Fracture mechanical analyses of high strength steels applying experiments and simulation

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Abstract. The paper contains information about the experimental and simulation test results of thermomechanically rolled high strength steel. The S960TM material grade was produced by a modern technological process, which provide longer estimated life time, better performance, and due to higher strength enable smaller applied wall thickness, which require less welding activity. The only disadvantage of this material grade is that they can contain material discontinuities in their microstructure. The characterisation of the response of these materials against load can be analysed by fracture mechanical investigation. Fracture mechanical experiments were carried out with three-point bending method, calculating fracture toughness value of crack-tip opening displacement (CTOD). To reduce the complicated real experiment in fracture mechanics, the simulation possibility of fracture mechanical behaviour of the investigated material was applied, using DEFORM software, which gave an acceptable narrowing to the measured phenomenon.

1. Introduction

Innovative steel production processes have resulted in novel material grades, with improved quality and enhanced performance. One of the significant driving forces behind the development is the requirement for lighter-weight structures. Light-weight structures provide several advantages, like smaller applied wall thickness, easier carriage, saving the required amount of welding, etc. The appearance and wider application of the weldable high strength steels, produced by novel technologies is the outcome of their characteristic features, i.e. higher strength and toughness [1],[2].

Based on the novelty, there is incomplete information about the detailed properties of these material grades in different application areas, which hinder its applicabilities in the engineering structures. However, there is relatively less data available for structure design engineer to accomplish the mechanical controls based on the fatigue or fracture mechanical approaches for design and operate structures built from high strength steels [3]. The Eurocode 3 [4], chapter 12. gives information about standard investigation results for steel grades up to a guaranteed yield strength of 700 MPa. The measures for fracture mechanical control are only available for grades with lower strength [5].

There exist several methods to increase the strength properties of steel materials [6]. One of them is thermomechanical rolling process, which is carried out in two main steps [7]. Firstly, the base material is heated to 1100°C, following that the rolling of the slab is carried out in austenitic state. In the next step the plate cools down on calm air to “as rolled” condition. Thermomechanical rolling is following, which is individually designed (rolling temperature and the number of rolling steps) by the producer.
The result of this manufacturing process is an extremely fine grain size with reduced carbon and alloying element content which further improved weldability due to cleaner steel composition.

Beside the several advantageous properties, the microstructure, produced by this process can contain material discontinuities, that influences the behaviour of the engineering structure under loading condition. Aiming to get information about the response of a thermomechanically rolled high strength steel containing material discontinuities (supposed crack = artificial failure), fracture mechanical investigations were carried out [8]. Due to tough behavior of the investigated advanced high strength steel and the complicacy of the experimental work [9] the possibility of application of simulation was also analysed.

2. Experimental work

2.1. Investigated materials

The experimental work was carried out on thermomechanically rolled ALFORM 960M grade steel produced by Voestalpine Anarbeitung GmbH. The chemical composition, according to the producer’s certificate, with the alloying elements of the investigated samples are given in Table 1.

| C  | Si | Mn | P  | S  | Al | Cr | Ni | Mo | Cu | V  | Ti | Nb | N  | B  |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 0.084 | 0.329 | 1.65 | 0.011 | 0.0005 | 0.038 | 0.61 | 0.026 | 0.29 | 0.016 | 0.078 | 0.014 | 0.035 | 0.006 | 0.0015 |

The yield strength according to the producer’s material certificate reached 1051 MPa, while the measured value showed only 958 MPa.

For fracture mechanical tests samples with 15 mm wall thickness were applied. The average surface roughness changed between 0.8…1.6 µm. The lower value belongs to the surface containing the notch.

The microstructure of the base material was analyzed in longitudinal section. This section contained elongated grains due to forming during rolling and as a result of fast cooling the microstructure contained predominantly martensite and bainite beside ferrites [11].

2.2. Experimental circumstances

Advanced high strength steels have an excellent combination of high yield strength and high toughness even at lower temperatures. In consequence of this the determination of general fracture toughness value is not unambiguous. Therefore, crack tip opening displacement (CTOD or COD) measurements were carried out on three-point bend specimens, worked out in T-L and L-T orientation from the sheet base material. For the reliable investigation result 5-5 specimen were cut out in each orientation. The geometry of the samples was 13 mm thickness, 26 mm width, and the machined notch depth varied between 11.46…11.52 mm. The specimens were prepared according to the ISO 12135 standard [10].

For fatigue precracking a maximum bending load of 8560 N was applied, which was reduced by degrees, in 7 steps, to the lowest load of 3230 N, as the crack at the notch tip arose and started to propagate. The fatigue precracking was carried out on MTS 810.23 type electro-hydraulic testing machine, with R=0.1 asymmetry factor. The planned crack length after precracking was selected as “longer than 1.3 mm”. Completing the fatigue precracking, the length of initial cracks on specimen surfaces (length of machined notch + crack from fatigue precracking) changed between a= 12.73…12.92 mm. The real crack length could be measured after opening broken the specimen at the final stage of the experimental procedure.

For fracture mechanical tests the above mentioned three-point bending test apparatus was selected, and the experiments were carried out at room temperature with the support distance of 104 mm. The lower support and the upper bending radius were 5 mm, the applied velocity during the test was 0.05 mm/s, and the applied load was static increasing. The crack tip opening displacement was measured by a strain gauge type MTS 632.02C attached to a clip placed between the two accurately positioned knife edges at the mouth of the machined notch. The controlled variable was the piston displacement. During investigation the piston displacement, the crack tip opening data and the applied load were registered.
and stored. After the three-point bending test the samples were marked by heat tinting in a chamber at 250°C for an hour, then they were broken open and the crack propagation was observed on the fracture surfaces.

2.3. Experimental results

Examining the recorded load-notch opening displacement diagrams three different types could be observed, related to the standard [10]. One type is a so-called maximal diagram, containing elongated plateau, as maximum value for load, shown in Figure 1., the other type of the recorded diagrams contains sudden springing, the so-called pop-in as shown in Figure 2. One type of a diagrams contained only one pop-in, while the other type of the diagrams contained two pop-ins. From these diagrams two basically different types are presented on Figure 1. and Figure 2., one with maximum value, and the other one with one significant pop-in.

![Figure 1](image1.png)

**Figure 1.** Recorded Load – Crack tip opening displacement diagram, type 1.

![Figure 2](image2.png)

**Figure 2.** Recorded Load – Crack tip opening displacement diagram, type 2.

In some cases, there are more pop-ins to observe on the recorded diagram. According to the test evaluation procedure [10], the first significant pop-in have to be considered for the calculation of CTOD value. In the case illustrated in Figure 1. F and V values were taken on that place, where the diagram
reached a maximum force plateau prior to fracture, without a significant pop-in. In these cases, the indices of F and V values are ‘m’. In the case, illustrated by Figure 2., a significant pop-in could be identified. It has no importance, which number of pop-ins was the first significant, for these cases the F and V values get an index ‘c’.

The CTOD values (δ₀) are calculated according to the standard [10]. The calculation details and the detailed results and conclusions for all measurement are already published in [11]. For the calculation, the real accurate crack length is also necessary, which was measured after heat tinting, on nine locations on the broken open surfaces as shown in Figure 3. The calculated CTOD values with additional pop-in data and the maximum forces are given in Table 2.

Table 2. CTOD results

| Measured value / Sample number | Significant pop-in | Orientation | F   | δ₀   | Type of F, V, and δ |
|-------------------------------|--------------------|-------------|-----|------|---------------------|
| TM1_1                         | no pop-in          | L-T         | 29402 | 0.200 | m                   |
| TM1_2                         | no pop-in          | L-T         | 30102 | 0.161 | m                   |
| TM1_3                         | 2. pop-in          | L-T         | 29908 | 0.113 | c                   |
| TM2_1                         | 1. pop-in          | T-L         | 27400 | 0.140 | c                   |
| TM2_3                         | no pop-in          | T-L         | 27805 | 0.228 | m                   |
| TM2_4                         | no pop-in          | T-L         | 29103 | 0.288 | m                   |
| TM2_5                         | 2. pop-in          | T-L         | 29101 | 0.155 | c                   |

From the planned measurements three successful results for L-T orientation and four results for T-L orientation are given in Table 2. In four cases no pop-in phenomena could be observed on the diagram, in one case the first pop-in was the significant, while in two cases the second pop-ins were significant.

In L-T direction one δᵣ and two δₒ values, while in T-L direction two-two δᵣ and δₒ values could be considered, at the investigated thickness of 13 mm.

As conclusion to the test results given in Table 2, it can be stated, that lower δₒ value, which correspond to δᵣ, belongs to brittle behaviour, while higher δₒ value, which becomes δₒ, belongs to more plastic behaviour, especially in the vicinity of crack tip.
The several requirements regarding the initial crack length, crack and notch location, surface roughness, the measuring equipment, precracking procedure, were observed and controlled during the complete investigation. It can be stated that they correspond to the requirements of the standard [10], except one minor difference:

- according to the requirement, given in the standard: no part of the fatigue precrack front shall be closer to the starter notch than 1.3 mm or 2.5%W, whichever is larger. This requirement is only valid for the seven interior cracks, the $a_1$ and $a_9$ crack lengths are usually closer to the crack starter notch than 1.3 mm, see also Figure 3.

3. Simulation with DEFORM

DEFORM is a Finite Element Method based process simulation system, designed to analyze various forming and heat treatment processes used by metal forming and related industries [12]. By simulating deformation processes on computer, it allows the designers and operators to reduce a real physical experimental need, and to get faster information about the material or structure behaviour possibly also as prediction. Nowadays it is increasingly applied for the deformation analyzes of advanced high strength steels in various conditions, thought there is no data available for the material in the software [13].

As it was mentioned before the fracture mechanical physical test is a complex investigation with several influencing parameters and several requirements. The simulation of this process needs partially different input information as the real physical investigation. The main benefits of using the simulation of this damage process could be time, material and cost saving. While the real experimental tests last approximately for weeks for one batch, the simulation can run in some hours with the appropriate input data and adjustment.

3.1. Input parameters

During the simulation the following input parameters were set:

- applied model: 2D model – supposed plain strain;
- applied material law: elastic-plastic;
- material characteristics:
  - for elastic deformation part: measured elastic modulus, $E=195000$ MPa;
  - for plastic deformation part: flow-curve, measured and converted data for true stress – true strain curve for true strain 0 - 0.2 value, and approximation applying Ludwik’s equation for the strain from 0.2 – 1., see Figure 4.:

\[
\begin{align*}
\sigma &= 1366.4\varepsilon^{0.0915} \\
R^2 &= 0.9831
\end{align*}
\]

- applied mesh: rectangular with remeshing;
applied damage model: Cockroft & Latham model [14], the critical fracture criteria: 0.5:
\[ \int_{0}^{E_f} \bar{\sigma} \left( \frac{\sigma^*}{\bar{\sigma}} \right) d\bar{\varepsilon} \]

where
- \( \varepsilon_f \): fracture strain;
- \( \bar{\sigma} \): equivalent stress;
- \( \bar{\varepsilon} \): equivalent strain;
- \( \frac{\sigma^*}{\bar{\sigma}} \): non-dimensional stress concentrating factor, representing the effect of the highest tensile stress, \( \sigma^* \).

- for the simulation the accurate sample geometry data was selected of TM2_5 sample;
- on Figure 5. the meshed sample is illustrated, with locally enriched meshing parts on places, where deformation and damage data are more interesting.

**Figure 5.** The meshed sample

### 3.2. Simulation results
With the application of finite element simulation several information can be extracted after the simulation is completed. For the investigated case the most important data were the load-deflection curve and the crack tip opening information.

The simulated load-deflection curve is illustrated in Figure 6. with red line. For comparison between simulated and real test diagram, the real testing diagram is also presented for the single investigated specimen, marked with blue line.

**Figure 6.** Comparison of load-deflection curve derived from experiment and simulation

In real physical experiment, the load-deflection curve contained two pop-ins, at load = 24700 N, deflection = 0.9 mm and at load = 29101 N, deflection = 1.33 mm. The running down of the curve of simulation follows the real experimental results, but the slope of the curve is higher, therefore the load values at the pop-ins are higher. The location of the pop-in in the x axes narrows the real results.
The crack tip opening was measured by the displacement changes during the investigation of two points at the top of the notch (P1 and P2 in Figure 7.), as it is measured also in the physical test. It is only possible to record a displacement-time diagram in the software. At the point of the first pop-in the process time is 19 s, while at the second pop-in the process time is 26 s. The crack tip opening value was measured at that times, as it is illustrated in Figure 7. At the location of the first pop-in the crack tip opening value is 0.64 mm, in the physical test it was 0.48 mm. At the location of the second pop-in the crack tip opening value is 0.82 mm, which was the same value also for the physical test.

Analyzing the damage rate, Figure 8., as the test/simulation is being proceed, two changes in the gradient of damage diagram can be observed in Figure 8.a. The damage slope changed first at 19 s of the test, close to the first pop-in observed in physical test. Here supposedly the crack started to propagate, so the damage got higher. Furthermore, the slope of the damage curve changed at 26 s, close to the location of the second pop-in in physical experiment. Both locations of slope changes in the simulated damage curve narrow the locations of pop-ins experienced during the physical investigation (dotted lines in Figure 8.a). Analyzing the damaged picture of the sample, Figure 8.b), the highest damage can be observed in the vicinity of the crack tip.

Concluding the simulation results it can be stated that DEFORM software simulation for fracture mechanical test, applying three-point bending test method gave a comparable approximation. Further refinement of the simulation can be tested, by for example choosing a different damage model, or considering a different fracture criterion.
4. Conclusion
In this paper the behaviour of thermomechanically rolled, high strength steel grade, ALFORM 960M was investigated applying real physical test and finite element modelling. During the experiment an artificial material discontinuity (notch and fatigue precrack) was machined and initiated in the samples. This discontinuity was also geometrically given to the FEM model.

In the real physical test crack tip opening displacement method was applied for the evaluation of fracture mechanical behaviour. The average value of the calculated $\delta_0$ measure is 0.183, at the investigated thickness of 13 mm, which value is lower for ‘c’ type measures, possessing more brittle character, and higher for ‘m’ type measures, possessing more ductile behaviour.

DEFORM simulation was carried out to simulate the response, of the investigated high strength steel containing material discontinuity, to load. The simulation result showed, that the extracted load-deflection diagram had an acceptable correspondence to the measured one, and even the values for the crack tip opening were close, or same as it was measured in the reality. For a reliable result in the simulation further refinements should be tested concerning for example damage model, damage criterion. The advantage of this simulation is, that the unknown fracture mechanical behaviour of the investigated sample can be predicted, even if the advanced high strength steel properties are not involved in the software database.

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References
[1] Lukács J, Dobosy Á and Gáspár M 2018 Adv. Mat. Res. 1146 pp 44-56, doi: 10.4028/www.scientific.net/AMR.1146.44
[2] Dobosy Á, Gáspár M and Lukács J 2018 Adv. Mat. Res. 1146 pp 73-83, doi: 10.4028/www.scientific.net/AMR.1146.73
[3] Glodez S, Knez M, Jazaernik N and Kramberger J 2009 Eng. Fail. Anal. 16 pp.2348-2356, doi: 10.1016/j.engfailanal.2009.03.023
[4] European Standard EN 1993-1-1 2009 Eurocode 3: Design of steel structures
[5] Hagedorn K E and Eckel M 1992 Nucl. Eng. & Design 137 pp.343-353
[6] Willsms R 2009 Proc. Nordic Steel Construction Conference pp 597-604, (Malmö, Sweden) ISBN: 9171270582
[7] Bandyopadhyay P S, Ghosh S K, Kundu S and Chatterjee S 2011 Metall. and Mat. Transact. A, 42A, pp 2742-2752, doi: 10.1007/s11661-011-0711-2
[8] Barsom J M and Rolfe S T 1999 Fracture and Fatigue control is Structures: Application of Fracture Mechanics Third Edition, (American Society for Testing and Materials, Philadelphia) ISBN 0-8031-2082-6
[9] Zhu X-K and Joyce J A 2012 Eng. Fract. Mech. 85 pp 1-46 doi: 10.1016/j.engfracmech.2012.02.001
[10] International Standard ISO 12135 2016 Metallic materials – Unified method of test for the determination of quasistatic fracture toughness
[11] Koncsik Zs 2020 Proc. of the 1st Int. Conf. on Eng. Sol. for Sust. Dev.; Solutions for Sustainable Development ed. Tóthné K Sz, Jármai K and Voith K (CRC Press, London) ISBN 978-0-367-42425-1, pp. 316-324. doi: https://doi.org/10.1200/9780367824037
[12] http://home.zcu.cz/~sbenesov/Deform2DLabs.pdf, DEFORM User Manual, available 10th of January 2020
[13] Tisza M and Lukacs Zs 2015 Acta Metall. Sinica Engl. Lett. 28 pp. 1471-81.
[14] Cockroft M G and Latham D J 1968 J. of the Inst. of Metals 96, pp. 33-39.