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Experimental determining of fracture behaviour of P460NL1 steel welded joint specimens

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Abstract

This paper is focused on the experimental measuring of impact energy as a part of the doctoral dissertation involving the fatigue behaviour of welded joints, made of fine grain normalised micro-alloyed low carbon high strength steel P460NL1 [1,2], typically used for pressure vessels working at subzero temperatures. VAC 65 [3] was used as filler material, and two plates were welded using the MAG welding procedure (with 82% Ar + 18% CO_2 shielding gas).
The specimens were taken from two opposite ends of the welded plate, taking into account the measured values of groove edge temperature in these locations, wherein the temperatures in Location 2 (near the end of the weld) were higher than those in Location 1 (near the weld's beginning). Based on their specific position, in terms of temperature and notch position (weld root or face), the specimens were divided into four groups of three. This testing was performed using a SCHENCK-TREBEL instrumented Charpy pendulum. The total impact energy was determined, along with its components, crack initiation and crack propagation energy.
The obtained results have confirmed that the test specimens were of high toughness, with total impact energy ranging from 165-200 J, at room temperature. The crack propagation energy was the dominant component, being several times greater than the crack initiation energy, as was expected.

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1. Introduction

The aim of this research was to determine the relationship between the components of impact energy, crack initiation energy and crack propagation energy [4-6], and how their values and ratios was affected by the locations from which the specimens were taken. This was performed in order to determine if the different temperatures, measured at opposite ends of the welded plate from which the specimens were taken, had a noticeable effect on the fracture behaviour, since these differences affected the microstructures of the welded joint specimens.

Impact test were performed using a total of 12 V-notched Charpy specimens, in accordance with ASTM E 1820:13 standard [7], wherein the notches were located in the heat affected zone, on either root or face sides of the welded joint. To account for the difference in temperatures measured along the joint during the welding process, specimens were taken from the opposite sides of the plate, referred to as locations 1.1 (lower temperature) and 1.2 (higher temperature) [8].

2. Materials and the experiment

Impact test specimens were made using micro-alloyed low-carbon ferrite steel P460NL1, with VAC 65 as filler material, whereas the welding was performed using the metal active gas (MAG) procedure, with a mixture of 82% Argon and 18% CO_2, with a total of six welding passes (root and five fills). Mechanical properties and chemical composition of the materials used can be seen in tables 1 and 2, whereas table 3 shows the results of temperature measuring during all six welding passes, at locations 1.1 and 1.2. Specimens for impact testing (which was performed using a SCHENCK-TREBEL instrumented Charpy pendulum) had dimensions of 10x10x55 mm, in accordance with standard ASTM E:1820-13, and a total of 17 specimens were cut. Two of these were taken from the weld metal, and will not be considered in this paper, beyond pointing out that there impact energy values were noticeably lower than the rest of the specimens, as expected. The welded plate and the specimen geometry are shown in figure 1.

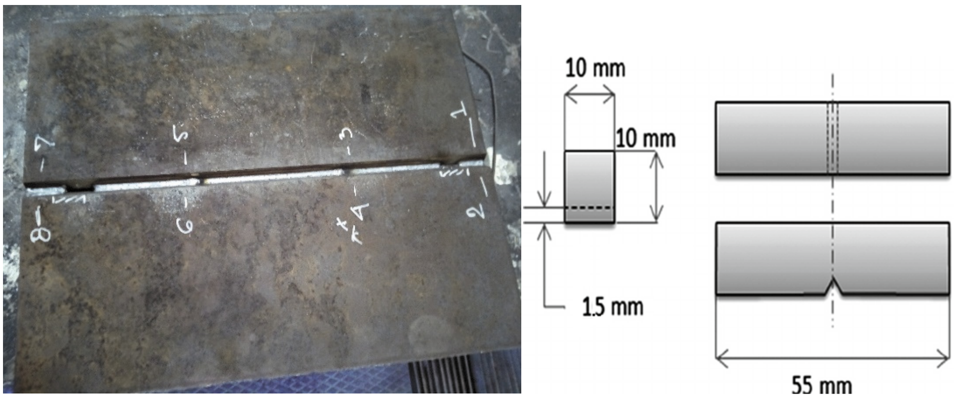

Figure 1. Welded plate, made of P460NL1 steel, and the geometry of the Charpy test specimens.

Table 1. Chemical composition of parent and filler material [8]

Material	C	Si	Mn	P	S	Al	N	Cr
P460NL1	0.16	0.39	1.42	0.007	0.003	0.03	0.0055	0.04
	Cu	**Mo**	**Nb**	**Ni**	**Ti**	**V**	**B**	
	0.093	0.10	0.038	0.67	0.03	0.098	0.0003	
VAC 65	**C**	**Si**	**Mn**	**P**	**S**			
	0.08	1.0	1.70	<0.025	<0.025			

Table 2. Mechanical properties of parent and filler material [8]

Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation %
P460NL1	460	570-720	≥ 17
VAC 65	≥ 460	560-680	≥ 22

Table 3. Temperatures during the welding for specimens taken from locations 1.1 and 1.2 [8]

Welding pass	Location 1.1		
	Temperature (°C)	Heat input Q (kJ/mm)	Cooling time $t_{8/5}$ (sec)
Root	94	0.69	3.4
Fill I	105	0.80	4.9
Fill II	113	0.84	5.6
Fill III	112	1.03	8.4
Fill IV	110	1.17	10.8
Fill V	110	1.08	9.2

Wedling pass	Location 1.2		
	Temperature (°C)	Heat input Q (kJ/mm)	Cooling time $t_{8/5}$ (sec)
Root	188	0.69	5.8
Fill I	178	0.80	7.4
Fill II	234	0.84	11.8
Fill III	269	1.03	23.3
Fill IV	230	1.17	22.2
Fill V	230	1.08	19.0

As for the remaining 15 specimens, three were notched in the parent material, whereas the rest had a notch in the heat affected zone. These 12 specimens were divided into four groups, in the following way:

- Specimens denoted 7-9, with a notch in the weld face side of the HAZ, taken from location 1.1
- Specimens denoted 10-12, with a notch in the root side of the HAZ, taken from location 1.1
- Specimens denoted 15-17, with a notch in the root side of the HAZ, taken from location 1.2
- Specimens denoted 18-20, with a notch in the weld face side of the HAZ, taken from location 1.2

The experiment involved measuring of total impact energy, and its components, crack initiation energy, A_i and crack propagation energy A_p. The goal was to determine the ratios between these two components and how they are affected by different factors, such as the temperature (and the resulting microstructures) and the notch position, for each group of test specimens. It was assumed that crack propagation energy values will be noticeably greater, since the material in question, P460NL1 is ductile, even at lower temperatures, whereas these tests were carried out at room temperature.

3. Results and discussion

In this section of the paper, the results for one specimen of each group are shown, in figures 2-5, in the form of diagrams showing the dependence of total Impact energy (J) from time (ms). The results for all 12 specimens are shown in table 4 below.

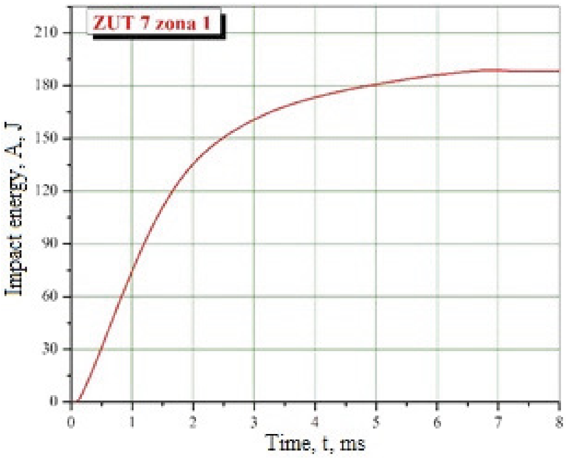

Figure 2. Total impact energy for specimen 7 (face side notch, location 1.1)

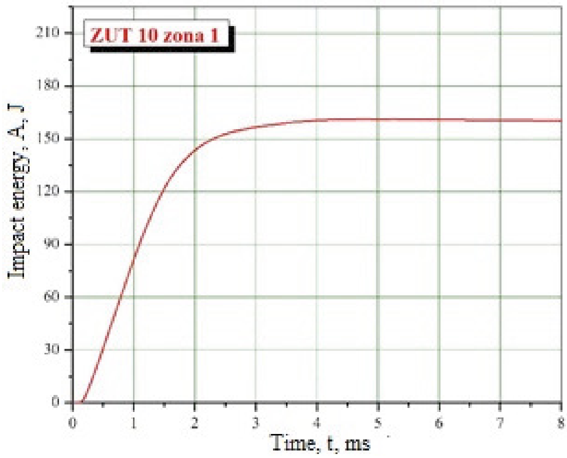

Figure 3. Total impact energy for specimen 10 (root side notch, location 1.1)

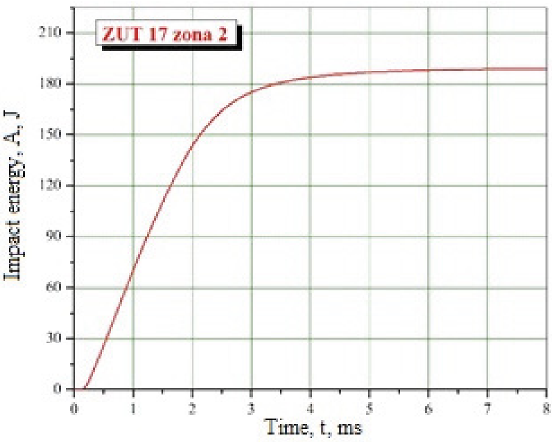

Figure 4. Total impact energy for specimen 17 (root side notch, location 1.2)

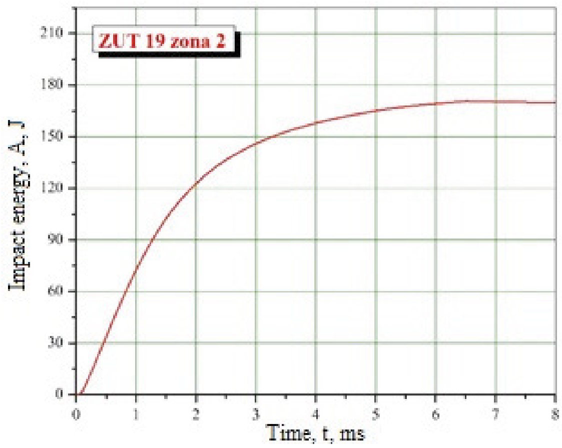

Figure 5. Total impact energy for specimen 19 (face side notch, location 1.2)

The crack propagation energy was the dominant component, being several times greater than the crack initiation energy, as was expected. Furthermore, the temperature differences, caused by the heat input during the welding, did not have a noticeable effect on the crack initiation and propagation energy ratio. Additionally, the total impact energy values of specimens taken from different ends of the welded plate showed negligible differences. The crack initiation and propagation energy ratios, however, were affected by the position of the notch.

Table 4. Results of impact testing.

Specimen	Impact toughness (J/cm^2)	Impact energy (J)	Crack initiation energy (J)	Crack propagation energy (J)
HAZ 7	237	189	50	139
HAZ 8	180	144	41	103
HAZ 9	247	198	52	146
HAZ 10	201	161	73	88
HAZ 11	231	185	80	105
HAZ 12	223	178	69	109
HAZ 15	226	181	74	107
HAZ 16	221	177	74	103
HAZ 17	237	190	67	123
HAZ 18	213	171	41	130
HAZ 19	213	171	41	130
HAZ 20	118	94	24	70

As can be seen from the results shown above, obtained values of impact energy and impact toughness varied between different specimen groups. Maximum impact energy was measured for specimen denoted as HAZ 9, from the first group (weld face notch, location 1.1), and it was 197.84 J, whereas the lowest value was measured for specimen HAZ 8 (same group as HAZ 9) and it was 143.74 J. It should be noted that the actual lowest value was measured in the case of specimen HAZ 20, however, since this value resulted from the presence of defects in that part of the welded joint, and was significantly different from the other results (being lower even than the values obtained for weld metal specimens) it was discarded altogether. On the other hand, its ratio of crack initiation to crack propagation energy was similar to the other two specimens from this group.

Despite the fact that both maximum and minimum values were obtained for specimens from the same group, the mean values for each group were somewhat similar to each other, and it was determined that the specimens with the notch in the root side of the HAZ have slightly higher and more even impact energy values, compared to specimens from groups 1 and 4 (with the weld face notch), specimen HAZ 20 notwithstanding. Maximum force values recorded for root HAZ specimens (ranging from 18.4 – 21.2 kN) were also greater than those of weld face HAZ specimens (16.6 - 18.4 kN).

Certain differences were observed between the ratios of impact energy components, A_i and A_p (crack initiation and crack propagation energy), for different specimen groups. In the case of specimens with the notch in the weld face side of the HAZ (7-9 and 18-20), crack propagation energy is noticeably higher than the crack initiation component, and their ratio ranges from 2.5 to 3.25x in its favour. It was also determined that specimens from the group taken from location 1.2 have a higher share of propagation energy in the total impact energy, i.e. that their Ap/Ai ratios are higher compared to location 1.1, suggesting that the ductility of these specimens improved with an increase in temperature during the welding process.

As for the remaining two groups of specimens, denoted as 10-12 and 15-17, the ratios of impact energy components are not as prominent in favour of the propagation component – they range from being 1.2 – 1.85 times greater than crack initiation energy for all of the specimens involved. However, their crack initiation energy is higher than that of specimens from groups 1 and 4, and the total impact energy is actually slightly higher due to this. Hence, it can be seen that, in the case of the notch being located in the root side of the HAZ, total impact energy and its crack initiation component are greater compared to the weld face notch specimens, although these specimens were less ductile than the root side groups, not only due to the A_p/A_i ratios being noticeably lower, but also due to crack initiation energy values, which were, on average, around 20-30% less than the values obtained for weld face notch specimens. Once again, specimens taken from the higher temperature region (18-20) had higher A_p/A_i ratios, resulting in higher ductility.

4. Conclusion

This research, carried out as a part of a doctoral thesis, involved the impact testing of a number of welded joint specimens, divided into four groups, based on the position of the notch and the location from which they were taken (which was considered due to differences in temperatures that occurred during the welding process). In addition to impact toughness and energy, crack initiation and crack propagation components were also measured and compared between different specimens.

Overall, the mean values of total impact energy for all groups were similar, ranging from 171 (for group 4) to 182.7 J (group 3). However, the ratios between their components, A_i and A_p, differed considerably, due to the factors previously described (notch location and temperature). It can be seen both highest and lowest mean values were observed at location 1.2 (higher temperature), i.e. that increased temperature resulted in more prominent differences. In addition, specimens with the notch in the root side of the heat affected zone had slightly higher impact energy and crack initiation energy values, whereas their crack propagation values were noticeably lower compared to weld face notch specimens. Based on this, it was concluded that the specimens taken from location 1.2 had shown better behaviour in terms of ductility, whereas the toughness was similar in both cases. Due to increased temperature, the heat affected zone in the case of location 1.2 was bigger compared to location 1.1, which contributed to the differences mentioned previously. While this resulted in better ductility, it also negatively affected the uniformness of the results, as can be seen from the increased differences in total impact energy between these specimens.

Further analysis will involve a more detailed investigation on how the microstructures (and their differences resulting from changes in temperature) affected the distribution of impact energy results, as well as the ratio between its components.

5. Acknowledgement

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