Sensitivity to defects and fracture mechanics for metallic materials under fatigue loading

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ABSTRACT: *The work presents a three dimensional graphical aid in which the fatigue limit of notched components is plotted as a function of the notch stress concentration factor* K_{tg} *and the equivalent notch length* $(\alpha^2 \cdot a+a_0)$ *to* a_0 *ratio, a and* a_0 *being the notch depth and the El Haddad material parameter respectively, while* α *is a shape coefficient. The diagram is seen to fit with the same slope the experimental behaviour of the notches, thought of like short or long cracks respectively.*

INTRODUCTION

The different behaviour of blunt and sharp notches has been known for a long time [1,2]. It is generally described in the so-called Frost-Miller diagram by means of two curves drawn by keeping constant the notch depth “a”. On the left hand side, the fatigue limit of the notched component (given in terms of nominal stress referred to the gross section) is $\Delta\sigma_{g,th}=\Delta\sigma_0/K_{tg}$, $\Delta\sigma_0$ being the fatigue limit of the smooth specimen under the same load conditions and K_{tg} the theoretical stress concentration factor referred to the gross area: the fatigue limit is fully controlled by the elastic peak stress range $\Delta\sigma_{pe}$. On the right hand side, the notch behaves as a crack with the same depth “a” and the fatigue limit is controlled by Linear Elastic Fracture Mechanics (LEFM) according to the expression $\Delta\sigma_{g,th}=\Delta K_{th}/\sqrt{(\pi a)}$, where ΔK_{th} is the threshold value of the stress intensity factor range of the material under the same load conditions. The diagram makes it possible to determine a characteristic K_{tg}^{*} value, which ideally separates the regions of applicability of the two criteria. Very accurate experimental results [3] confirmed that, beyond the branch point located in correspondence of K_{tg}^{*}, there will exist two different fatigue limits: the former is related to cracks that nucleate but are unable to propagate; the latter, on the contrary, is related to cracks that nucleate and then propagate. Beyond K_{tg}^{*}, the two curves define the region of the so-called “non propagating cracks”. Nisitani and Endo [3] demonstrated that, when $K_{tg} < K_{tg}^*$, the fatigue behaviour is not rigorously constant while varying the notch depth “a”. More precisely, as the notch depth “a” decreases, for the same K_{tg} the fatigue limit increases.

As it is well known, the described fatigue behaviour is schematic, a gradual transition from the peak criterion (controlled by K_{tg}) to the field criterion (controlled by ΔK_{th}) really taking place.

Recently, the authors proposed a new log-log diagram able to describe the transition from usual notch-based Mechanics to LEFM and separated clearly the notch sensitivity and the defect sensitivity [4]. Such a diagram refers to the case of a notch with parallel flanks centred in an infinite plate subjected to a remotely applied tensile load. The diagram correlates the fatigue limit variation to the variation of the notch size, the notch being scaled in geometrical proportion in order to assure the constancy of K_{tg}. It also shows that, for constant notch depth “a”, material and load conditions, a variation of the notch acuity (due to variations of the notch tip radius) modifies the fatigue limit only for K_{tg} lower than K_{tg}^*, that is when the fatigue limit is controlled by the elastic peak stress value. Schematically, the central zone located between a_o and a^* is fully governed by LEFM (so that the fatigue limit coincides with that of a component weakened by a crack having the same size). When $a>a^*$, the notch sensitivity is complete, due to the achievement of the value ρ^* for the notch tip radius; on the contrary, when $a<a_o$, the defect sensitivity vanishes.

In reality, as above said, the transition from zone to zone happens gradually, so that the material exhibits a defect sensitivity in the neighbourhood of a_o and a notch sensitivity in the neighbourhood of a^*. The two sensitivities are correlated to two different length parameters, a_o and a^*, and to neglect them results in different estimates, which are either into a safe direction or into an unsafe direction, as widely discussed in the past [4,5]. The two length parameters are correlated to each other by means of the simple expression $a^*/a_0 = K_{tg}^2$ [4,6].

The above mentioned diagrams actually represent two sides of the same phenomenon, so that they can be synthesised in the three-dimensional diagram shown in figure 1 [7]. Atzori-Lazzarin’s 2D diagram can be easily obtained by intersecting the 3D diagram with a vertical plane, parallel to the a/a_0 axis. Such a diagram has been verified by using a large number of experimental data related to different materials, notched specimens and loading conditions, as shown in figure 2 [8].

This immediately gave the possibility to assume the length a_0 as a through-thickness equivalent crack in an infinite width plate, statistically correlated to the length of non-propagating cracks which are present at load levels close to the fatigue limit [9].

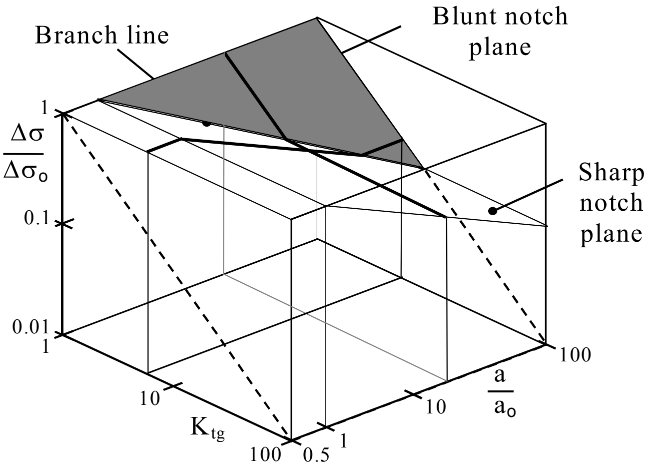

Figure 1: Fatigue limit of a notched component given as a function of the stress concentration factor K_{tg} and the notch depth ”a”.

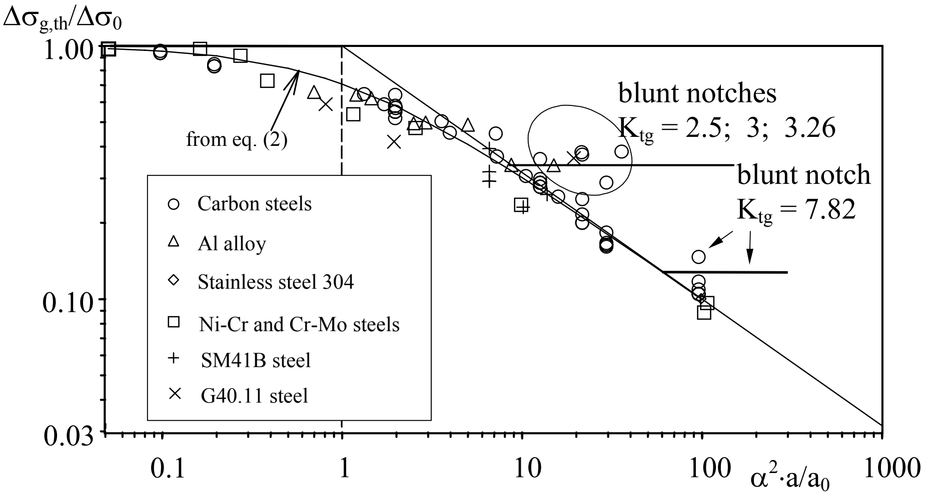

Figure 2: Fatigue strength of specimens containing defects and notches [8]. The factor α was obtained by means of FE analyses, the real notch being modelled as a crack with the same depth.

Suppose a_0 dependent only on the material and not on the geometry of the notched component. Moreover, assume that, independently from the K_{tg} value, a crack with a length comparable with a_0 to be always present at the notch tip in correspondence of the fatigue limit. These hypotheses enable us to simplify the three dimensional diagram shown in figure 1 and, consequently, the two-dimensional diagrams which can be obtained from it by means of planar sections parallel to the K_{tg} and a/a_0 axes. The main aim of the paper is to demonstrate that the so-called "short crack" behaviour can be fitted with the same slope typical of the "long crack" behaviour and that in such a way the Frost diagram remains valid also for short cracks. Then the new diagram proposed here will be verified by means of several experimental results taken from the literature, related to different materials, specimen geometries and loading conditions.

A UNIVERSAL THREE DIMENSIONAL DIAGRAM

The law $\Delta\sigma_{g,th}/\Delta\sigma_0=f(a/a_0)$ displayed by the 3D diagram of figure 1 has to be considered as a simplified representation, in that the actual short crack behaviour (already shown in figure 2) does not appear. It is well known, in fact, that in the vicinity of a_0 the experimental fatigue limits deviate from both the plain specimen behaviour and the sharp notch behaviour. The actual trend is well fitted by a well known expression due to Topper [10]:

$$\Delta K_{th} = \Delta\sigma_{g,th} \cdot \sqrt{\pi \cdot (a + a_0)} \qquad (1)$$

In the case of real components it is necessary to introduce a shape coefficient α and modify eq.(1) in the form [8]:

$$\Delta K_{th} = \Delta\sigma_{g,th} \cdot \sqrt{\pi \cdot (\alpha^2 \cdot a + a_0)} \qquad (2)$$

In eq.(2) $2(\alpha^2 \cdot a+a_0)$ can be thought of as the length of an equivalent crack centred in an infinite plate and subjected to the same gross nominal stress applied to the real component.

As soon as one reports the equivalent notch depth, equal to $(\alpha^2 \cdot a+a_0)$ [9], instead of the real notch depth "a", the three dimensional diagram simplifies as shown in figure 3, where the plateau at the top level disappears. The two-dimensional diagrams modify consequently: in the Frost-Miller diagram the position of the horizontal line will vary in the vertical direction, whereas in the Atzori-Lazzarin diagram the horizontal line previously drawn in the short crack zone will disappear. Now there exist only one transition zone in each diagram.

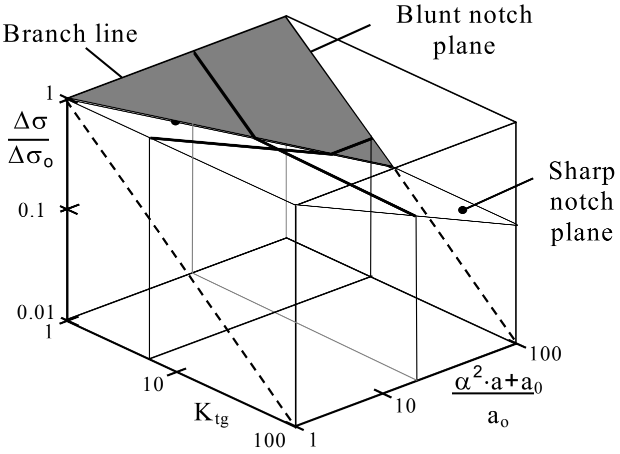

Figure 3: Fatigue limit of notched components by using a notch equivalent size equal to ($\alpha^2 \cdot a+a_0$).

EXPERIMENTAL VALIDATION

The degree of accuracy of Eq. (2) was checked by means of several fatigue test data taken from the literature [3,6,11]. Original papers reported accurately the material properties, the specimen geometries and the loading conditions. The same data base was already reported and used in [8] in order to validate Atzori-Lazzarin's diagram.

In this work the experimental data will be plotted both in the Atzori-Lazzarin diagram and in the Frost-Miller diagram. Afterwards, both diagrams will be presented by using non-dimensional coordinates, in order to make more evident the experimental behaviour close to the knee point, that is at the intersection between the sharp notch and the blunt notch behaviour.

Figures 4 and 6 compare theoretical and experimental behaviour in the Atzori-Lazzarin and Frost-Miller diagram respectively. Figures 5 and 7 show the corresponding validations close to the knee point. It is evident that all the available data define the same trend and that there exists a good agreement between the theoretical predictions and the experimental evidence.

It is interesting to note that in figures 5 and 7 the experimental results show a little deviation around the knee point, thus following quite closely the cut-off behaviour predicted by the asymptotic slopes.

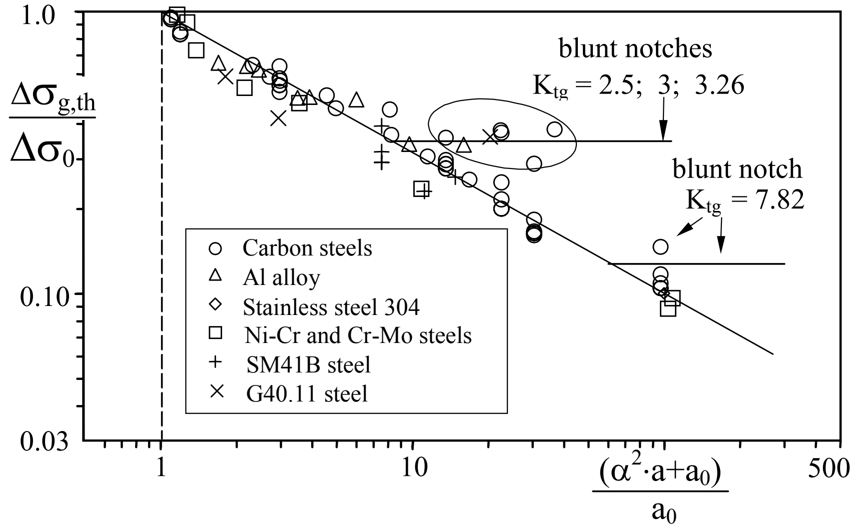

Figure 4: A comparison between equation (2) and the experimental data.

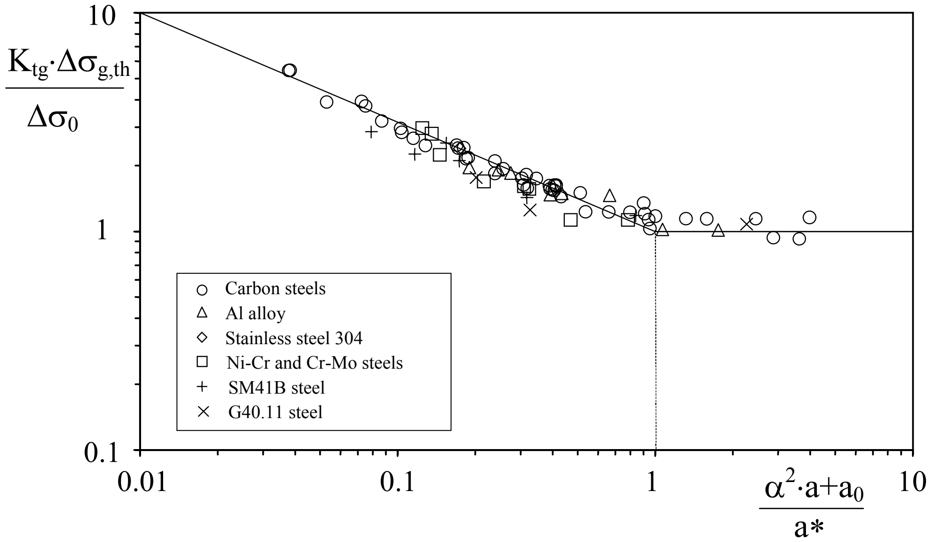

Figure 5: Transition between the sharp and blunt notch fatigue behaviour, the equivalent notch size being normalised with respect to a*.

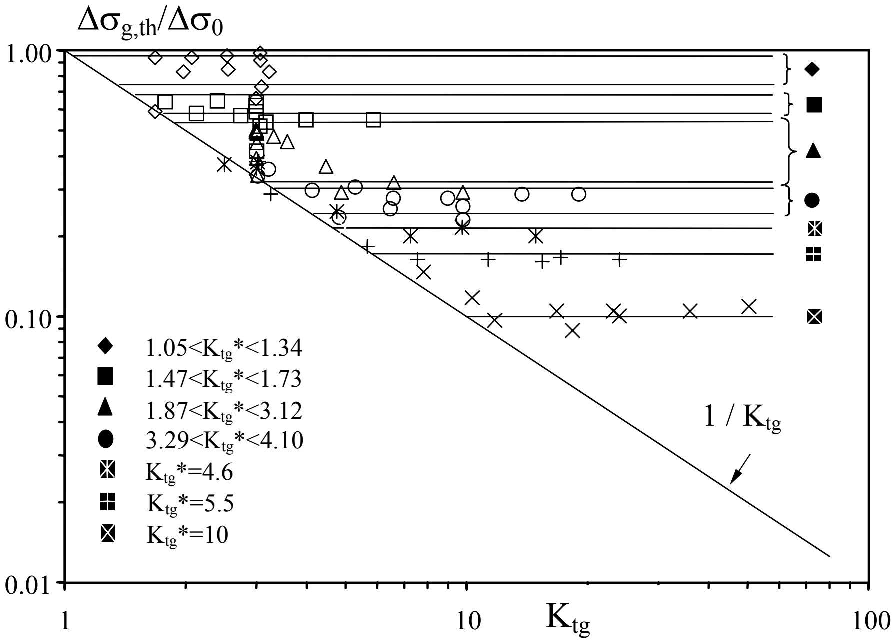

Figure 6: Frost-Miller diagram for the available experimental results (equivalent notch depth equal to $\alpha^2 \cdot a + a_0$).

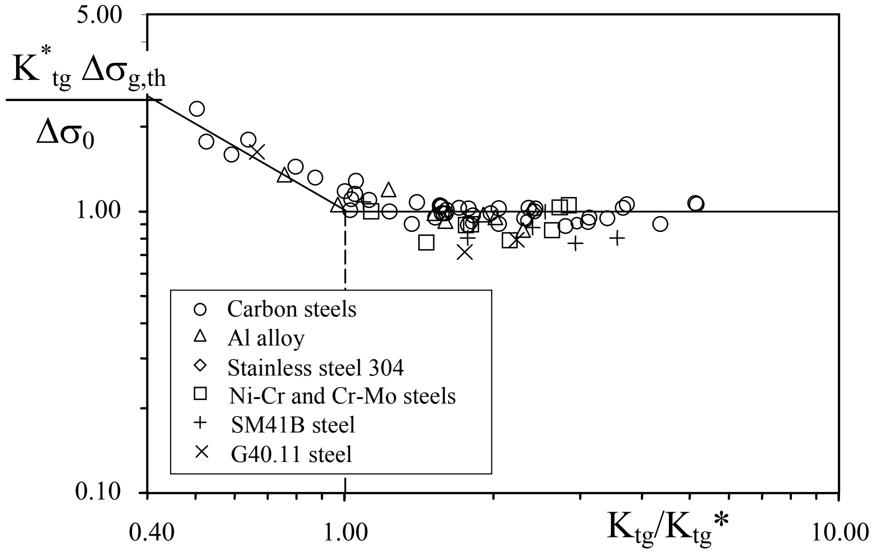

Figure 7: transition between sharp and blunt notch fatigue behaviour versus the variation of the notch acuity.

CONCLUSIONS

A three dimensional diagram has been presented, where the fatigue limit of notched components of different shape and size has been plotted versus two parameters: the notch stress concentration factor and the *equivalent* notch size, of which an *ad hoc* definition has been given here. The diagram, reported in a schematic form in figure 1, clarifies the different fatigue behaviour of blunt and sharp notches, as well as the position of the branch line that ideally separates them. The diagram has been validated by means of several experimental results taken from literature, referred to different materials, specimen geometries and loading conditions. As a result, the asymptotic slopes, representing blunt and sharp notch behaviour, are seen to fit quite closely the experimental data even near to the branch line, showing a cut-off behaviour in the transition zone.

REFERENCES

1. Frost, N.E., Marsh, K.J., Pook, L.P. (1974) *Metal Fatigue*. Oxford University Press, Oxford.
2. Smith, R.A., Miller, K.J. (1978) *Int. J Mech. Sci.* **20**, 201.
3. Nisitani, H., Endo, M. (1988) *ASTM STP 924*, 136.
4. Atzori, B., Lazzarin, P. (2001) *Int. J Fracture* **107**, L3.
5. Taylor, D. (1999) *Int. J Fatigue* **21**, 413.
6. Ting, J.C., Lawrence, F.V. (1993) *Fatigue Fract. Engng. Mater. Struct.* **16**, 93.
7. Atzori, B., Lazzarin, P. (2001) *A three dimensional graphical aid to analyze fatigue crack nucleation and propagation phases under fatigue limit conditions*, Int. J Fracture, submitted for publication.
8. Atzori, B., Lazzarin, P., Meneghetti, G. (2001) *Fracture mechanics and notch sensitivity*, Fatigue Fract. Engng. Mater. Struct., submitted for publication.
9. Atzori, B., Lazzarin, P., Meneghetti, G. (2002). In: *Proceedings of the 8th International Fatigue Congress*, Stockholm, Sweden.
10. El Haddad, M.H., Topper, T.H., Smith, K.N. (1979) *Eng. Fract. Mech.* **11**, 573.
11. Du Quesnay, D.L., Yu, M.T., Topper, T.H. (1988) *J Test. Eval.* **4**, 375.