Review of Doctoral Thesis

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Title: Fracture Toughness Analysis of Automotive Steel in Plane Stress Reviewer:
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General description

The aim of the thesis is determination of the fracture toughness of thin sheets of automotive steels using the method of essential work of fracture. The steels involved are: a dual-phase steel DP450, and an interstitial-free (IF) steel. Tensile tests were made on standard tensile specimens and fracture toughness tests were carried out using double edge notched tension specimens (DENT), the thickness of specimens being less than 1 mm. Beside introduction and conclusion the thesis is composed of eight chapters which cover problems encountered in the area of automotive manufacturing.

Chapter 2 deals with the objective and aim of the research work and in the Chapter 3 the author presents fundamentals of fracture mechanics: linear elastic and elasto-plastic.

The essential work of fracture is the subject of Chapter 4. This work is that part of the total energy of fracture which is consumed by the fracture process zone. The rest of the total energy of fracture is consumed in the formation of the outer plastic deformation. Tests on the essential energy of fracture also make it possible to determine several parameters which can be used in fracture analysis, e.g. the total elongation at fracture vr or the crack tip opening displacement (CTOD) $\hat{o}c^{e}$. The author also indicates in this chapter how the specific essential work of fracture can be related to the J integral and how to extend the essential work of fracture concept to the mode Il loading and the mixed mode (I + Il) loading.

Chapter 5 deals with fracture forming diagrams. Presented in this chapter are schematic representations of the forming limit diagram, forming limit curve, fracture forming limit and shear fracture forming limit curve, as taken from literature. Strains in plane stress prevailing conditions are also briefly discussed.

The subject of Chapter 6 refers to materials and methodology used in the research. The author describes in some details the structure and mechanical properties of both steels, namely DP450 and IF, used in the tests. The chemical composition of these steels was determined by the use of a spark atomic emission spectrometer and characterization of their microstructures was made by the use of electron back scattered diffraction technique. Tensile specimens were taken from a rolled sheet in three directions with regard to the rolling direction, namely 0 , 45 , and 90 and they were monotonically loaded up to fracture. During loading the displacements were measured by means of inbuilt extensometers in longitudinal and transverse directions. The strain rate at the tests was è =0.002 s- . Essential work of fracture tests were carried out on (i) double-edge notched tension specimens in mode I loading, (ii) double-edge notched shear specimens in mode Il loading, and (iii) staggered double-edge notched tension specimens in mixed loading. In these tests the crosshead speed was I mm/min. The specimens were manufactured, including notch starters, by two different technologies, these being high intensity laser and electrical discharge machining. Specimens with notch starters were pre-cracked by high-cycle fatiguing to obtain a crack of at least 0.2 mm in length on both sides of the ligament. A digital image correlation with post-processing was used to obtain a full-field strain distribution at the surface. In order to apply electron backscatter diffraction to specimens from DP450 and IF steels for analyzing their grain size, crystallographic orientation, and other parameters, specimens of a rectangular shape of 15 x 10 mm were first grinded, then mechanically- and electrolytically polished, and finally they were placed inside the scanning electron microscope with EBSD to become a subject of the EBSD analysis before and after the EWF tests. A hole expansion and Nakajima tests are also described in this chapter.

Chapter 7 is devoted to the results and discussion of EWF tests. The experimental procedure of the EWF method consists of testing up to fracture a series of DENT specimens with different ligament lengths and record the load — displacement curves. After that the energy under the load-displacement curves, W/ , is calculated, divided by the initial cross section area and plotted as a function of the ligament length. By a linear regression of the data the specific essential work of fracture we is obtained in the intercept. Similarly, displacements at fracture vrare plotted against ligament lengths L. By a linear regression of these data the crack tip opening displacement is determined in the intercept.

The results of the tests are presented for notched specimens as well as for pre-cracked specimens of both steels.

The content of Chapter 8 is connected with metallographic and fractographic examination of both steels used in the investigations with the aid of (i) electron back scatter diffraction method in metallography and (ii) scanning electron microscope in fractography. The results are richly illustrated.

Chapter 9 is concerned with strains during EWT tests of both steels. It is shown that plastic strains are limited to the ligament area, the shape of the plastic zone being slightly elliptical. In the necking zone the local strains are significantly higher than in the outer plastic zone. After complete yielding the strains in the vicinity of notches become higher than those in the rest of the ligament and, as the crack propagates, the stress patterns intersect. During EWF tests a large portion of the ligament is in plane strain. This is referred to DP450 steel. In the case of IF steel the shape of plastic deformation zone is slightly different. It is also elliptical but the major axis is in the loading direction. The development of major and minor strains during EWF tests is shown for both steels in modes I and Il, as well as in mixed mode 30 ^{0}. Dependences of the equivalent strains on the triaxiality parameter are also presented for both steels. As for the results of the hole expansion tests it was found that at the zero clearance the hole expansion ratio of the IF steel is about three times higher than that for the DP450 steel. At the maximum clearance 0.4 mm this factor is even higher and it exceeds the number six.

Minor remarks

There is a discrepancy in sub-chapter numbering (page 129: it should be 9.1.1, page 133: it should be 9.1.2) and repeating the same figure number for two different figures (in the beginning of page 136: it should be Figure 9.15). These are, however, minor issues which can be easily corrected.

Specific comments and questions

l . When doing EWF tests on laser-notched DENT specimens from DP450 steel the author obtained maximum stresses which exceeded the yield stress by 67% to 84% depending on the ligament length. They exceeded even the tensile strength. For specimens from IF steel the maximum stresses exceeded the yield stress even more: by 120% to 140%. The maximum stresses also markedly exceeded the tensile strength. It is argued that similar stress states (dominantly plane stress) in the ligament are maintained in all ligaments when the maximum stress in the ligament falls to the range 1.15 - 0.9 ou for DP450 steel, where ou is the ultimate tensile strength and to the range 1.1 0.9 for IF steel, where is the average of omax. Could the author explain this and also the fact that maximum stresses in the ligaments notably exceed the ultimate tensile strength?

2. How did the final fracture of specimens look like? What was the contraction of the ligament? Was the fracture plane tilted with regard to the specimen plane?

3. The smallest magnitudes of both the specific essential work of fracture and the crack tip opening displacement were found for pre-cracked specimens when using extensometers. So that they are relevant for choosing the most appropriate values of manufacturing parameters. Could the author estimate to what extent may these magnitudes be substituted by magnitudes obtained on notched specimens with displacements measured by the crosshead movement without causing a considerable un-conservativeness of the result?

4. From the results of the EWF tests it is seen that before fracture the ligament is fully plasticized. How did the author explore a possible role of the loss of plastic stability prior to the final separation?

5. In the areas of utilization of classical fracture mechanics the knowledge of fracture toughness makes it possible to predict fracture of a component. Such a possibility does not seem to be provided by the concept of the essential work of fracture. As a matter of interest, how concretely is the knowledge of specific essential work of fracture (determined experimentally) used in typical applications?

6. Has the author attempted to transform the fracture toughness based on the specific essential work of fracture we to the J integral Ji?

Conclusion

The thesis presents new original experimental results of a great importance concerned with the fracture toughness of thin sheets of two automotive steels. The fracture toughness is considered and measured in terms of the essential work of fracture. The thesis is well written and structured. The author has shown a fruitful publication activity: he is the main author or co-author of eight papers, including six papers in high impact factor journals.

In summary, my conclusion is that the high quality of the research work of the author provides an evidence of his high qualification and readiness for the scientific work. The results he obtained can be a stimulus for the future research in this field. Therefore, I strongly recommend that the author is awarded the doctoral degree.

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