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Fracture Mechanical Analysis of Gleeble Simulated Heat Affected Zones in High Strength Steels

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Abstract

During the research work the fracture mechanical investigation of heat affected zones of thermomechanical rolled high strength steels (Voestalpine Alform 960M) were carried out. For production of appropriate heat affected zones Gleeble 3500 physical simulator was applied, with different heating cycles and specific cooling times. Following the simulation, fracture mechanical investigations were performed, in favor of determination crack tip opening displacement (*CTOD* or *δ*) values.

Keywords

Gleeble simulation, heat affected zones, fracture mechanics, CTOD

1 Introduction

The application of the modern high strength steels obtains an important role in different sectors of industry, especially in automotive industry. In such cases, the thickness of the structural elements can be decreased together with the mass of the structure and the welded joints [1–3]. Directly and indirectly the emission of greenhouse gases can also be decreased [4]. In general, we can state that with the increasing of the yield strength, the applied thickness can be decreased, so the amount of the filler metal and the time of the welding decrease, as well. The most effective way of strength increasing is the decreasing of grain sizes. In the 1970 years a new process, called thermomechanical rolling was developed to achieve outstanding strength and advanced weldability properties. In this case the yield strength can be increased without changes in chemical composition, only by selection the appropriate rolling parameters. The developments on the field of steel production as well as on rolling and application are still undiminished [5–7].

On a different point of view, it is important to note, that high strength steels often contain material discontinuities, e.g. cracks or crack like defects, and their behavior under different loading conditions can be predicted only by fracture mechanical data. Not only the base material, but the welded microstructure is also important for a designer. In many cases it is impossible to investigate certain heat affected zones (HAZs) of a real welded joint, because during the real process the thermal gradient is so high in the material, that strong inhomogeneous microstructure occurs, which is changing per 0.1 mm. Applying physical simulation [8] homogeneous samples in high amount can be prepared, aimed to following mechanical tests, like impact toughness test, fracture toughness and microstructural analyses [9, 10].

The advanced high strength steels have further advantages, they show high toughness values as well. Due to this behavior the common fracture toughness parameter (the valid K_{Ic}) is not possible to measure, to evaluate. For this reason, in the HAZ and according to the valid standard ISO 12135:2016 [11], the evaluation of crack tip opening displacement (*CTOD* or *δ*) becomes conspicuous.

The investigation results published in this paper fit to a larger research topic, in which the focus is on changes of toughness in HAZ during welding [12–20]. The long-term aim of this research is the fracture mechanical analyses of HAZs created by physical simulation. The previous weld-technological research [21–23] has been proved significant impact energy reduction in less tough HAZs on the S960M materials grade [24–27]. Therefore, as the first step fracture mechanical investigations were carried out on base material at room and at low temperatures.

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The next step of the research work, presented in this paper is the analyses and evaluation of the fracture mechanical properties, *CTOD* fracture toughness of Gleeble simulated heat affected zones (HAZs) of S960M thermomechanical rolled high strength steel (Voestalpine ALFORM 960M).

2 Materials and methods

2.1 Investigated samples

A 15 mm thick plate was selected as base material for the physical simulation experiments. A precise preparation of HAZ specimen is needed with required geometrical shape of 10 × 10 × 70 mm and appropriate surface quality aiming for accurate crack detection. The chemical composition of the investigated S960M samples is shown in Table 1.

According to the certificate of Voestalpine the room temperature tensile properties of the investigated samples are as follows: YS = 1051 MPa, TS = 1058 MPa, and A_5 = 17% [28]. Our own control measurement showed different value for the yield strength: YS = 958 MPa, and the measured Youngs-modulus is 195 GPa. During the evaluation of the fracture mechanical investigation results the measured values were applied.

2.2 Simulation circumstances

HAZ tests [29] were performed in a new generation of thermomechanical simulator, Gleeble 3500 [29–31], which is capable for the reproduction of real material processing (e. g., welding, heat treatment and metal forming) in laboratory circumstances. For temperature measurements K-type thermocouple (NiCr-Ni) was applied which was welded onto the middle of specimen for temperature record and control by means of the induction heating.

The maximum temperature, holding time and cooling rate of the thermal cycle parameters were selected based on the possible procedures during the gas metal arc welding (GMAW). Heat cycles were determined according to the Rykalin 3D model [32], where the whole heat cycle, including heated part as well, was described by time-temperature points instead of automatic software settings. In order to simulate the HAZ area, with the lowest toughness (CGHAZ = coarse grained HAZ), specimens were heated up to 1350 °C and cooled down to room temperature with different cooling time, 5 s, 15 s, 30 s. Furthermore, specimens were created with the same parameters, in addition with a second heating cycle at 775 °C aiming to create ICGHAZ (intercritical coarse grained HAZ) zone. The heating models of the simulations are given in Fig. 1.

The experimental work was carried out on 4 specimens for each variant, applying 6 different simulation parameters altogether 24 specimens were prepared. From every testing variant 3 specimens were meant for fracture toughness test, and 1 specimen for microstructural analyses and hardness tests to control the efficiency of simulation. Two different microstructures of simulated specimens are shown in Fig. 2. The upper part of the figure shows finer grain sized microstructure resulting from fast cooling, while the lower part shows larger grain size from double heating cycle and slow cooling. Applying double heating cycle the grain boundaries are more explicit.

As further control of the simulation process, HV1 hardness values were also measured on the specimens. A mean hardness value of 340 HV1 (standard deviation coefficient: 3.3%) was measured for specimens with 5 s cooling

Table 1 Chemical composition of investigated samples according to certificate, in wt% [28]

C	Si	Mn	P	S	Cr	Ni	Mo
0.14	0.30	1.13	0.007	0.001	0.3	0.04	0.167
V	Ti	Cu	Al	Nb	B	N	–
0.011	0.003	0.01	0.034	0.001	0.002	0.003	–

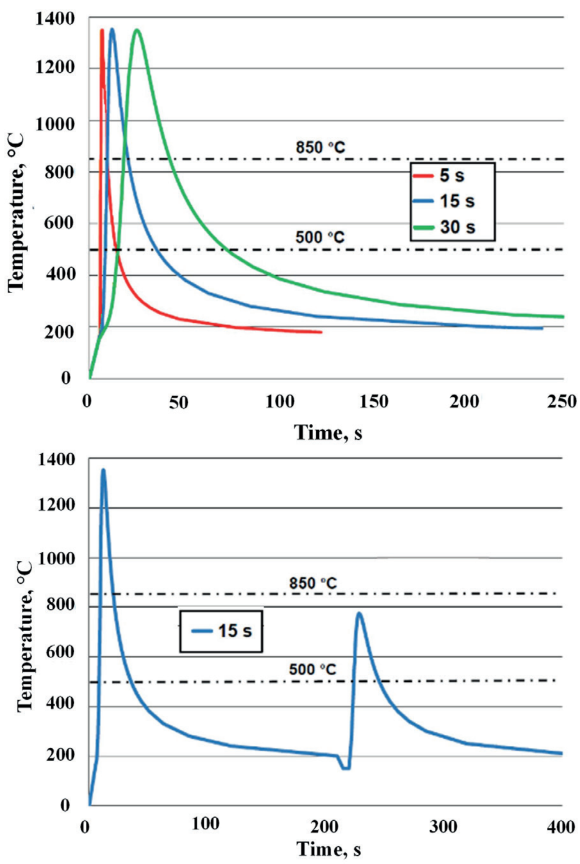


Fig. 1 Heating models for Gleeble simulation

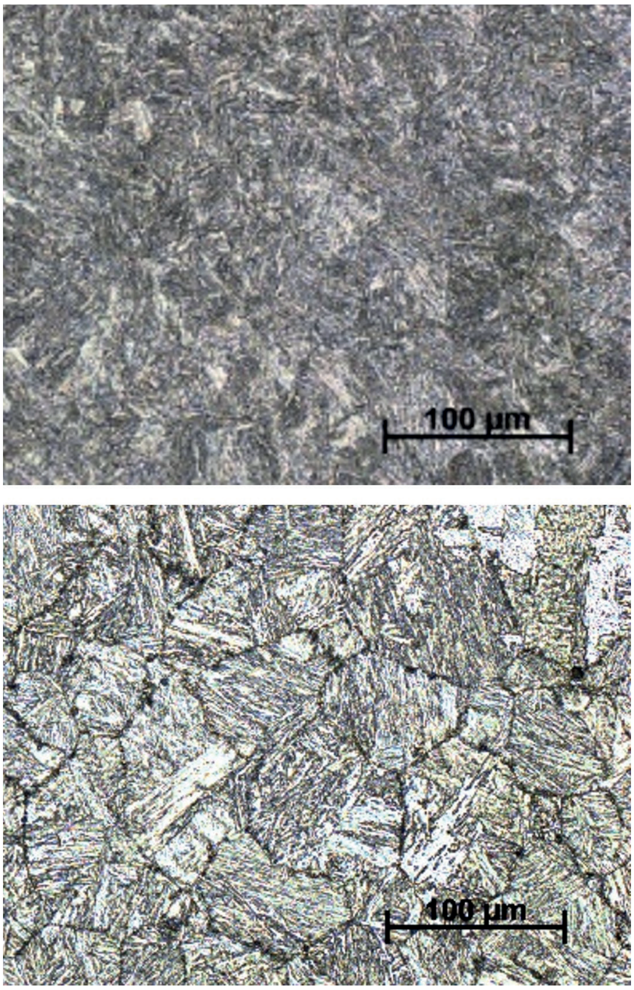


Fig. 2 Microstructure of the specimens, above: T_{peak} = 1350 °C, $t_{8.5/5}$ = 5 s, below: T_{peak} = 1350 + 775 °C, $t_{8.5/5}$ = 30 s cooling time

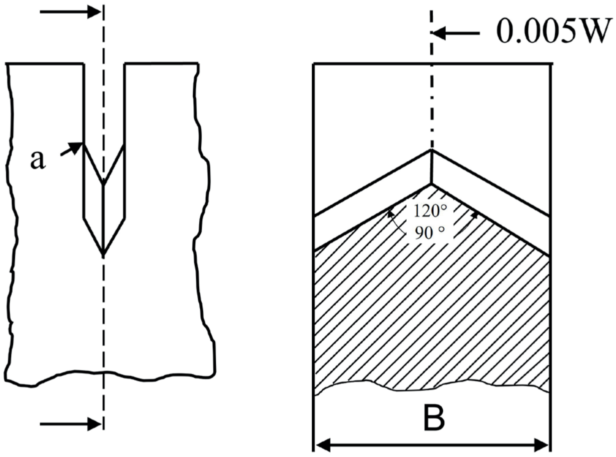


Fig. 3 Chevron notch geometry applied for the simulated specimens (*a* = crack length, *B* = specimen thickness, *W* = specimen width)

rate and a mean value of 273 HV1 (standard deviation coefficient: 2.3%) was measured for specimens with 30 s cooling rate.

2.3 Fatigue precracking procedure

After simulation, the 18 specimens were prepared for the fracture mechanical test. Chevron notch, see Fig. 3, was machined in each specimen, in the HAZs.

The specimens were fatigue precracked, according to the ISO 12135 [11] standard, with a maximum force of 3160 N in 9-14 steps, until the precrack length reached 1.3…1.5 mm on the surface. The crack propagation on the surface was observed with a digital camera.

2.4 Three-point bending tests

Three-point bending tests were carried out on universal mechanical testing machine MTS 810.2, at room temperature.

The adjusted experimental circumstances are:

- applied load: static increasing;
- applied velocity: 0.05 mm/s;
- lower support and upper bending radius: 5 mm;
- span: 40 mm.

The crack tip opening displacement was measured by a strain gauge type MTS 632.02C attached to a clip placed between two accurately positioned knife edges at the mouth of the machined notch, applied with measurement range of ±1.5 mm.

For the investigation, own developed program was applied in the frame program of MTS TestWare, the controlled variable was the piston displacement. During investigations, the piston displacement and crack tip opening data were registered. Test data were collected from the applied load and the clip gauge displacement and were recorded electronically and stored on the computer.

After loading, the specimens were marked by heat tinting in a chamber at 250 °C for an hour. Following that they were broken open and the fracture surfaces and different types of crack length were examined at 9 locations (see numbers 1…9 in Fig. 4).

3 Test results

The recorded data for the investigated HAZs of S960M material grade showed a maximum force plateau on the load – CTOD diagram, see Fig. 5.

In order to determine the *CTOD* value (δ_0), the original crack length a_0, and any stable crack extension, Δa that may have occurred during the test have to be measured on 9 locations on the fracture surfaces (see Fig. 4 on the left hand side). The identification of different crack types on the fracture surfaces was not unambiguous. The typical

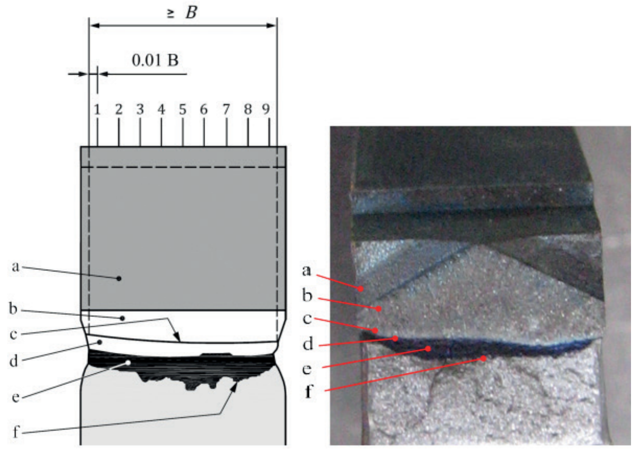


Fig. 4 Measurement of different crack length on the fracture surface according to ISO 12135; (a) machined notch, b) fatigue precrack, c) initial crack front, d) stretch zone, e) crack extension, f) final crack front)

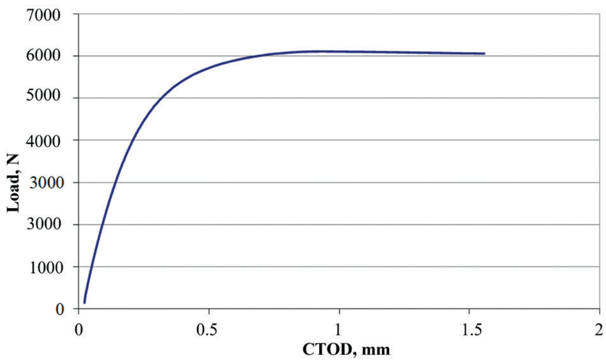


Fig. 5 Typical load – CTOD diagram showing maximum phenomenon

lines for fatigue crack extension during the different loads could not be identified, furthermore no stretch zone could be realized on the fracture surface. The stable crack extension was marked significant after heat tinting, thus the final crack length could be measured accurately.

The *CTOD* value was calculated applying the formula [11] given by Eq. (1):

$$\delta_0 = \left[\frac{S}{W} \cdot \frac{F}{\left(BB_N W\right)^{0.5}} \cdot g_1\left(\frac{a_0}{W}\right) \right]^2 \cdot \frac{1-\nu^2}{2YS \cdot E} + \frac{0.4\left(W-a_0\right)}{0.6a_0 + 0.4W + z} \cdot V_p, \quad (1)$$

where

S: span, mm;

W: specimen width, mm (nominally 10 mm);

F: applied load, N;

B: specimen thickness, mm (nominally10 mm);

B_N: specimen net thickness between side grooves, mm;

g_1: geometry function given in standard [11];

a_0: initial crack length, mm;

ν: Poisson's ratio, –;

YS: Yield strength, MPa;

E: modulus of elasticity, GPa;

z: the initial distance of the notch opening gauge measurement position from the notched edge of the specimen, mm;

V_p: plastic component of V, mm.

When the test record exhibits a maximum force plateau prior to fracture without significant prior pop-ins (sudden increase in force followed by sudden decrease), values of F_m and V_m shall be obtained from the test recorded at the point corresponding to the first attainment of the maximum force.

3–3 result are available for the simulation with one heating-cooling cycle, however during the fracture mechanical investigations some unexpected circumstances occurred, therefore only 2–2 result could be evaluated for simulations with double heating cycle. The results of fracture mechanical investigations and calculations are given in Table 2. The qualification of δ_0 fracture toughness is in every investigated case δ_m. In the last column of Table 2 the mean CTOD values of differently simulated HAZ are given. According to these values it can be stated that there is no unambiguous tendency between the $t_{8.5/5}$ cooling times and the CTOD values for one heating cycle and nor for double heating cycle. The lowest δ_m values belong to $t_{8.5/5} = 5$ s cooling time, in both cases. The highest δ_m values

Table 2 CTOD values of different simulated HAZ areas

	$t_{8.5/5}$ s	Nr.	F_m, N	a_0, mm	V_p, mm	δ_m, mm	δ_m mean, mm
1350 °C							
	5	1	9253	3.88	0.39	0.17	0.22
		2	9100	4.00	0.71	0.28	
		3	9300	3.97	0.51	0.21	
	15	6	7600	3.91	0.64	0.26	0.29
		7	7200	4.02	0.76	0.29	
		8	9075	3.76	0.74	0.31	
	30	9	9451	3.91	0.59	0.24	0.25
		10	6600	4.01	0.65	0.25	
		11	6100	3.95	0.64	0.25	
1350 °C and 775 °C							
	5	14	4852	3.95	0.38	0.15	0.15
		15	5251	4.04	0.39	0.15	
	15	17	6601	3.91	1.19	0.46	0.40
		18	4300	3.91	0.87	0.34	
	30	21	5150	3.96	0.66	0.26	0.27
		22	4352	3.91	0.75	0.29	

belong surprisingly not to $t_{8.5/5}$ = 30 s, but to t$t_{8.5/5}$ = 15 s cooling time, in both cases. Concluding all the evaluated results, it can be stated, that the δ_m values do not differ significantly applying different simulation methods.

However, the fracture mechanical investigation, the three-point bending test, takes only some minutes, if the total time is summarized with sample preparation and the measurements and evaluation after the test, the fracture mechanical analyses of one specimen takes 1.5…2 days. Furthermore, the machining of a high strength steel is an expensive process. Due to the long investigation time and the higher cost of sample preparation it is advantageous to give reliable results from only a few specimens. The reliability is increased with the control calculation following the investigations given in the standard [11].

For the given investigation, the requirements are fulfilled for the following parameters: specimen geometry, surface roughness, accuracy and reliability of the testing machine, the value of stress intensity factor of fatigue precracking.

The requirements are not fulfilled or only partially fulfilled for the following parameters: all parts of the fatigue precrack have extended at least 1.3 mm or 2.5% of W, whichever is greater, from the root of the machined notch (this value is generally smaller in our case); none of the seven interior final crack length measurements differs by more than $0.1(a_0 + \Delta a)$ from the nine-point average final crack length (this value is changing in our case).

4 Discussion

Since there are already measured data available for base material at room temperature for fracture mechanical behavior, it is possible to compare the results with the results measured for the HAZs.

Different investigation parameters can be considered, to have a wider impression about the properties.

The first parameter could be a maximum load, which was necessary for the initiation of crack propagation during the fatigue precracking stage. In case of the base material a maximum force was 8560 N, while in case of the HAZ specimens only 3160 N.

During the fracture mechanical three-point bending tests the suffered maximum load was significant (almost three times higher in case of base material specimens), 26000…30000 N for base material and 4300…9500 N for HAZ specimens.

The mean stable crack extension during the three-point bending tests was smaller for the base material's specimens, 0.3 mm, while for the HAZ specimens 0.46 mm.

The recorded diagrams during the fracture mechanical three-point bending tests were also different, see Fig. 6.

In case of base material's specimens pop-in phenomenon could be identified for several measurements. In these cases, the δ value was under 0.2 mm, and its index was δ_c. In cases, when the recorded diagram showed maximum force plateau, the value of δ was over 0.2 mm, and its index was δ_m. In case of HAZ specimens only diagrams with maximum force plateau could be recorded, where the value of δ was over 0.2 mm, and its index was δ_m.

All these mentioned behaviors led to a conclusion that no decrease in toughness could be observed, the specimens of HAZ showed more tough behavior than the specimens of the base material.

Further interesting behavior could be analyzed on the fracture surfaces of the specimens, see Fig. 7. On the fracture surface of the base material wider and smaller straight holes can be seen, oriented in one direction, it seems like if the microstructure would contain pancake-like structure-elements. This behavior is not visible on the fracture surfaces of HAZ, but it has to be considered, that the whole specimen was heat treated by Gleeble simulator.

5 Summary

The present paper represents results of physical simulation experiments on the HAZ of S960M advanced high strength structural steel. In the Gleeble 3500 simulator the applied peak temperature was 1350°C furthermore with an additional tempering temperature of 775 °C, the adjusted $t_{8.5/5}$ cooling times changed among 5 s, 15 s and 30 s, appropriate to GMAW parameters.

Common fracture toughness values are not simple to determine, due to the ductile behavior of high strength steels. Based on these properties crack-tip opening dis-

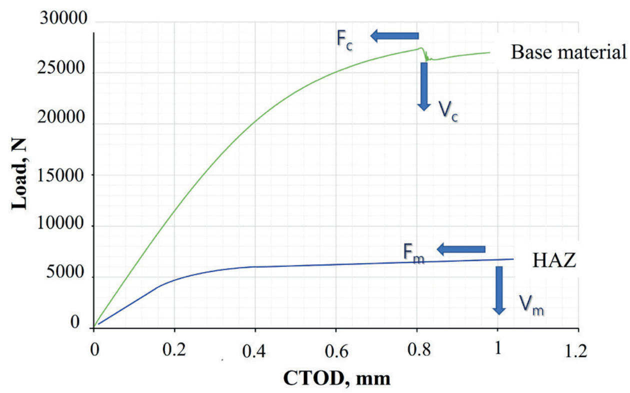
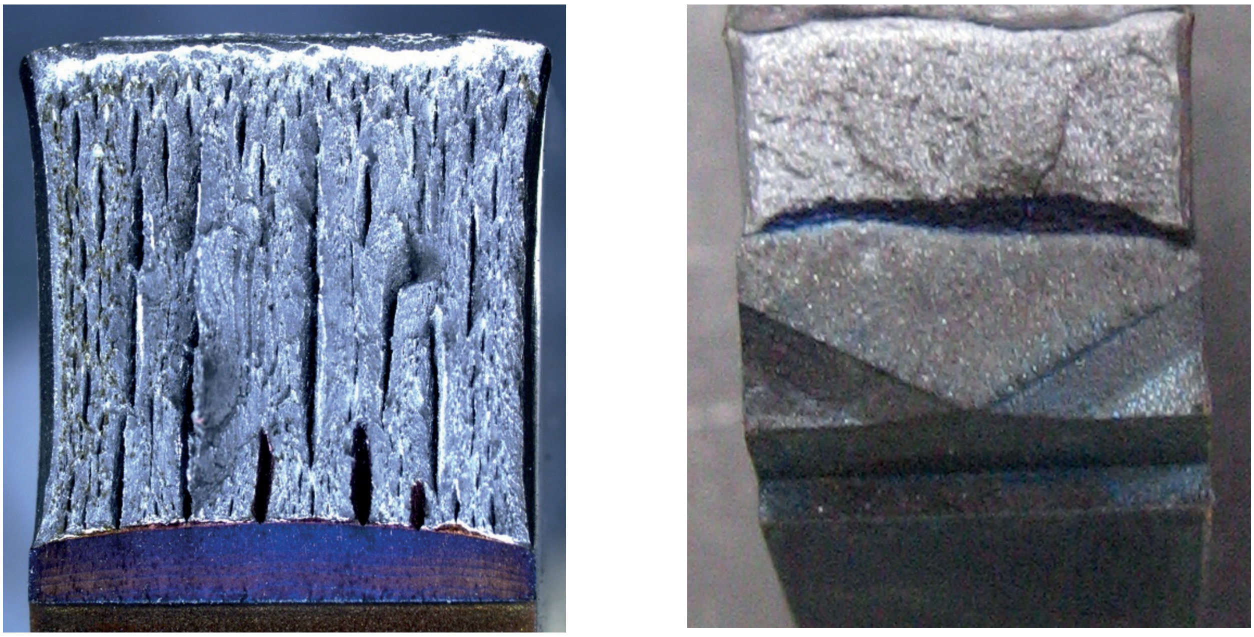


Fig. 6 Comparison between the typical recorded load – CTOD diagram for base material and HAZ specimens



(a) (b)

Fig. 7 Fracture surfaces of base material (a) and typical HAZ (b) specimen

placement (*CTOD* or δ) values were characterized on the simulated HAZs, according to the ISO standard [11]. The δ_0 values were calculated, but no unambiguous conclusion could be drawn for the different simulated heat affected zones. However, it can be concluded, that all the registered load-crack tip opening displacement diagrams showed a maximum force plateau, and a δ_m characteristic measure could be determined.

Compared the results with the base material properties it can be stated that no decrease in toughness could be observed in the specimen prepared for HAZ.

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