation between D_ε and D_H

One of the reasons why D_H and D_ε differ is the hypothetical value of H^*. This value depends on the model used to describe strain hardening of the material in tensile test. Also it was assumed that H and H^* can be expressed as the linear function σ_s. For a more independent value of D_H the reference hardness can be taken as hardness in the virgin part of a piece of the material (H') [10]. The damage parameter in that case ($D_{H'}$) will be expressed as:

$$D_{H'} = 1 - \frac{\sigma_y \cdot H_{\sigma_u}}{\sigma_u \cdot H'}$$

(15)

Where σ_u is ultimate strain, H_{σ_u} is hardness in the damaged part of a piece of the material, σ_u is ultimate stress.

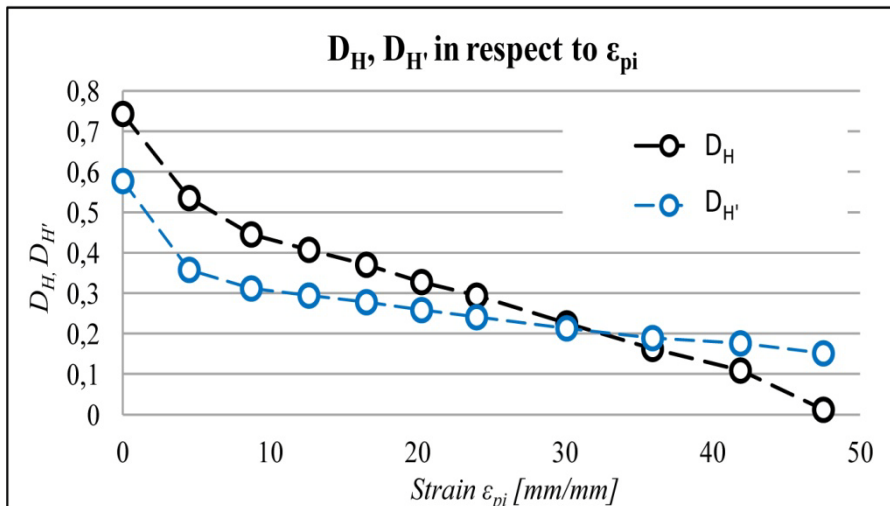The value of $D_{H'}$ calculated in the same area of plastic strain as value of D_H are lower (Figure 14) but better match the value of D_ε (Figure 15).

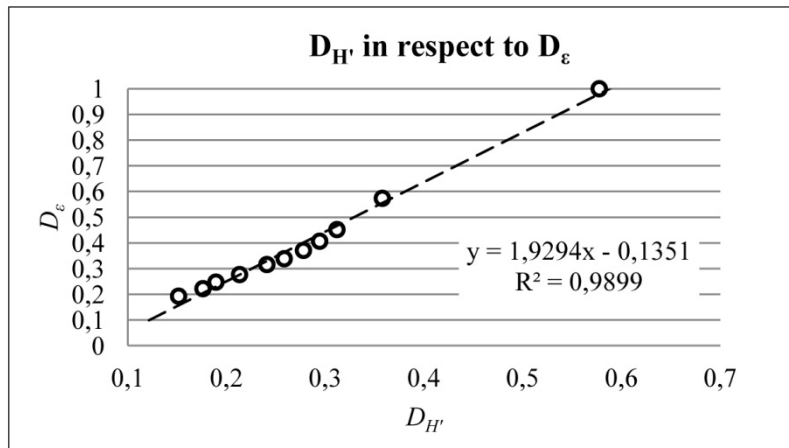***Figure 14. Damage parameter calculated form Equation (5) and (15) in relation to ε_{pi}***

Figure 15. Correlation between D_ε and $D_{H'}$

SUMMARY AND CONCLUSIONS

- It was shown that the hardness test can be a useful method to approximate the damage parameter D_ε.
- Damage related to debonding and cracking in NbC carbides doesn't change the trend of the material's hardness to increase with increasing the strain of tested Inconel 718.
- To obtain independent D_H and $D_{H'}$ from material strain hardening it is proposed to measure real hardness [11]. Real hardness measurement require annealing the material after the tensile test. For this reason there is no plastic hardening of the material and measured hardness should be more sensitive to material damage.
- Accuracy in determining σ_y, σ_u and the true strain-true stress curve is very important. This is so because these data are used to calculate D_H. To increase this accuracy a new tensile test using an extensometer should be done. Tensile test should be performed on a specimen that has a regular cross section in the reduction area.

ACKNOWLEDGMENTS

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