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Growth of fatigue cracks in specimens welded under bending with torsion

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Abstract. The paper presents the results of crack development in specimens welded from S355 steel under bending and torsional loading. Welded joints, as a method of inseparable joining of technical structures, are commonly used in many areas of human activity. The aim of the study was to analyse the influence of the shape of concave and convex fillet joints on the development of fatigue cracks. The experimental tests (fatigue tests) were performed with the use of the fatigue machine MZGS-100, at a constant amplitude of the moment M_a = 9.20 N·m, and the stress ratio R = - 1 with a load frequency of 28.4 Hz.

Introduction

Research on the durability of structures, materials and various types of connections (separable and inseparable) carried out in scientific units must answer the questions posed by designers and constructors, whether the applied solutions will be optimal. Optimal, fully understood areas of life, i.e. economy, security, rational management of material resources, technical equipment or human potential. The results of these tests should be helpful in determining the service life of each structure in which the failure occurrence is at the lowest possible level [1,2].

The method of inseparable joining of elements by welding is widely used. It includes products, structures and machines from all branches of industry. Therefore, the constant interest of scientists in this subject allows them to publish the results of their research and improve the quality and durability of the joined elements [3-5]. Materials used in industry and welded joints are not without material and welding defects. Therefore, they should be taken into account in the durability assessment. There are a number of publications discussing the influence of material, welding and geometric defects, as well as residual stresses [6,7]. The aim of the work is to present the results of fatigue crack development of T-shaped welded joints with fillet welds, made of steel S355 subjected to bending with torsion, taking into account the shape of the welds and the selected heat treatment.

Materials and Methods

The test specimens were made of structural steel grade S355, in the normalized state. This steel is widely used in industry, including the construction of ships, bridges, lifting devices, devices and construction of used in the mining industry, tanks and pipelines, etc. Table 1 shows the chemical composition of the material and Table 2 some mechanical properties. The starting material of the specimens was a drawn rod with a diameter of Ø 30 mm. Then, as a result of the performed machining and the TIG welding process, ready-made samples were obtained. T-welded joints, with fillet welds, were made in two variants of the weld face, i.e. concave and convex.

Table 1. Chemical composition (in wt %) of the S355 steel

C	Mn	Si	P	S	Cr	Ni	Cu	Fe
0.2	1.49	0.33	0.023	0.024	0.01	0.01	0.035	Balance

Table 2. Mechanical properties of the S355 steel

σ_y (MPa)	σ_u (MPa)	E (GPa)	ν (-)	A_5 (%)
357	535	210	0.30	21

The experimental tests were carried out on specimens welded without heat treatment and on specimens after heat treatments. The heat treatment was performed by subjecting the specimens to annealing at the temperature of 630°C for 2 hours. Shapes and dimensions of the tested specimens are presented in Fig. 1.

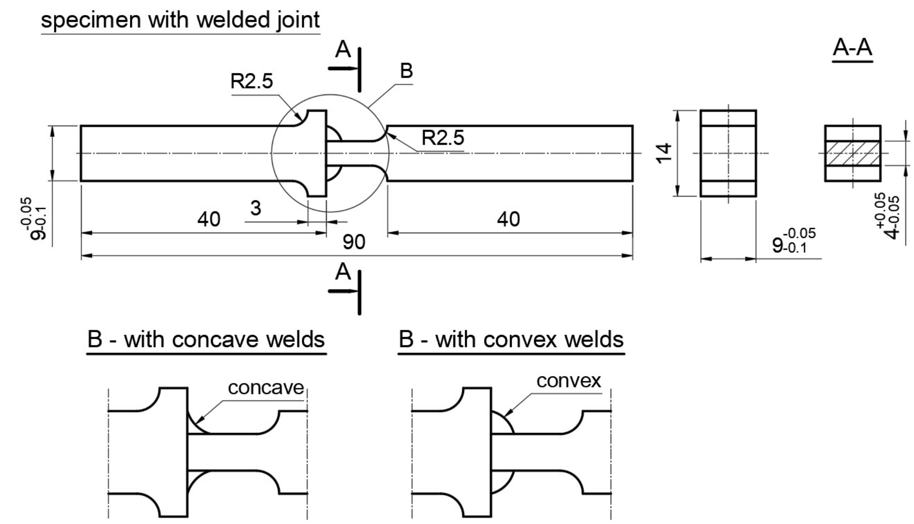


Fig. 1. Geometries of specimen with: (a) concave welds, (b) convex welds (dimensions in mm)

Metallographic tests were performed with the use of an optical microscope OLYMPUS IX70. Hardness measurements on the Vickers scale were carried out using a LECO MHT 200 hardness tester (LECO Corporation, St. Joseph, MO, USA), under a load of 100 g. The test to fatigue crack growth under cyclic bending with torsion were performed in the laboratory of the Department of Mechanics and Machine Design at Opole University of Technology on the fatigue test stand MZGS-100 [8,9] (Fig. 2). The loading method and the division into load components caused by bending and torsion are shown in Fig. 3. The tests were conducted under the amplitude of the total force moment control with the loading frequency of 28.4 Hz. The specimens restrained on one side were loaded with a constant amplitude of moments with the value M_a = 9.2 N·m and the load ratio R = - 1. The theoretical stress concentration factor, estimated with use of the model [10], in the solid specimen with concave weld under bending was K_t = 1.38 while it was 1.56 for the convex weld configuration.

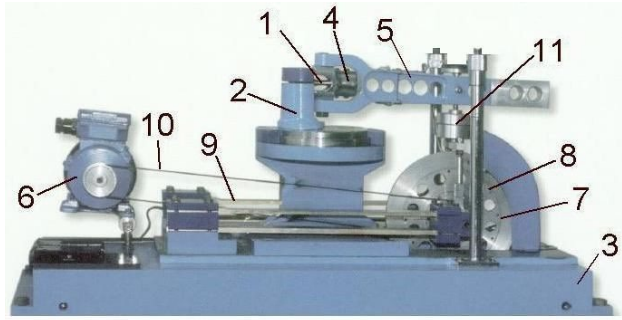
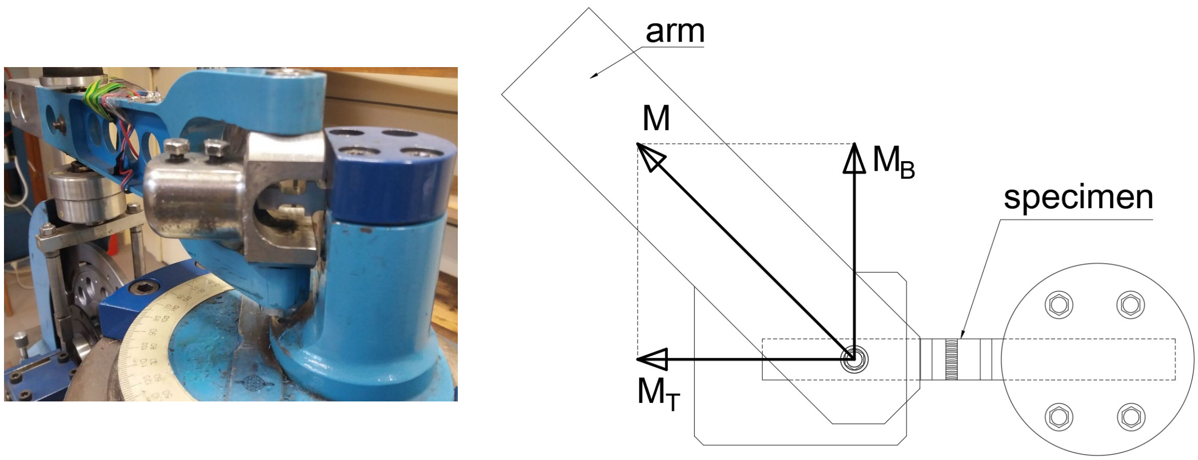


Fig. 2. MZGS-100 machine, where: 1 - specimen, 2 - rotational head with a holder, 3 - bed, 4 - holder, 5 - lever, 6 - motor, 7 - rotating disk, 8 - unbalanced mass, 9 - flat springs, 10 - driving belt, 11 - hydraulic connector



(**a**) (**b**)

Fig. 3. The loading method and the division into load components caused by bending and torsion: (a) specimen clamped in MZGS-100 machine, (b) scheme of bending with torsion loading applied to the specimen

During the tests, the number of load cycles N was recorded. However the fatigue crack increments were measured with the micrometer located in the portable microscope with magnification of 20 times and accuracy up to 0.01 mm.

Results

As a result of the metallographic tests carried out in welded specimens, without heat treatment, a dendritic structure was observed in the areas of welds, and in the heat-affected zone (HAZ), a thick acicular structure of martensite and bainite was observed. On the other hand, in the specimens welded after heat treatment in the area of welds and HAZ, a coarse-grained structure of bainite and sorbite was observed (Fig. 4).

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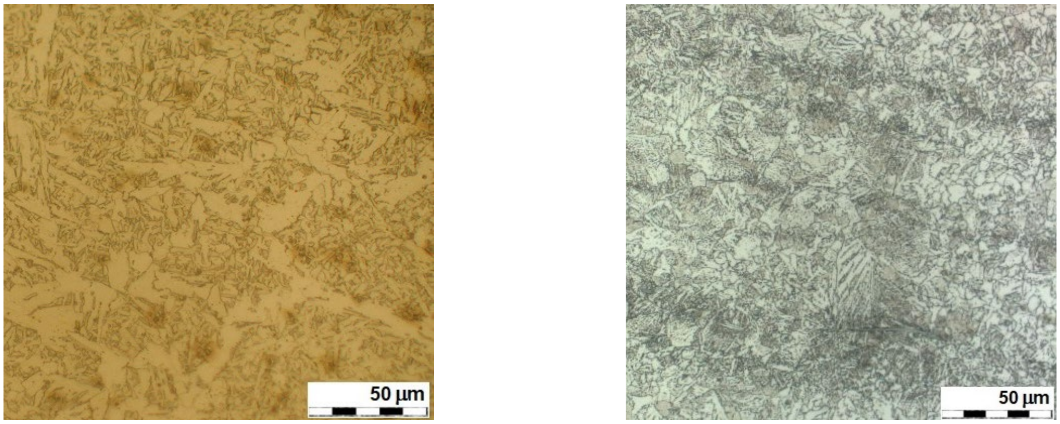

(**a**) (**b**)

Fig. 4. The microstructure of welds in HAZ for a) without heat treatment, b) after heat treatment

The results of hardness measurements of welded specimens without heat treatment (HT) and after HT for the averaged results of specimens with concave and convex welds attained values:

- for specimens welded without HT, the hardness values changed significantly depending on the place of measurement. For the base material, the hardness remained the same (188–189 $HV_{0.1}$). While in the heat-affected zone (HAZ) large fluctuations in hardness were observed (194–248 $HV_{0.1}$). Then, moving to the weld metal, the measured values decreased and stabilized (230–220 $HV_{0.1}$).
- in the specimens subjected to relief annealing, the measured hardness and their variability were lower compared to the hardness of the specimens without HT. The smallest values were measured in the base material (about 135 $HV_{0.1}$), then in HAZ the hardness increased and ranged from 137 to 149 $HV_{0.1}$. However, the highest hardness values were measured in the weld material (about 150 $HV_{0.1}$).

Figure 5 presents the fatigue crack length versus number of cycles for proportional bending with torsion. In Fig. 5 can be observed that the longest fatigue life indicates specimens welded with concave welds without heat treatment.

Crack initiation (0.10 mm) was at 53000 cycles. The further development of the crack was rather quick and the specimens failed at 58000 cycles. The lowest fatigue life indicates the specimen with convex welds after normalizing (HT). Crack initiation (0.10 mm) was at 9000 cycles, and the failure of the specimens occurred at the number of cycles of 17,000.

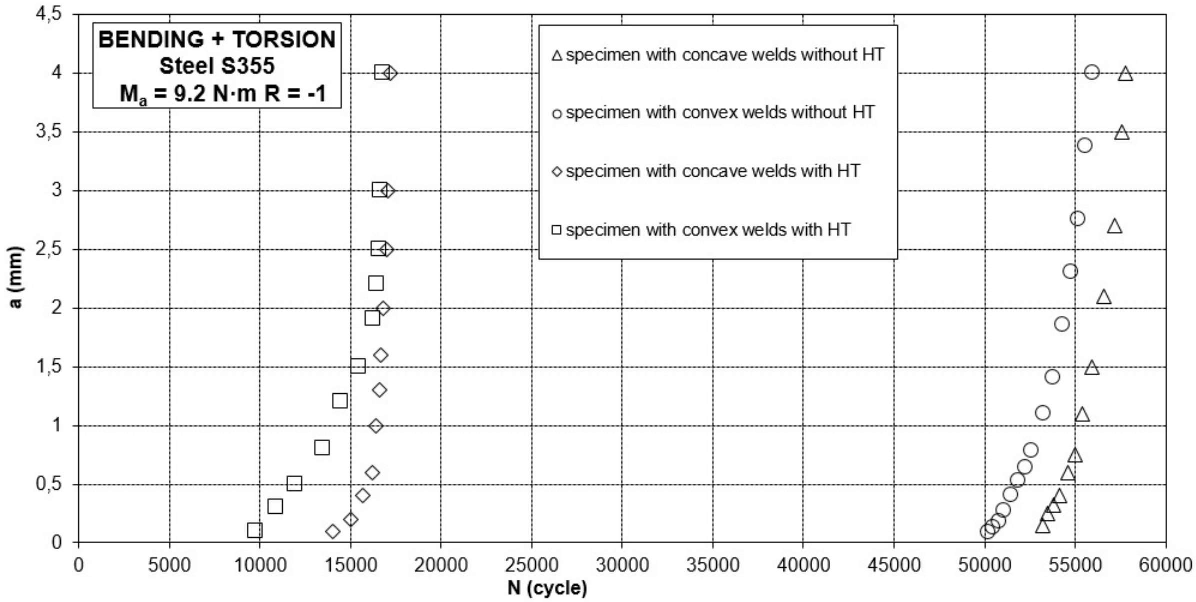

Fig. 5. Fatigue crack length vs. number of cycles under proportional bending with torsion

The differences in the fatigue life of the tested specimens welded with and without heat treatment are significant. In the case of specimens with concave welds, the decrease in fatigue life of relief annealed specimens was 69% compared to specimens without heat treatment. As in the case of specimens with concave welds, a 70% decrease in fatigue life of relief annealed specimens was observed for samples with convex welds compared to specimens without heat treatment. When comparing the durability of samples with concave and convex weld faces, for the same specimen (without heat treatment and after heat treatment), it can be seen that for specimens with concave welds, the durability was always higher compared to specimens with convex welds. The decrease in fatigue life of specimens with convex welds without heat treatment was 4.5% in comparison to specimens with concave welds. However the decrease in fatigue life of specimens with convex welds after heat treatment was 5.5% in comparison to specimens with concave welds. According to the authors, the significant drops in fatigue life in the specimens subjected to heat treatment were caused by structural changes taking place in the tested material. The higher durability of specimens with concave welds compared to specimens with convex welds is due to the occurrence of sharp notches in specimens with convex welds, which gave rise to cracks. The results of the fatigue life of the specimens without HT and with HT (annealing) obtained and presented in the publication are consistent with the results described in the work [11, 12], in which the authors examined the impact of heat treatment, i.e. hardening with tempering and annealing, on the fatigue life of steel.

Exemplary fatigue crack path is shown in Fig. 6 for a specimens without heat treatment with concave (a) and convex (b) welds and in Fig. 7 for a specimens with heat treatment. During laboratory tests, initiation and development of cracks occurred from one side of the specimen (from top or bottom) were observed, at the place of highest stress concentration, and after a certain period of propagation, the crack growth occurred also on the other side. The photos reported in Figs 6, 7 show crack paths whose shapes are typical of mixed modes I+III of fracture (bending with torsion). In all the considered cases the cracks were initiated perpendicular to the maximum normal stresses, in the fusion line, hence it can be assumed that the crack initiator was a geometric notch at the point of transition of the base material into the weld. After initiation, crack growth path develop along different planes depend on local stress state ahead of a crack tip strongly associated with weld geometry, microstructure and residual stresses after welding process.

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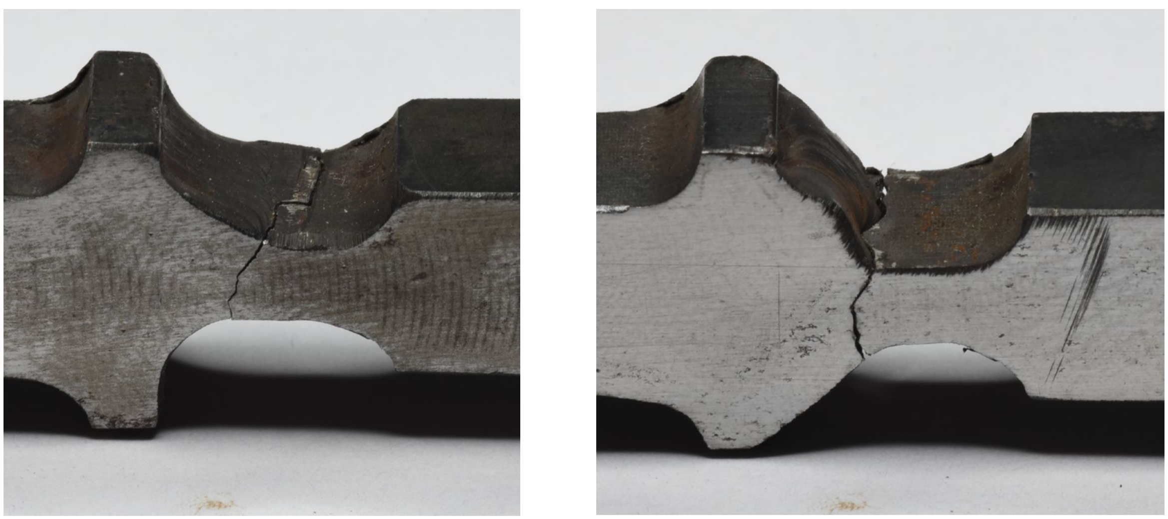
(**a**) (**b**)

Fig. 6. Examples of stages of crack development in a weld specimen without HT: (a) concave welds, b) convex welds



(**a**) (**b**)

Fig. 7. Selected stages of crack development in a weld specimen with HT: (a) concave welds, b) convex welds

Conclusions

The study presented the results concerning the fatigue crack growth in S355 steel specimens subjected to bending and torsion loading. The experimental outcomes allow to state the following conclusions:

- Fatigue life of the welded specimens without heat treatment were higher compared to the welded specimens with heat treatment, with slightly higher durability of specimens with concave welds.
- Initiation and fatigue crack growth in all test specimens started on one-side of the specimen, at the place of highest stress concentration, in the fusion line.
- The tested specimens, with heat treatment and without heat treatment, show different cracking courses.
- Cracking paths in tested specimens, with heat treatment and without heat treatment, show different courses.

- The propagation of cracks usually occurred in the HAZ where the highest hardness was measured.
- The highest material hardness was measured on specimens without heat treatment in HAZ, and the lowest in specimens after heat treatment.

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