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Fatigue endurance of weldable steel STN 41 1373 by ADINA

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Abstract. The tested material — steel 11 373 was subjected to experimental fatigue tests, by which the dependence of fatigue crack propagation velocity on the applied value of the stress intensity factor amplitude ΔK_{apl} was obtained. Measured results were compared to the dependence of fatigue crack propagation velocity obtained by simulation in the finite-element software ADINA. Compared results show very good correlation with low error variance in the results.
Keywords: fatigue test, cracks propagation, method of finite elements, fatigue cracks, fatigue strength
Universal Decimal Classification: 539.43

1. Introduction

Nowadays, a large number of commercial computational programs are available which allow analyzing fatigue crack propagation. There are many papers dealing with propagation of main crack from global viewpoint and its influence on functionality of given mechanical parts [1, 2, 3]. The aim of this paper is to take a closer look on the damage initialization and its propagation in the material on the microstructure level. ADINA is a FEM system suitable for solving large variety of problems. Reliability of modelling is in greater rate supplied by the accuracy in material properties, boundary conditions and last but not least in modelling proper material behaviour at crack tip, including singularity if zero radius is presented. Linear and nonlinear fracture mechanics analysis can be performed with ADINA system including computation of conservation criteria (J-integral, energy release rate) in 2D and 3D finite element models. Two different numerical methods are available for the computation of the conservation criteria — the line contour method and the virtual crack extension method. However, the fracture mechanics allows performing an analysis with only one crack. The crack line or surface can be located on the boundary or inside the finite element model.

ADINA is thus fully capable of solving fracture mechanics problems in general with large amount of options in stack under various loading conditions or thermal conditions utilizing wide variety of material models. Also there is the ability to model rupture criteria and thus, it is possible to model material damage caused by cavities or impurities and its progression under cyclical load or under creep conditions. When more defects or stress concentrators are present in the material, it is convenient to use the mechanics of material damage which was used in the paper. In the analysis, various environment effects might be included like thermal dependence of the material, time dependent effects like creep, and material fatigue, which makes this analysis universal. It allows to model special conditions for material damage and using multi-linear plastic material model, also the hysteresis of the material under cyclical load can be simulated. The result of the solution is not only the crack propagation in the structure, but also the stress and strains which are essential to determine the velocity and direction of crack propagation.

2. Experimental material

Soft low-carbon cast steel STN 41 1373 without heat treatment was used as an experimental material. Such steel is used for building transport machinery and devices, for chosen mechanical parts, parts of constructions, frames and suspension of rail vehicles and other transport vehicles. Chemical composition and selected material properties are shown in Tables 1 and 2. Microstructure of the tested steel is depicted in Fig. 1.

Table 1

Chemical composition of steel STN 41 1373 (mass. %)

	C	Mn	Si	P	S
STN 41 1373	0.15	0.93	0.44	0.01	0.009

Table 2

Selected material properties of steel STN 41 1373

Re [MPa]	Rm [MPa]	A_5 [%]	Z [%]	E [MPa]	HRB
235	372	24	57	2.06×10^5	132

3. Experimental part

The dependence of fatigue crack propagation velocity for applied value of the stress intensity factor amplitude, $da/dN = f(\Delta K_{apl})$ was determined for the examined material STN 41 1373. The experimental fatigue tests were performed first and using finite-element software ADINA, the simulation of crack propagation velocity was done and dependence on intensity factor amplitude obtained.

Fig. 1. Microstructure of steel STN 41 1373, magn. 100x, etch. 1% Nital

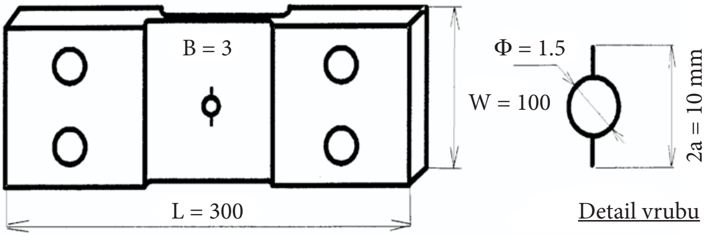

Fig. 2. Shape and dimension of specimens

The fatigue tests were realized on the pulse device connected to test device EDZ 100 DYN. Experimental specimens (Fig. 2) in the location of fatigue crack propagation were of area 100×3 mm and had primary notch of the initial length 2a = 10 mm. With the shape, the specimens are fulfilling the condition of initiation, propagation and rest of fatigue crack under cyclic loading and also the condition of plane stress inside the specimen. The loading was realized under the following conditions: f = 10 Hz, temperature T = 20 ±10°C, asymmetry of the loading cycle R = 0.35; 0.45; 0.5; 0.6.

In regular time intervals, the surface crack length 2a and the number of loading cycles were measured. For processing of the experimental results, the starting point was the dependence of crack length 2a on the number of cycles N. From the dependence 2a — N, the dependence of fatigue crack propagation velocity da/dN on the crack length 2a was numerically obtained and also the dependence of fatigue crack propagation velocity da/dN on the applied value of stress intensity factor amplitude ΔK_{apl} was numerically obtained (Fig. 3) [4].

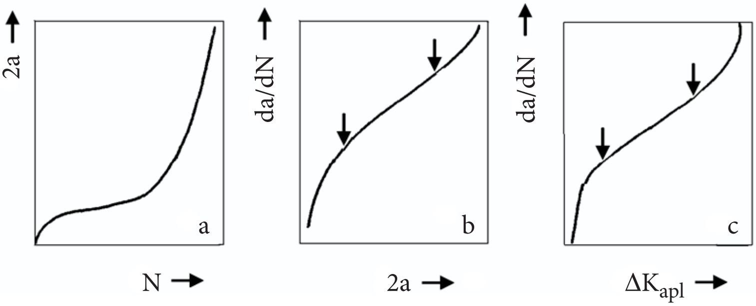

Fig. 3. Method of experimental results processing

Using the finite-element program ADINA, a fatigue test was simulated for the given material — steel STN 41 1373. It was a low cycle fatigue and a model of corresponding test bar was used on which the experimental tests were performed. The test bar shows double symmetry and this knowledge was effectively used to reduce the model and only one quarter of the bar together with boundary conditions for symmetry was modelled. The loading was given the same as in the case of experiment as a cyclic stress with maximum equivalent to force 100 000 N and with asymmetry of the loading cycle R = 0.35; 0.45; 0.5; 0.6. The microstructure of the material represented by tightly packed grains was modelled by using the finite-element software ADINA. The geometry of each grain was modelled by Pro/Engineer software and it was exported as a plain surface in IGES file to ADINA, where a 2D dynamic analysis was performed. For the analysis, each surface representing individual grain of the microstructure was discretized using finite element mesh. In this case, quadratic elements were used, which means that unknown quantities were approximated by a polynomial of the second order inside of each element. The only factor limiting the fineness of the mesh is of course available hardware, but for extremely fine mesh, a lower numerical stability can be expected. Multilinear plastic material model was used in the simulation. Quadratic elements were used to discretize the model. In the area of crack propagation and in the vicinity finer mesh was produced in order to achieve higher accuracy. It turned out that the quality of the mesh has significant influence on the accuracy of the results. The material is modelled as an ideal elastic-plastic material with no defects or imperfections, except for the defined initial crack. Afterward, the stress-strain curve was imported into ADINA and allocates each element. The analysis was performed by using large deformations and large displacements incorporated into the mathematical model.

Each grain was considered as a standalone body and contact conditions between each pair of grains were implemented. In the microstructure model, a stress concentrator was made. Issue of damage propagation of materials in the microstructure is considerable demanding for the exact model. It is because some effects are manifested in the atomic structure and they can be described by the continuum mechanics only by certain optimal conditions or on the base of experimental measures. Meshed model is shown in Fig. 4

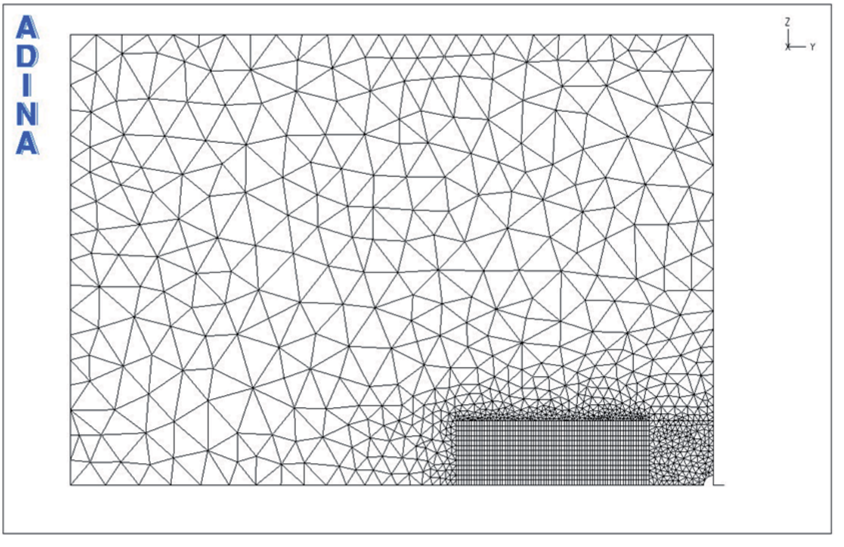

Fig. 4. Meshed model

Following the above mentioned procedure, the dependence 2a — N was obtained experimentally for the steel STN 41 1373 an also numerically in ADINA and both results — experimental and simulation ones were compared (Fig. 5).

Crack propagation for the lengths 2a < 20 mm is influenced by creation and forming a plastic zone on the tip of the crack. For the lengths 2a > 35 mm, unstable crack propagation occurs when it would be more objective to use Forman's equation:

$$da/dN = C.\ \Delta K^m/(1\text{-}R).\ K_{IC}\text{-}\Delta K. \tag{1}$$

Because of this, stable propagation of crack was assumed for the crack lengths 20 mm ≤ 2a ≤ 35 mm. Obtained dependence of crack propagation velocity da/dN on ΔK_{apl} is shown in Fig. 6.

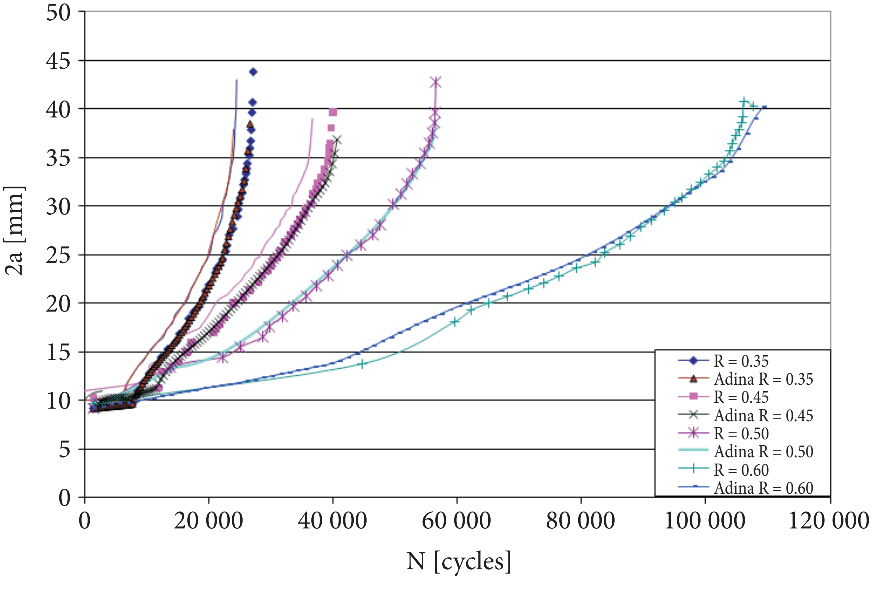

Fig. 5. Experimentally obtained dependence 2a — N for R = 0.35, STN 41 1373

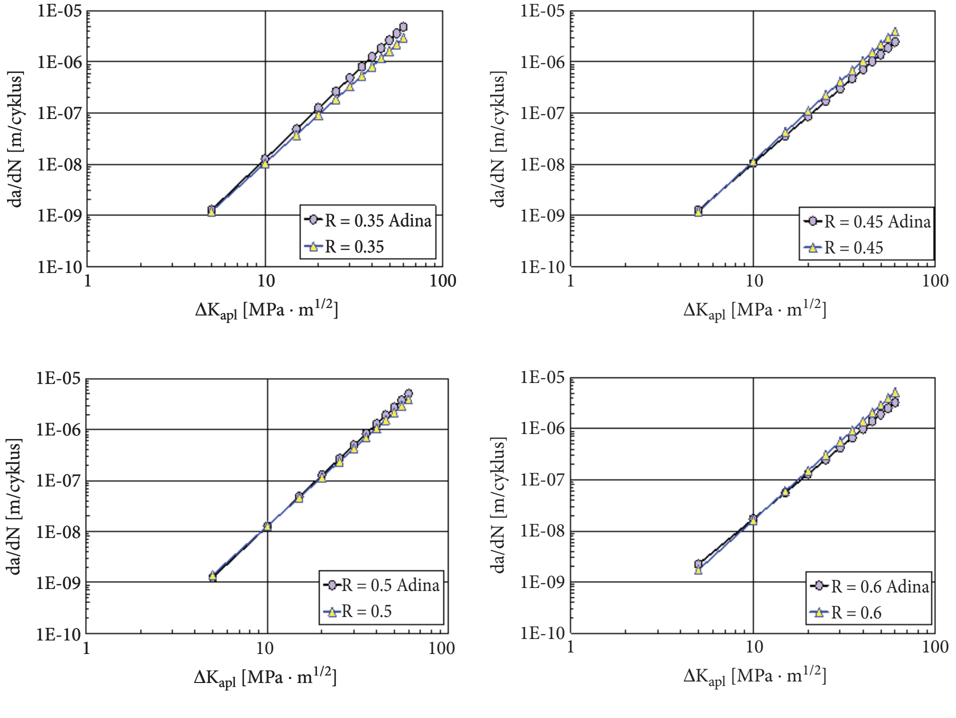

Fig. 6. Comparison of the dependence 2a — N for R = 0.35; 0.45; 0.5; 0.6, STN 41 1373

As it is depicted in Fig. 5, we can see that fatigue crack length increase with the increasing number of cycles and the loading cycle asymmetry R. It is more obvious in Fig. 6 which presented the dependence of fatigue crack propagation velocity da/dN on applied value of the stress intensity factor amplitude. The lowest fatigue crack propagation velocity is for R = 0.35 and the highest velocity is for R = 0.6. The picture shows the results obtained by experimental measurement and numerical simulation as well. According to the comparison, we can consider the difference between two results as negligible. It was caused by some factors influencing experimental tests, for instance more defects and impurities in comparison to simulation.

4. Conclusions

On the basis of information analysis which is consequent from a theoretical analysis of the solved problem [5, 6] and discussion of experimental and numerical results, it is possible to say the following conclusions:

- The used experimental device was fully certified by experiments and allowed the study of propagation at the test conditions.
- Finite element software ADINA is able to solve a problem of fatigue crack propagation and its results are fully comparable to experimental results.
- For used low carbon weldable steel STN 41 1373, the dependences 2a — N and da/dN — ΔK_{apl}, were obtained.
- With increasing the loading cycle asymmetry R, the fatigue crack propagation velocity increases too.
- According to comparison of these two results, it is possible to state a good correlation between the experimental measurement and numerical simulation.
- Variance in results is strongly dependent on fineness of the mesh in the crack propagation area and also on material model.

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Określenie trwałości zmęczeniowej spawalnej stali STN 41 1373 programem ADINA

Streszczenie. Badany materiał — stal w gatunku 11373 został poddany próbom zmęczeniowym w wyniku których określono zależność prędkości propagacji pęknięcia zmęczeniowego od wartości współczynnika intensywności naprężeń ΔK_{apl}. Rezultaty pomiarów eksperymentalnych porównano z wartościami prędkości propagacji pęknięć zmęczeniowych otrzymanych w wyniku symulacji komputerowej realizowanej w programie ADINA. Wyniki symulacji wykazały dużą zgodność z rezultatami eksperymentalnymi.

Słowa kluczowe: badania zmęczeniowe, propagacja pęknięć, metoda elementów skończonych, pęknięcia zmęczeniowe, wytrzymałość zmęczeniowa

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