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The stress raisers effects on the materials mechanical characteristics, analyzed by local microhardness measurements

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Abstract. There have been few studies on the effects of stress raisers on the parts that are plastically deformed, at least into a certain extent of their volume. Such a situation may arrive near a stress raiser, when the peak stress value rises over the material yield stress limit. Some tensile tests are described in the paper, on flat aluminum specimens, with and without the presence of a stress raiser on their surface, namely a through frontal hole, at the center of their calibrated region. Some of the mechanical characteristics (yield limit, elongation at break, Young’s modulus) were affected by the stress raiser presence, but its ductile behavior and tensile strength were not. The effective values of stress and strain concentration coefficients were calculated using the Neuber’s rule, but the results may be considered as overestimated. The plastic strain enlargement in the specimen volume was also evaluated by measuring the Vickers microhardness values in the stress raiser vicinity. The tests results were shown that the plastic deformation is more pronounced for the measuring points that are closer to the hole’s edge; that fact was confirmed by the specimens appearance, after the material failure. A hardness values ratio is finally proposed as an evaluation of the effective stress concentration coefficient.

1. Introduction

The presence of various types of stress raisers, on the mechanical parts surfaces, leads to significant growths of local stress values; this fact is well known, and it was intensively studied, for the case of mechanical loading that are included into the elastic domain of material response. As a result, substantial database is available, containing nomograms and tables that could be used, in order to find the proper values of stress concentration coefficients, for stress raisers with different shapes and dimensions, grouped by the loading category. On the other hand, less study was made on the effects of stress raisers on the parts that are plastically deformed, at least into a certain extent of their volume.

Such a situation may arrive near a stress raiser when, for example, by multiplying the local stress values (that are clearly situated into the elastic domain of material deformability) with the theoretical concentration coefficient, the resulting values are above the yield stress limit of the material. In other words, some plastic strain may appear in that material volume, corresponding to some loading levels that normally lead only to elastic deformation of the respective material.

The present paper aims to establish an effective value of the stress concentration coefficient, for a part that is loaded in tension, above the yield stress limit of a material, using a calculus method that was proposed by Neuber. An analysis is further proposed, on the possible correlation between the stress raiser effects, into the plastic domain of the material part response, and the material local microhardness values, in the stress raiser vicinity.

2. Theoretical principles

The stress concentration coefficient α_k is used for quantifying the effects of a sudden change of geometry, loading or material nature, on the local stress distribution, into a somewhat loaded mechanical part. This coefficient must be understood as an ideal value, obtained by assuming a linear elastic material response, and being not influenced by the part material, or by the loading level; in fact, it depends on the stress raiser geometry and shape, and also on the type of loading. Is interesting to observe that, when multiplying the part (and the stress raiser) dimensions with a positive number, the stress concentration effects should not be modified!

It actually appears [1] that there are several factors, as local plastic strains, residual stresses, notch radius, part size, temperature, and some characteristics of material (grain size, work-hardening behavior) and of applied loading (static, cyclic, or impact) that may influence the extent to which the peak stress approach the theoretical value of $\alpha_k \times \sigma_{nom}$. As a consequence, the existence of some *effective* values must be assumed, for the stress concentration coefficients, and some experimental methods must be used in order to establish those values. Working this way is more necessary when one can evaluate that the peak stress, in the stress raiser vicinity, may overcome the yield limit of the part material determining, for the theoretical values of stress concentration factors, to be unusable.

A calculus method for such situations was proposed by Neuber [2], on the basis of the following relationship:

$$\alpha_{k\sigma} \cdot \alpha_{k\varepsilon} = \alpha_t^2 \quad (1)$$

This equation connects the *theoretical* value (α_t) of the stress concentration coefficient, and its *effective* values that refer to stresses ($\alpha_{k\sigma}$), and respectively to strains ($\alpha_{k\varepsilon}$); each of them is the ratio of the maximum to the nominal value of the respective physical quantity, corresponding to a certain point of the studied part volume. It must be observed that the maximum local strain value $\boldsymbol{\varepsilon_{max}}$ corresponds to the peak stress value $\boldsymbol{\sigma_{max}}$ (that appear as an effect of the stress raiser presence), and those values are connected (in principle) by a *non-linear* relationship, from the time when the yield stress limit of the material is exceeded.

By using the definition of effective stress concentration coefficients, the above equation leads to:

$$\sigma_{max} \cdot \varepsilon_{max} = \alpha_t^2 \cdot \sigma_{nom} \cdot \varepsilon_{nom} \quad (2)$$

One may understand that the value of theoretical coefficient α_t and that of nominal stress σ_{nom} are usually easy to establish, from calculus relations that are suitable with the real stress raiser shape and dimensions, and with the sizes of part loading and cross-section, respectively. In addition, the nominal strain value ε_{nom} can be found (corresponding to σ_{nom}) from the *stress-strain curve* of the part material (its knowledge is a precise requirement for the present method appliance). As a result, the right member of the equation from above represents a constant numeric value C, that can be calculated, for the real loading situation, so the equation can be written as:

$$\sigma_{max} \cdot \varepsilon_{max} = C \quad (3)$$

The equation can be graphically solved, in order to obtain the maximum values $\boldsymbol{\varepsilon_{max}}$ and $\boldsymbol{\sigma_{max}}$, by searching the intersection point of the material stress-strain curve, with the hyperbolic curve xy=C, when C is the numeric value that was calculated above. The coordinates of that point are even the maximum values of the two physical quantities, and their knowledge allow for the effective values of concentration factors to be calculated.

It should be noted that Neuber specifically developed this calculus method for two-dimensional shear of a prismatic bar, with sharp notches [3], but it is also applied, as a useful approximation, for different types of loading, especially those in plane stress condition. The method is important because it makes possible to estimate the local plastic strain values, avoiding the appliance of a complicated elastic-plastic analysis, using for example the finite elements method.

On the other hand, it is known that one can evaluate the enlargement of plastic strain, into a region of a loaded part, by measuring the microhardness values in many points of that region [4]. It was found that in such points the material becomes harder, in comparison with the situation in which it is elastically loaded; more than that, its microhardness values proportionally increase with the extent of plastic strain, in the respective region of the loaded part. As a consequence, one can imagine that, even for a part being loaded into the elastic domain of its material, when the stress concentration effect determine the stress values to overcome the yield stress limit of the material, some plastic strains appear, into the stress raiser vicinity, and so the local material microhardness values may increase. Such a phenomenon is proposed to be studied in the present paper.

3. Materials and method

The here described experiments were conducted using flat specimens for tensile testing (with a rectangular cross-section of 30×5 mm^2), from Al 2014 (AlCu4SiMg) aluminum alloy. The material response in uniaxial tension was firstly analyzed (see figure 1 from below): the metal has a ductile prevailing character, with a high level of elongation at break (30%), without a yield zone on the stress-strain curve, having a conventional yield stress limit at 120.58MPa, and the ultimate tensile strength at 244.34MPa.

A through frontal hole, at the center of the calibrated region of the specimens, is used as a stress raiser, having the diameter d=10mm, so one third of the specimen width H. For such a situation, the theoretic value of stress concentration factor, in tensile loading, is recommended to be established using the following calculus relation:

$$\alpha_t = 3.000 - 3.140\left(\frac{d}{H}\right) + 3.667\left(\frac{d}{H}\right)^2 - 1.527\left(\frac{d}{H}\right)^3 \quad (4)$$

With the present dimensional ratio d/H=1/3, the thoretical concentration coefficient α_t=2.3046 is obtained, available for the elastic domain of the specimen material deformability; that value may be adopted as α_t=2.3, and it will be used later into the Neuber's rule appliance.

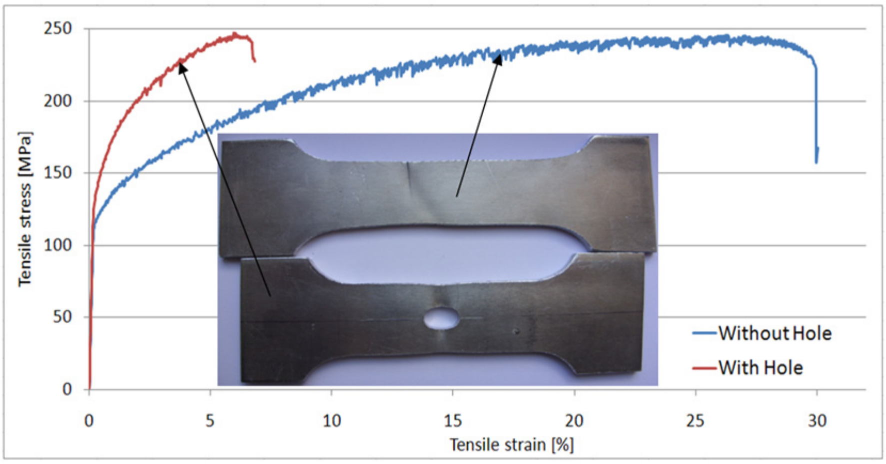

Figure 1. The stress-strain curves and the specimens' appearance, for samples with and without a stress raiser, in the form of a central through hole.

In order to firstly evaluate the specific behavior of the specimens, with and respectively without stress raisers, some tensile tests were also conducted on specimens having a through central hole, as were described above. Some rather surprising results were obtained (see figure 1): although the material ductile behavior was not changed, it was less prominent, the conventional yield limit increased to 143.7MPa, but the ultimate tensile stress was practically the same as for the specimens without a hole.

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An important difference was observed regarding the Young's modulus value – that was automatically calculated by the machine software, using the displacement data from the extensometer: the modulus increased at 89.98GPa, from the level of 73.57GPa, corresponding to the specimens without a stress raiser. It is very suggestive the superimposed presentation of the two stress-strain curves (see again figure 1), emphasizing the differences of deformability, from the two types of specimens: for those with a central hole, the elongation at break was only a quarter of that from the other category. This feature is also clearly shown by the image from figure 1, including one specimen of each type, at the moment of being extracted from the testing machine, after the specimen failure.

The following step of the present study was to observe the effects of the stress raiser presence on the local microhardness values of the specimen material; at this aim, a stepwise tensile test was conducted on a specimen with central hole. The stress-strain curves, corresponding to each step, are successively disposed in figure 2, being superimposed on the stress-strain curve that was obtained for a similar test and specimen, but conducted without stopping till the sample failure.

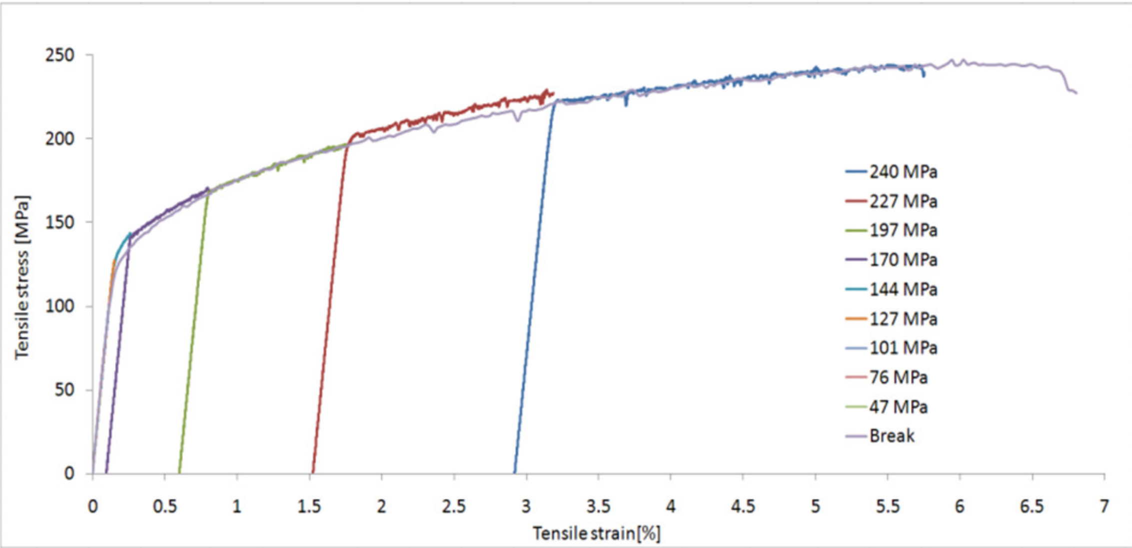


Figure 2. The stress-strain curves for all the loading steps successively placed corresponding to the process of material plastic deformation and superimposed on the non-stop testing curve ("Break").

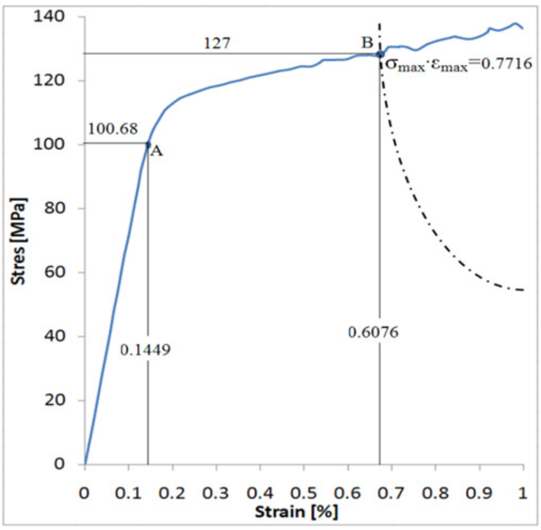


Figure 3. The Neuber's rule appliance.

The numerical values (in MPa) that are indicated for every curve represent the maximum stress level that was reached in the respective step of the test. The first value of 47MPa was established such that it represents one third of the conventional yield limit, for a specimen with a stress raiser on its surface. After the appearance of material plastic strain (for the step with σ_{max}=144 MPa), each of the following steps of tensile test was started, on the strain axis, at the plastic strain corresponding to its preceding step. This presentation form clearly shows that the successive loading steps were correctly conducted, such that their stress-strain curves cover to a great extent the previous curve, corresponding to the non-stop tensile test.

4. Calculus of effective stress and strain concentration factors

As it was presented above, the Neuber's rule gives a method for establishing the effective values of the concentration factors $\alpha_{k\sigma}$ and $\alpha_{k\varepsilon}$, on the basis of the preceding known stress-strain curve for the material of the studied part, at the respective loading type. For the present situation, it was also shown that a value α_t=2.3 was adopted, for the theoretical concentration coefficient.

As a calculus example, the stress and strain *nominal* values were chosen, from the real stress-strain curve (see figure 3), as σ_{nom}=100.68MPa and ε_{nom}=0.1449%, and as a consequence Equation (2) gives $\sigma_{max}\cdot\varepsilon_{max}$=0.7716; the coordinates of the intersection point for the two graphs are the effective stress and strain maximum values, namely σ_{max}=127MPa and ε_{max}=0,6076%.

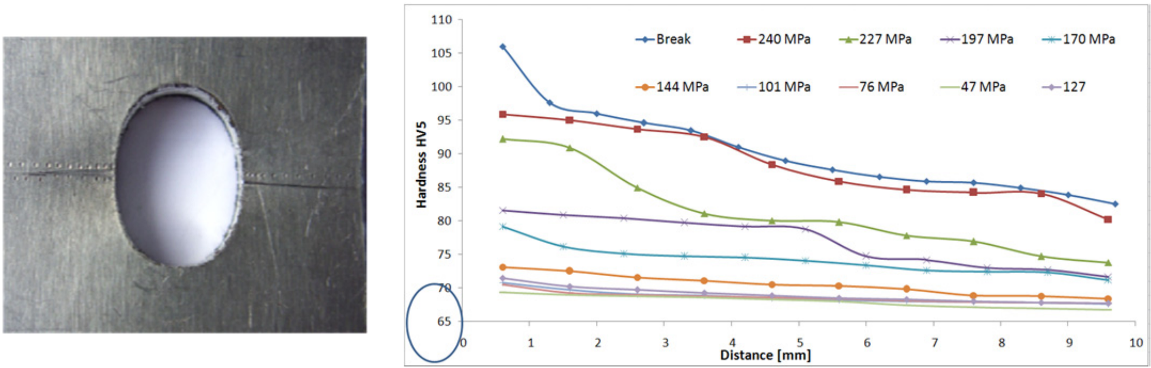
With these values, the effective stress and strain concentration coefficients values are:

$$\alpha_{k\sigma}= \sigma_{max}/ \sigma_{nom} =127/100.68=1.26 \quad \text{and} \quad \alpha_{k\varepsilon}= \varepsilon_{max}/ \varepsilon_{nom} =60.76/14.49=4.19$$

One can observe the important magnitude of the strain concentration effect, in comparison with the low stress coefficient value. It should be noted again that the above obtained peak values σ_{max}·and ε_{max} represent the estimated stress and strain local values, into the stress raiser vicinity. On the other hand, one may understand that the coordinates of each point from the stress-strain curve, for any specimen and any loading type, are some average conventional values, obtained by a sort of integration from the stress and strain values acting in all the points of the specimen material. As a result, one may consider that calculus method as a conventional one, which should be used with precaution, and only for ductile materials, that are characterized by important amounts of plastic deformation.

5. Microhardness values variation, in dependence with the plastic strain enlargement

After each of the above described loading steps, the Vickers microhardness values were measured in ten collinear points from the stress raiser vicinity, placed on segments that were perpendicular to the specimen longitudinal axis (see figure 4a); those measuring points were spaced at 1mm each, starting at 0.6mm from the edge of the central hole, and ending at the distance of 9.6mm from that edge. All the obtained microhardness values are presented in figure 4b, for all the loading steps, on the form of some graphs of material hardness variation, in dependence with the distance from the hole's edge.



(a) (b)

Figure 4. The placement of measuring points the microhardness values variation, in dependence with the distance from the stress raiser edge.

One can observe the local increase of material hardness, with the increase of maximum stress level (and of the plastic deformation enlargement) of the loading steps, and also with the placement of the measuring point, closer to the edge of the hole. The differences between the hardness values, in the points from a same segment (and respectively from a certain loading step) is more significant beginning with the load step having the maximum stress level at 144MPa, namely at the yield conventional limit of the material (that was obtained for specimens with stress raiser, tested without stopping).

The graph from figure 5 illustrates the material local hardness dependence with the maximum stress level of the loading steps, for the measuring points that is placed at the minimum distance (0.6mm) from the edge of the specimen central hole.

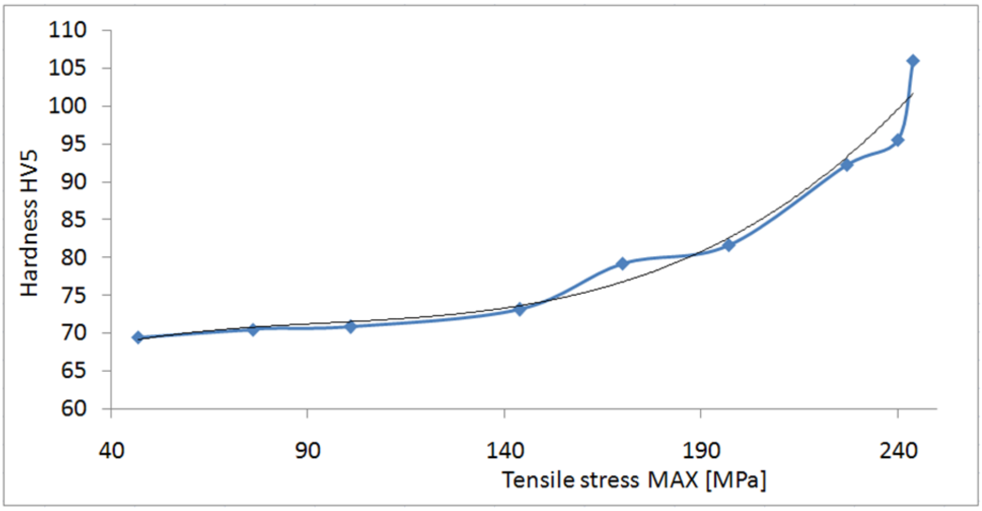


Figure 5. The increase of microhardness maximum local values, close to the stress raiser edge, with the increase of maximum stress level of tensile loading steps.

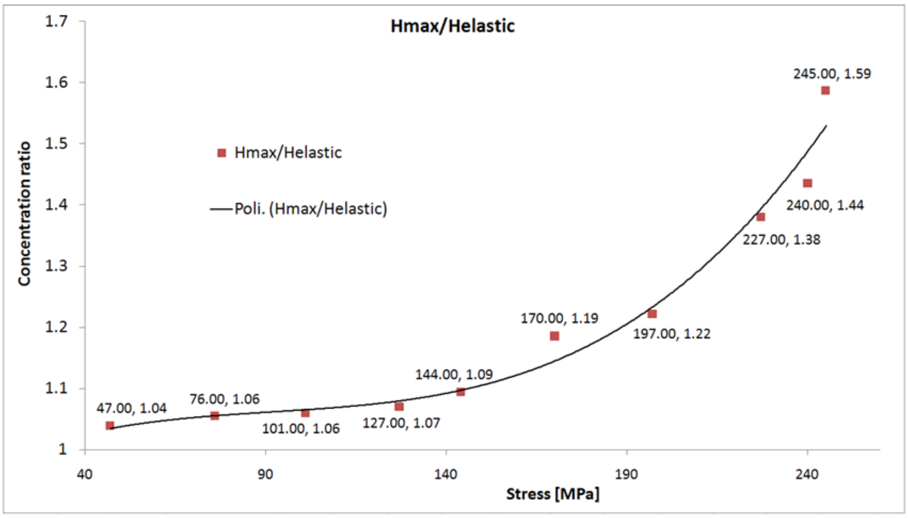


Figure 6. The variation of H_{max}/H_{el} ratio, with the increase of maximum stress level of tensile loading steps.

One can assume (as it was also shown in figure 4a, by the appearance of the specimen after failure) that the hardness growing rate increased, together with the plastic strain enlargement, when the maximum stress level of loading steps is closer to the material tensile strength. On the other hand, it must be noted that those stress values (from figure 5) are conventionally obtained, by the machine software, as it was stated above, and they are not coincident with the effective local stress values, in the stress raiser vicinity.

The effects of the stress raiser presence on the specimen surface may also be illustrated (see figure 6) by the variation of a hardness values ratio (C_H=H_{max}/H_{el}), at the increase of maximum stress level of the loading steps; H_{max} is the maximum local hardness value, for each of the loading steps, and H_{el} is the hardness value (66.8 HV5) that was measured on a specimen loaded in tensile, into the elastic domain of its material deformability.

The results shown on this graph for the hardness values ratio could be assumed as some more realistic values of the effective stress and strain concentration effects, having in view the probable overestimation of those coefficients, as a result of Neuber's rule appliance.

6. Conclusion

The presence of a through frontal hole, at the center of the calibrated region of flat tensile specimens, modifies the mechanical response of the tested material, and the values of yield limit, elongation at break, and Young's modulus; the tensile strength seems to be not affected. The possible premature appearance of plastic deformations in the stress raiser vicinity, as a result of local stress increase over the yield limit of the material, may be detected by measuring the local microhardness values in the stress raiser vicinity. The tests results were shown that the plastic deformation is more pronounced for the measuring points that are closer to the hole's edge, and that fact was confirmed by the specimen appearance, after the material failure. One may assume that the hardness values ratio C_H=H_{max}/H_{el} could be used as an effective stress concentration coefficient, for the practical situations when the Neuber's rule seems to give some overestimated values for the stress and strain effective concentration factors.

7. References

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