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# Marine Shaft Steels (AISI 4140 and AISI 5120) Predicted Fracture Toughness by FE Simulation

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Optimal selection of material can be considered as one of the most critical steps in engineering design process. That is especially emphasized when dealing with constructions that operate in marine environment; high stresses and harsh operating conditions assert the importance of proper material characterization before its selection. This paper presents comparison of two types of steel usually used in marine shaft manufacturing, chromium-molybdenum steel AISI 4140 and chromium low-alloy steel AISI 5120. Comparison was made using numerically determined *J*-integral, an important fracture mechanics parameter. *J*-integral values are determined numerically using finite element (FE) stress analysis results of compact tensile (CT) and single-edge notched bend (SENB) type specimens usually used in standardized *J*-integral experimental procedures. Obtained *J* values are plotted versus specimen crack growth values ($\Delta a$ – crack length extension) for different specimen geometries ($a/W$ – relative crack length). Higher resulting values of *J*-integral for AISI 5120 than AISI 4140 can be noticed. In addition to that, *J*-integral values obtained by using FE model of CT specimen give somewhat conservative results when compared with ones obtained by FE model of SENB specimen. Although this procedure differs from experimental analysis, results can be used a suitable fracture parameter value in fracture toughness assessment.
*Keywords:* AISI 4140, AISI 5120, marine steel, fracture.

## 1. INTRODUCTION

Material selection is a step of a great importance in the process of engineering design. Besides understanding the nature and intensity of the stress that occurs in a designed structure, optimal selection of the material can significantly reduce the possibility of failures. Causes of failure, recognized from engineering practice, usually include one or few of mentioned: excessive force and/or temperature induced elastic deformation, yielding, fatigue, corrosion, creep, etc. Selection of improper material may affect profitability of production process, reduce operational lifetime cycle and result in flaw appearance and structural failure.

Several requirements have to be met during material selection process. These requirements include appropriate strength of material, sufficient level of rigidity, heat resistance, etc. For structures susceptible to crack growth, it is necessary to ensure that material has been selected on the basis of fracture mechanics parameters.

Considering marine environment, fracture mechanics approach to design must be used in order to account for high stresses and harsh operating conditions. Several examples of failed marine constructions are brought to attention here where designers would benefit from implementation of fracture mechanics approach. Severe consequences of fatigue induced fracture are presented in the study of marine main engine crankshaft failure [1]. Cranes and forks, similar to those used in port transportation, collapsed due to failures in axle shaft [2] or drive and gearbox shafts [3]. Catastrophic failures can occur in marine anchoring systems due to poor design and wrong material selection of couplings used in anchor hoisting [4] or faults in the manufacturing process of anchor studs [5].

Most of the mentioned failures occurred on some grade of alloy steels that are used in marine applications where corrosion resistance of stainless steels is not necessary. To be able to properly choose suitable material for marine construction, characterization of material is essential.

Characterization of materials is usually done using experimental routines [6] which can be complemented and, in some cases, even substituted with numerical prediction of material properties [7 – 11] with the use of powerful computers and numerical analysis routines.

Fracture mechanics parameters that define material resistance to crack propagation are usually determined through experimental investigations of material under consideration. Fracture behavior is usually estimated using some of the well-established fracture parameters, like stress intensity factor (*K*), *J*-integral or crack tip opening displacement (*CTOD*). When dealing with ductile fracture of metallic materials that includes nucleation, growth and coalescence of voids [12], *J*-integral is appropriate for quantifying material resistance to crack extension. For growing crack, *J*-integral values can be determined for a range of crack extensions ($\Delta a$) and can be presented in the form of the *J*-resistance curve. This curve is usually obtained experimentally following standardized procedures but it can be successfully complemented or even

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substituted by numerical methods, e.g. finite element (FE) method. Some of the recent articles on that topic include discussion on accuracy of *J*-integral obtained by experiment, two-dimensional (2D) FE analysis, three-dimensional (3D) FE analysis or the EPRI method [13]. FE analysis of Mode I fracture in a CT specimen has been conducted to reveal effects on micro, meso and macroscale [14]. Advantage of using *J*-integral in fracture mechanics calculation stands in the fact that it can be correlated with stress intensity factor in linear elastic region. Some of the recent work dealing with this correlation include research on the advantages of the *J*-integral approach for calculating stress intensity factors using 2D and 3D FE models of CT specimens and cracked round bars [14]; comparison of stress intensity factor calculations by displacement extrapolation method, stress extrapolation method, node displacement method and *J*-integral method based on FE analysis results [15] and using *J*-integral evaluation by the FE method for the prediction of fatigue crack growth in girth-welded pipes [16].

This paper presents a comparison of numerically predicted *J*-values taken a measure of crack driving force for two types of steel commonly used for various marine applications, AISI 4140 and AISI 5120. Obtained material data may help designers to find the best solution in appropriate material selection.

## 2. MATERIAL PROPERTIES

Two materials compared are chromium-molybdenum steel AISI 4140 (42CrMo4) and chromium low-alloy steel AISI 5120 (20MnCr5). Both are widely used in marine applications as material for marine propeller shafts, stern shafts, tail shafts, crankshafts and rudder spindles. AISI 4140 has an excellent strength to weight ratio along with a good atmospheric corrosion resistance. This steel is readily machinable and suitable for forging between 900 and 1200 °C. AISI 5120 has similar forging abilities, good weldability and it is best machined in the normalized condition prior to case hardening.

AISI 4140 has the following composition in mass %: C (0.45), Cr (1.06), Mn (0.74), Si (0.32), Mo (0.17), S (0.018), P (0.014), Ni (0.04), Al (0.02), V (0.01), Nb (0.02), W (0.02), Cu (0.04) and rest (97.078).

AISI 5120 has the following composition in mass %: C (0.22), Cr (1.11), Mn (1.23), Si (0.29), S (0.025), P (0.021), Nb (0.03), Cu (0.06), Ni (0.08), Ti (0.02) and rest (96.914). Engineering stress-strain ($\sigma - \varepsilon$) diagrams of both steels are given in Fig. 1 [17, 18].

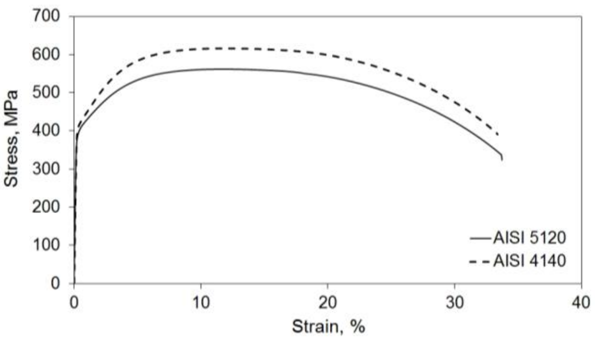



**Fig. 1.** Uniaxial engineering stress-strain ($\sigma - \varepsilon$) diagrams for steels 4140 and 5120

In Tab. 1 yield strength ($\sigma_{0.2}$), tensile strength ($\sigma_{\mathrm{m}}$) and elastic modulus ($E$) of steels 4140 and 5120 is given.

**Table 1.** Yield strength ($\sigma_{0.2}$), tensile strength ($\sigma_{\mathrm{m}}$) and elastic modulus ($E$) of considered steels

| Material | $\sigma_{0.2}$, MPa | $\sigma_{\mathrm{m}}$, MPa | $E$, GPa |
|---|---|---|---|
| 4140 | 415 | 617 | 221 |
| 5120 | 397.6 | 561.6 | 219 |

## 3. PREDICTED FRACTURE BEHAVIOR OF CONSIDERED MATERIALS

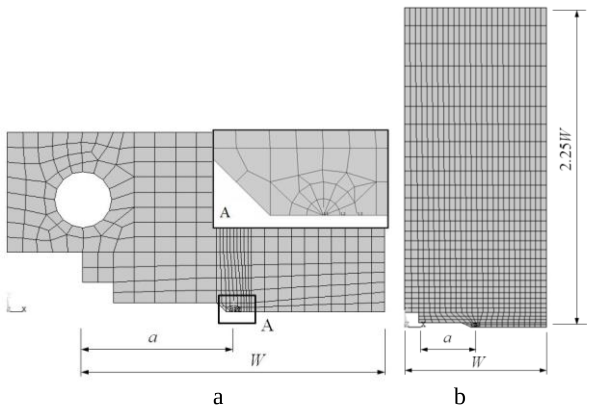
To predict fracture behavior of the considered materials, *J*-integral is used. *J*-integral was introduced by Rice and Cherepanov [19, 20] separately as a path-independent integral which can be drawn around the tip of a crack and viewed both as an energy release rate parameter and a stress intensity parameter. In a two-dimensional form it can be written as:

$$J = \int_{\Gamma} \left( w \mathrm{d}y - T_i \frac{\partial u_i}{\partial x} \mathrm{d}s \right), \tag{1}$$

where $T_i = \sigma_{\mathrm{ij}} n_{\mathrm{j}}$ are components of the traction vector, $u_{\mathrm{i}}$ are the displacement vector components and $ds$ is an incremental length along the arbitrary contour path $\Gamma$ enclosing the crack tip.

In order to predict fracture behavior, i.e., to predict resistance to fracture of steels AISI 4140 and AISI 5120, experimental single specimen test method [21] following elastic unloading compliance technique was numerically simulated. It is a test method that uses measured crack mouth opening displacement to estimate growing crack size. Resulting *J*-integral values can be taken as a fracture toughness parameter and plotted versus crack extension. First step of the numerical procedure is to conduct structural stress analysis.

According to appropriate ASTM standard, Fig. 2, 2D FE models of two types of specimen, compact tensile (CT) and single edge notched bend (SENB), are defined and initial $a/W$ ($W = 50$ mm) ratio of 0.25, 0.5 and 0.75 is taken.




a b

**Fig. 2.** FE model of: a – CT specimen; b – SENB specimen

Material behavior is considered to be multilinear isotropic hardening type. FE models of specimens are meshed with 8-node isoparamateric quadrilateral elements. Mesh is refined around the crack tip to be able to capture high deformation gradients in the regions where yielding occurs. Quasi-static load was imposed on specimen in order to simulate compliance procedure of single specimen test method (3-point bending for SENB specimen). Since specimens are symmetrical, only half of them need to be modeled. To simulate crack propagation node releasing technique was used.Second step was to use FE stress analysis results from integration points of finite elements surrounding the crack tip, evaluate $J$-integral values in these points using following equation [22] and sum them along a path that encloses crack tip giving total value of $J$, Fig. 3.

$$J = \sum_{p=1}^{np} W_p G_p \left( \xi_p, \eta_p \right), \tag{2}$$

where $W_p$ is the Gauss weighting factor, $np$ is the number of integration points and $G_p$ is the integrand evaluated at each Gauss point $p$:

$$G_p = \left\{ \frac{1}{2} \left[ \sigma_{xx} \frac{\partial u_x}{\partial x} + \sigma_{xy} \left( \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) \frac{\partial u_x}{\partial x} + \sigma_{yy} \frac{\partial u_y}{\partial y} \right] \frac{\partial y}{\partial \eta} \right. . \tag{3}$$

$$\left. - \left[ \left( \sigma_{xx} n_1 + \sigma_{xy} n_2 \right) \frac{\partial u_x}{\partial x} + \left( \sigma_{xy} n_1 + \sigma_{yy} n_2 \right) \frac{\partial u_y}{\partial x} \right] \sqrt{\left( \frac{\partial x}{\partial \eta} \right)^2 + \left( \frac{\partial y}{\partial \eta} \right)^2} \right\}_g .$$

Three different paths around crack tip have been defined in each example and their average value was taken as final. Although $J$-integral is independent of chosen path, this was done in order to account for any possible $J$-values variation in the vicinity and away from the crack tip.

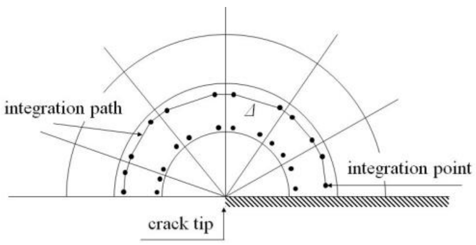



**Fig. 3.** $J$-integral path enclosing crack tip through FE integration points

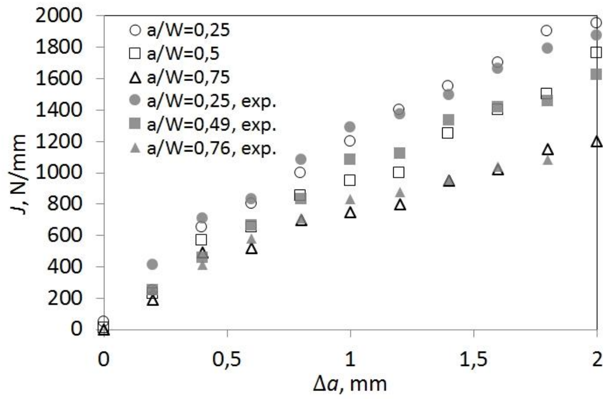
## 4. RESULTS

Since no fracture experimental results were available for steels AISI 4140 and AISI 5120 to verify accuracy of the algorithm, $J$-integral values were first determined for SENB specimen with initial crack length of $a/W = 0.25$, 0.5, 0.75 made of 20MnMoNi55 steel and also for CT specimen with initial crack length of $a/W = 0.36$ made of the same steel. Numerically obtained results were compared with available experimental data for the same specimen configuration and material [23, 24], Fig. 4. Good correspondence between numerically predicted and experimental results encouraged in further application of the $J$-integral calculation method. Also, previous work of the authors on the similar topic proved successful [25, 26].

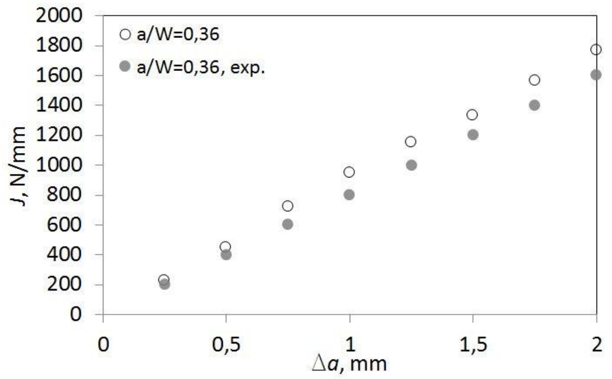
Fig. 5 and Fig. 6 show final numerically predicted $J$ values for steels AISI 4140 and AISI 5120 as a measure of crack driving force versus crack growth size ($\Delta a$) using FE models of SENB and CT specimen. Initial $a/W$ ($W = 50$ mm) ratio of 0.25, 0.5 and 0.75 is taken with $\Delta a = 0...2$ mm.

## 5. DISCUSSION

Fracture behaviour of mentioned materials is given in Fig. 5 and Fig. 6 using $J$-integral as a measure of fracture toughness parameter versus crack growth size.

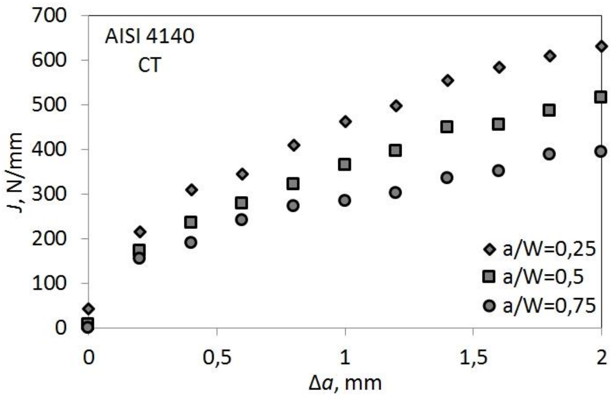



a

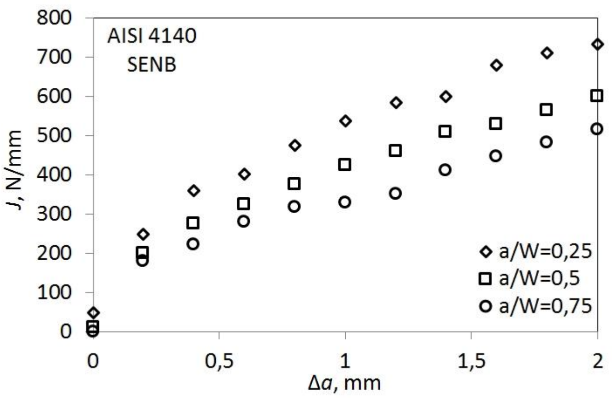



b

**Fig. 4.** Numerically predicted and experimentally obtained $J$ values comparison for 20MnMoNi55 steel using: a – SENB specimen: b – CT specimen




a




b

**Fig. 5.** Numerically predicted $J$ values for steel AISI 4140 using FE models of: a – CT specimen; b – SENB specimen

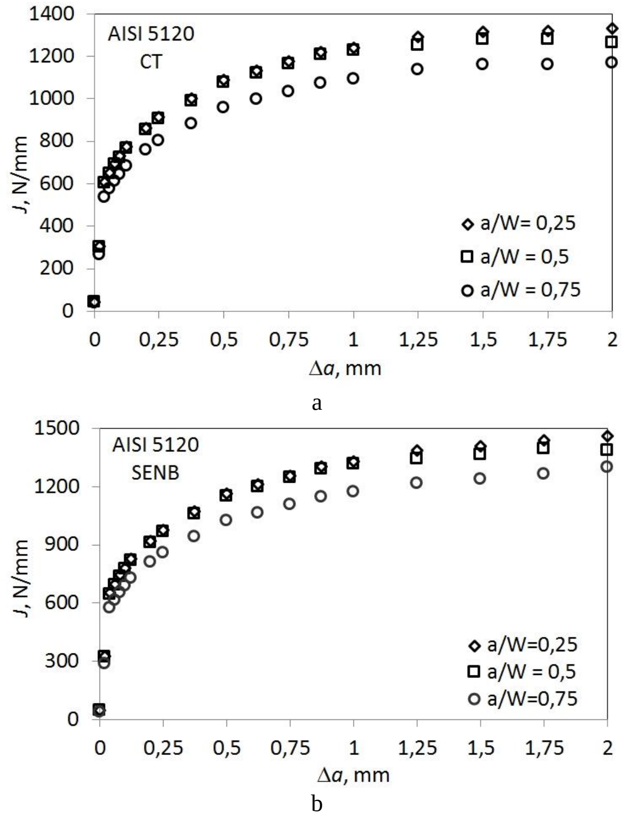



**Fig. 6.** Numerically predicted *J* values for steel AISI 5120 using FE models of: a – CT specimen: b – SENB specimen

It can be noted that steel 5120 has higher resulting values of *J*-integral than steel 4140 making it more suitable for structures that need less susceptibility to fracture. *J*-integral differs greatly for $a/W = 0.75$ when compared with $a/W = 0.25$ and 0.5 that are quite close in values for AISI 5120. Also, higher *a/W* ratios correspond to lower *J*-integral values of materials and vice versa. *J*-integral values obtained by using CT specimen FE model give somewhat conservative results when compared with ones obtained by using the SENB specimen FE model. Although mentioned numerical procedure does not give results which can be directly related to ones obtained experimentally, given results can be useful for the assessment of fracture toughness.

## 6. CONCLUSION

Numerical assessment of *J*-integral for steels AISI 4140 and AISI 5120 can be useful as a prediction of material's possible fracture behavior. Although not experimentally validated, good correspondence between experimental and numerical results obtained for steel 20MnMoNi55 assures confidence in using the *J* values for steels AISI 4140 and AISI 5120. In the engineering design procedure that includes any of considered material, obtained results can be useful in the initial assessment of material's susceptibility to crack growth.

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