# INFLUENCE OF WELDING HEATING ON FATIGUE STRENGTH OF HOLLOW STRUCTURES FROM HIGH-STRENGTH FINE-GRAINED STEELS

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Welding trials and technological assessment of square hollow sections of 80 × 80 × 10 mm size from steel of SG69Q grade were performed. Welds were assessed on macrosections, by hardness measurement, their static bending and impact testing. In order to determine fatigue strength at bend testing with cycle asymmetry factor $R = 0.5$ under the conditions of rail transport works, these sections were joined by mechanized gas-shielded solid and flux-cored wire welding. Comparison of section testing results and their compliance to normative requirements was performed. Recommendations on application of various sections in structures with cyclic loading are given. 18 Ref., 5 Tables, 12 Figures.

***Keywords:*** *arc welding, metal electrode, shielding gas, high-strength steels, hollow sections, fatigue strength, light-weight structures, recommendations for application*

Such structural elements as square and rectangular hollow sections have been applied in mechanical engineering and instrument making, in vehicle manufacture and steel structure fabrication for dozens of years. Seamless hot-rolled hollow sections without a longitudinal weld are exactly the elements with uniform material properties over the entire cross-section. As the profiles are not subjected to cold deformation in manufacturing, they feature excellent weldability, particularly in the vicinity of the edges. Moreover, seamless hot-rolled hollow sections have a wide range of wall thicknesses, even at a comparatively small edge length. Owing to their large flat contact surfaces as a result of small angular rounding-off, the sections are highly suitable for compact structures exposed to high loads [1, 2].

Steels of 355 MPa strength class are predominantly used for steel structures. Higher strength steels are needed for agricultural machinery, where square and rectangular sections with up to 500 MPa yield limit are used (Figure 1). In addition, high-strength steels with up to 960 MPa yield limit, proposed by Vallourec & Mannesmann, already begin to be applied in transportation engineering that became an essential contribution to solving the task of reducing structure weight.

However, application of high-strength steels in transportation engineering involves the need to allow for fatigue properties of the joints. In

**Figure 1.** Production of square MSH-sections in the last rolling stand (*a*), and their application in agricultural machinery engineering (*b*)

terms of admissible number of load cycles at a specified loading pattern, evaluation of metal properties, primarily in the weld area, is highly important.

In this connection investigations were conducted to assess the loading impact on properties of welded parts of a certain configuration. Selection of dimensions, steels, spectrum and scope of investigations is oriented towards the requirements of transport engineering.

The subject of discussion is rectangular or square hollow steel sections of MSH grade, manufactured from unalloyed or fine-grained structural steels by Vallourec & Mannesmann in compliance with EN 10 210–1 [3]. Supply spectrum includes hot-rolled sections of 40 × 40 to 300 × 300 mm size (square) and those of 50 × 30 to 300 × 200 mm size (rectangular). In addition, MSH-sections can be manufactured with longitudinal welds made by high-frequency induction resistance welding, and MSH-sections of 400 × × 400 (square) or 500 × 300 mm size (rectangular) from hot-rolled metal can be produced. Wall thickness is standard — up to 20 mm.

Improved MSH-sections developed on the basis of the concept of alloying fine-grained steels of the strength from 690 to 890 MPa are put on the market under the name of FineXcell®. They have minimum yield limits of 690 MPa in the lower range of wall thickness (≥16 mm) and good toughness.

**Welding of fine-grained structural steels.** In welding it is necessary to make sure that material properties will not deteriorate more from thermal impact than) from the load of the structure proper. As welding conditions essentially influence the joint properties, the task of specialists is to ensure the required metallurgical properties of the deposited and HAZ metal. Mechanical properties of welded joints are determined by temperature-time welding cycle. Current, voltage, welding speed, as well as item thickness and weld geometry, have a great influence. These parameters proper determine the temperature-time cycle of welding, often characterized by metal cooling rate in the temperature range 800–500 °C. High rate of metal cooling from the austenitic region can lower the toughness of welded joint HAZ metal. More over, the risk of cold cracking in the deposited and HAZ metal can become higher. As a result of slower cooling of the weld, its strength can decrease and it will no longer correspond to strength properties of base metal.

An effective means of cold crack prevention is preheating. Preheating temperature is understood to be item temperature in the vicinity of the weld directly before welding. Preheating temperature is assigned, depending on the material, its wall thickness, weld geometry and heat input value. Temperature is increased with increase of metal thickness that slows down cooling of weld metal zone and promotes hydrogen evolution. In addition, preheating has a positive influence on inner stressed state of the joints. Steel proneness to cold cracking has an essential influence on welding operations cost. For this reason it is important to classify steels, depending on their crack resistance. Useful information on this problem is published in [4–7], where carbon equivalent CET (%) is proposed as crack resistance criterion:

$$\mathrm{CET} = \mathrm{C} + (\mathrm{Mn} + \mathrm{Mo})/10 + (\mathrm{Cr} + \mathrm{Cu})/20 + \mathrm{Ni}/40.$$

At appearance of cold cracks the situation can be such that preheating temperature was selected correctly, but the actual heat removal in the item was incorrectly assessed. First, according to [8], preheating temperature should be measured at a sufficient distance from the weld. Secondly, it is necessary to thoroughly heat the locations where several welds meet, and where, alongside a more intensive heat removal, a 3D stressed state can be in place, further promoting cold cracking. In addition to chemical composition of base and deposited metal, appearance of cold cracks largely depends also on wall thickness, hydrogen content in the deposited metal, as well as inner stressed state of the joint. Method of calculation of minimum preheating temperature, known as CET concept, is included into «STAHL-EISEN-Werkstoffblatt SEW 088» journal [9], as well as into EN 1011 standard [10].

Heat input $Q$ is calculated by determination of energy input $E$ and depending on thermal efficiency of the process η by a known equation described in [10]:

$$E = \frac{U_a I_w \cdot 60}{v_w \cdot 10000}\ (\mathrm{kJ/mm}) \text{ or } Q = \frac{\eta U_a I_w \cdot 60}{v_w \cdot 10000}\ (\mathrm{kJ/mm}),$$

where $U_a$ is the arc voltage, V; $I_w$ is the welding current, A; $v_w$ is the welding speed, cm/min; η = 0.85 is the MAG welding thermal efficiency.

**Technological investigations.** *Selection of welding consumables*. For welding high-strength fine-grained steels the filler materials of various manufacturers and suppliers are selected, depending on their yield limit. Both solid and flux-cored wire is used, in keeping with EN DIN 18276, in shielding gas atmosphere M21 ($CO_2$ + + 82 % Ar), according to EN ISO 14175 [11]. When selecting the wire, it is necessary to take into account not only its cost, but also fabrication costs for the produced structure.

In this respect, seamless rutile, basic or flux-cored wires with metal core have advantages, compared to solid wire, as they provide specific properties. The following filler consumables were used in welding experiments described below:

• to EN ISO 16834-A solid wire GMn4Ni1.5CrMo [12] (ED-FK 800);

• according to EN ISO 17632-A T69 6 flux-cored wire with metal powder for root welding MnN2NiCrMo MM1H5 (STEIN-MEGAFIL 742 M) [13], as well as to EN ISO 17632-A T69 6 ZPM1H5 rutile flux-cored wire for filling and facing beads (STEIN-MEGAFIL 690 R).

The above materials are suitable for welding fine-grained structural steels, in particular the studied MSN-profiles. In this work the influence of these consumables on weld geometry and long-term strength of welded joints was assessed.

*Experimental procedure*. Requirements to welded joint quality are made, first of all, at application of these hollow sections in structures with a dynamic load [14, 15]. Hollow sections were welded both for determination of mechanical and technological characteristics, and for fatigue strength assessment. In the latter case, dimensions and geometry of welds in welded assemblies were determined. 36 assemblies were made, where a hollow section of 150 mm length was inserted between the joined sections (Figure 2). Solid and flux-cored wire were used to weld 18 samples each. Then welding parameters were determined, depending on the groove. In parallel, fixtures for tack welding and welding were developed, and welding sequence was determined. During technology development preheating temperature and thermal mode was calculated. Preheating and interpass temperature of 80–100 °C was assigned, and M21 gas was used as shielding atmosphere.

The process consisted of mounting the parts in the fixture for alignment, positioning and tack welding of sections, grinding the tack welds be-

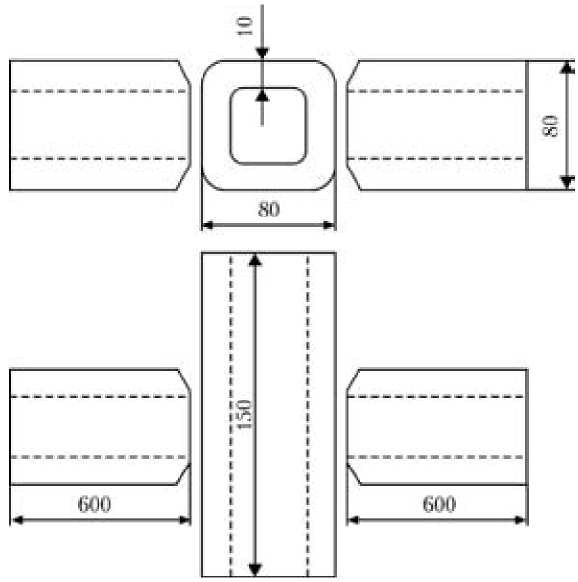



**Figure 2.** Schematic and dimensions of samples

fore root welding, welding the root bead in the downhand position alternatively from two sides, mounting the parts in the fixture for welding of intermediate beads (HV-welds when making a fillet weld (Figure 3, *a*)), upper bead welding (HV-weld when making the butt weld). Finished welded joints, made for fatigue strength studies, are shown in Figure 3, *b*.

*Edge preparation and welding sequence*. In order to prepare samples for welding for future evaluation of joint fatigue strength, the sections were machined so that in the vicinity of the weld the angle of opening was 45° at root face height of 1 mm. A gap of 3 mm was made for reliable welding of weld root; joint geometry and welding sequence are given in Figure 4.

**Testing methods.** *Macrosections*. Non-destructive testing (NDT) was performed to assess welded joint quality. Then macrosections were cut out of butt and fillet welded joints (Figure 5).

*Tensile testing*. This kind of testing should show the correspondence of yield limit and relative elongation of the joints to requirements made

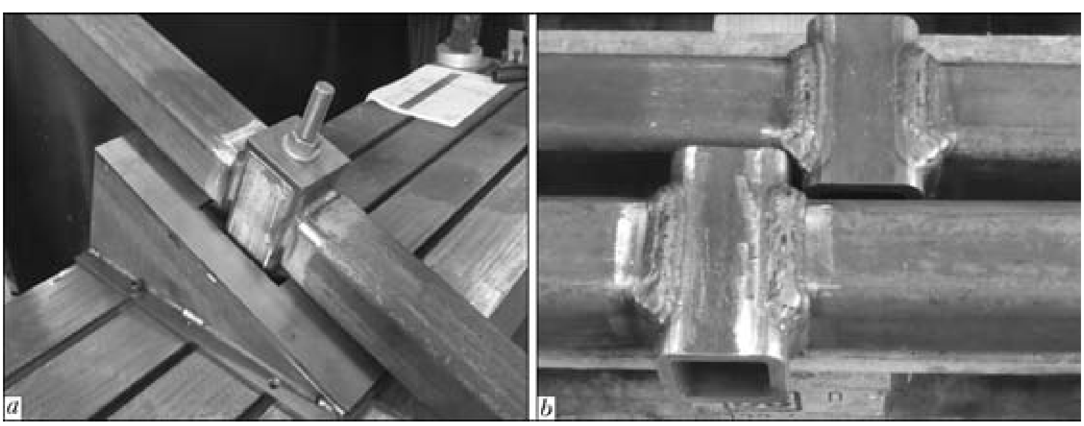



**Figure 3.** Welded assemblies with fillet (*a*) and butt (*b*) welds

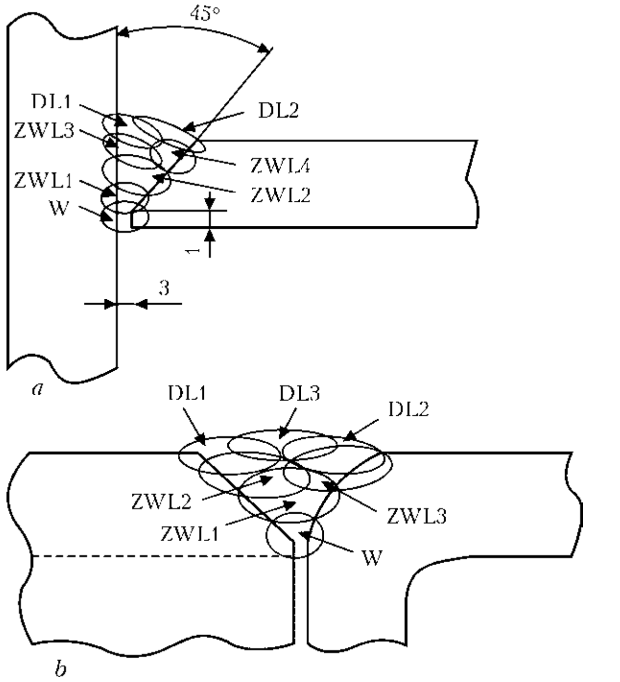



**Figure 4.** Schematic of edge preparation and sequence of welding for fillet (*a*) and butt (*b*) weld: W — weld root; ZWL — intermediate layer; DL — upper bead

of hollow sections from FineXcell® 690ImpactFit50 with a certain wall thickness.

Test results presented in Figure 6 showed that both the butt and fillet joints meet the requirements made of them. Tensile strength of the deposited and base metal was higher than the normative requirements in all the joints.

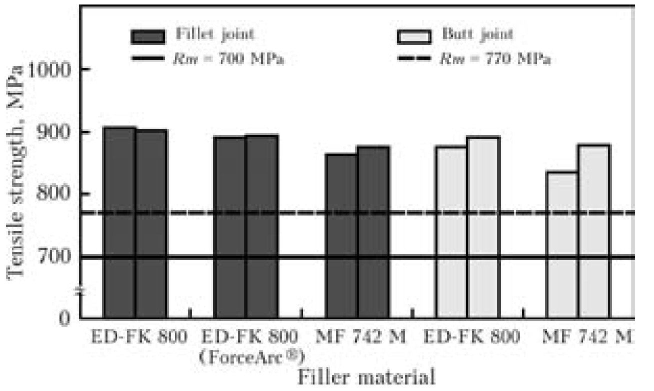



**Figure 6.** Experimental data on static strength testing of SG69Q steel welded joints

*Toughness*. Table 1 gives the requirements to FineXcell® 690ImpactFit50 material. As is seen from Figure 7, both in the HAZ and deposited metal the required impact energy (23 J) in the longitudinal direction of the butt joint was achieved at all the testing temperatures, in keeping with EN 10025-1 and 10025-6.

*Hardness characteristics*. In samples, shown in Figure 8, hardness was measured (*HV*10) from the side of weld surface and from its lower side. Comparison of measured hardness values of metal deposited by flux-cored and solid wires showed lower hardness for flux-cored wire. Maximum values were observed in HAZ metal. Series of hardness measurements from the weld upper side demonstrated higher values — this comparison

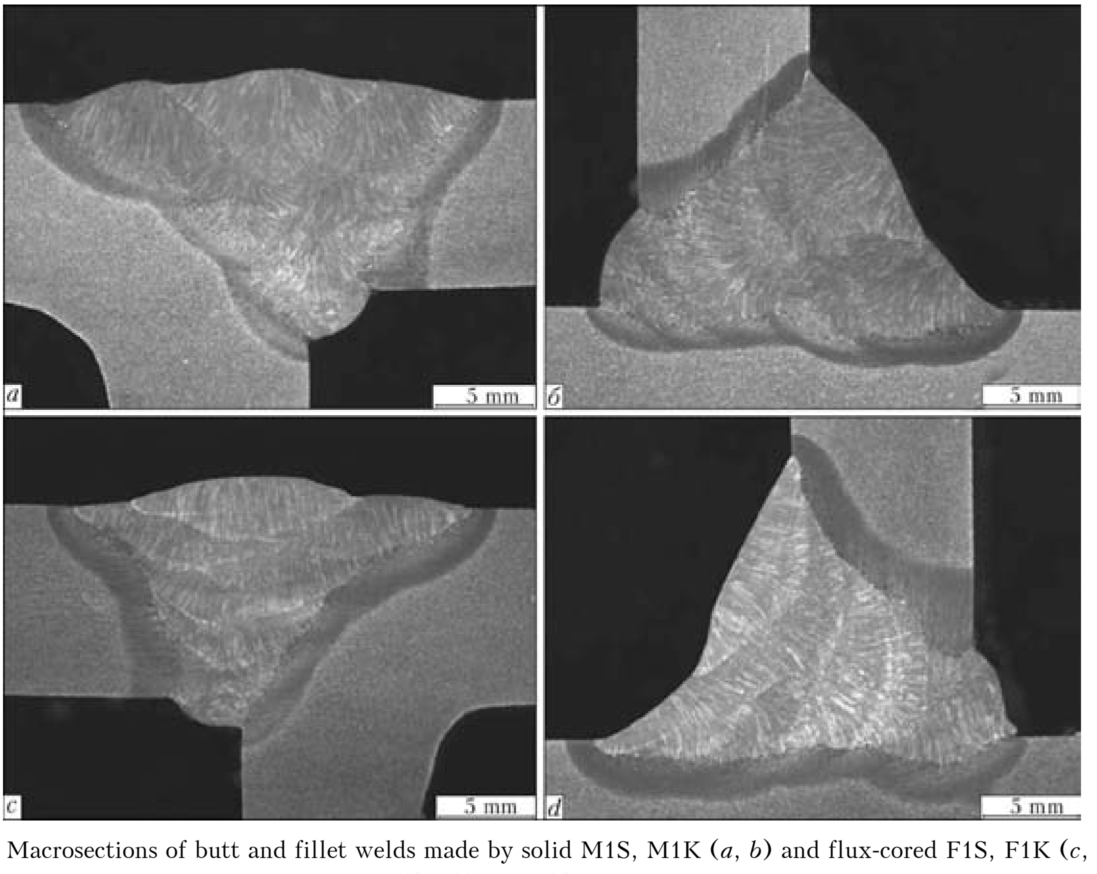



**Figure 5.** Macrosections of butt and fillet welds made by solid M1S, M1K (*a*, *b*) and flux-cored F1S, F1K (*c*, *d*) wires

**Table 1.** Impact toughness requirements made of hollow sections from FineXcell® 690ImpactFit50 material with wall thickness ≥20 mm

| Joint direction | Minimum impact energy, J, on three Charpy samples at control temperature, °C | | | |
|---|---|---|---|---|
| | −50 | −40 | −20 | 0 |
| Across | 27 | 30 | 40 | 65 |
| Along | 16 | 27 | 30 | 40 |

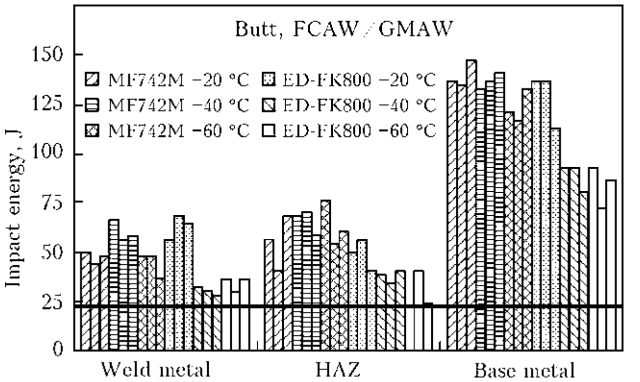



**Figure 7.** Impact energy of 80 × 80 × 10 mm samples from SG69Q steel

is given once more in the diagram (Figure 9). It is seen that in samples welded with flux-cored wire hardness values are lower both in the deposited and in the HAZ metal.

*Fatigue strength.* Let us consider the approach and results of fatigue testing of welded joints of 80 × 80 × 10 mm sections from SG69Q steel, made taking IIW recommendations [16] into account. It was necessary to study the types of loads given in Table 2, allowing for the applied filler materials.

To determine the fatigue strength, Woehler testing was performed. About 7-8 full-scale samples were made for each Woehler line, which were tested for four-point bending (Figure 10).

In order to compare the steady-state fatigue strength with IIW recommendations [16], testing with a constant coefficient of cycle asymmetry $R = 0.5$ was required. Then comparison was performed, allowing for reliability probability $P_u = 97.5$ % with randomly taken scatter band $T_s$ ($P_u = 90$ %:$P_u = 10$ % = 1:1.5 [17]), first in the form of tolerable stress. After that recalculation to the range of alternating stress $\Delta S$, allowing for the coefficient of cycle asymmetry, was performed for comparison with IIW recommendations. Samples without tearing, tested up to stress of $N = 5 \cdot 10^6$ cycles, were called random and were not taken into account at evaluation.

In order to determine the normal nominal stress, moment of resistance of rolled section $W_{el} = 53.5$ cm$^3$ [18] was assumed as the charac-

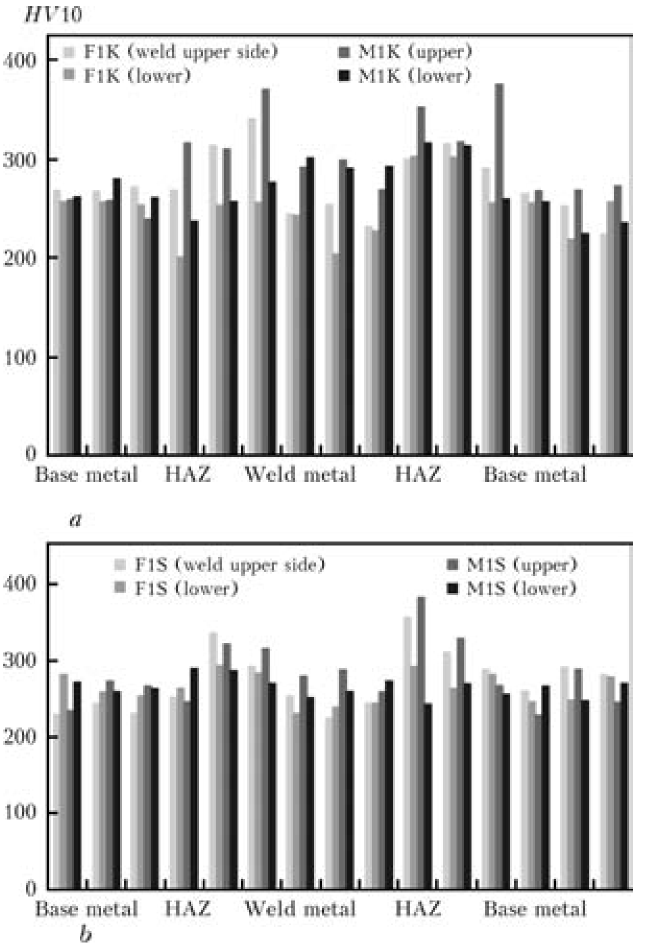



**Figure 8.** Hardness measurement in fillet (*a*) and butt (*b*) welds made with flux-cored F1K, F1S and solid M1K, M1S wires

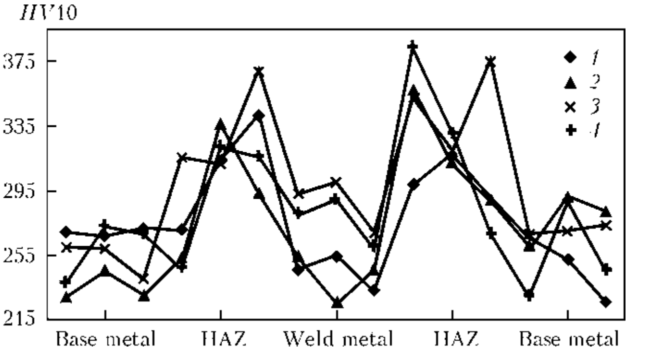



**Figure 9.** Hardness measurement on weld upper side: *1* — flux-cored wire F1K — fillet weld; *2* — flux-cored wire F1S — butt weld; *3* — solid wire M1K — fillet weld; *4* —

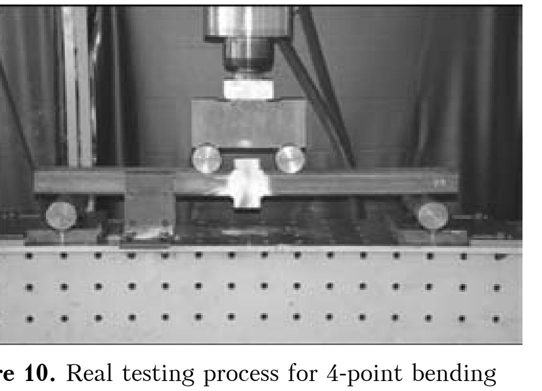


**Figure 10.** Real testing process for 4-point bending

**Table 2.** Sample schematic and kinds of load

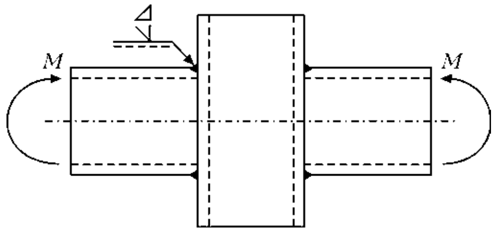
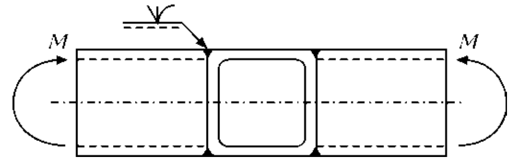
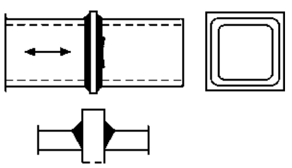
| Samples with fillet welds | Samples with butt weld |
|---|---|
|   |   |
| Solid wire, HV–K–M | Solid wire, HV–R–M |
| Flux-cored wire, HV–K–F | Flux-cored wire, HV–R–F |

**Table 3.** FAT 50 IIW classification [16] for HV-weld when making fillet weld on sample No.424

| Structural detail | Description | FAT | | Remark |
|---|---|---|---|---|
| | | Steel | Aluminium | |
|  | Splice of rectangular hollow section, single-sided butt weld, potential failure from toe<br>Wall thickness >8 mm<br>Wall thickness <8 mm | <br><br>50<br>45 | <br><br>20<br>18 | NDT of welds in order to ensure full root penetration |

teristic of welded joint cross-section with bending load after control testing in a real section. Bending moment $M$ required furtheron was calculated by geometrical conditions of four-point bending, in keeping with the theory of elasticity.

As is seen from Figure 11, the point of crack initiation in all the samples is located predominantly in the corners at transition to the weld, in connection with a higher stress concentration, associated with higher rigidity of the part in this area.

Figure 12 gives a comparison of experimental results with the data of IIW recommendations. As was noted above, IIW recommendations express fatigue strength by Woehler lines. FAT strength class implies the admissible range of nominal stress $\Delta S$ [MPa] in the case of an undercut at a stationary stress cycle $N = 2\cdot10^6$. Here the slope of steep-falling portion of Woehler curve is assigned as $m = 3$ for welded joints.

Some results are more obvious at further comparison of samples with undercuts in keeping with IIW recommendations. In both the joints the slope of Woehler curve is $m = 3$. HV-weld at performance of fillet weld (HV–K–M, HV–K–F) can be tentatively included into fatigue strength class FAT 50 (Table 3). The formed circumstances are even more unfavourable, as here, in view of the lower rigidity of the hollow section placed in-between, additional stresses are applied to the corner regions (compare tears in Figure 10).

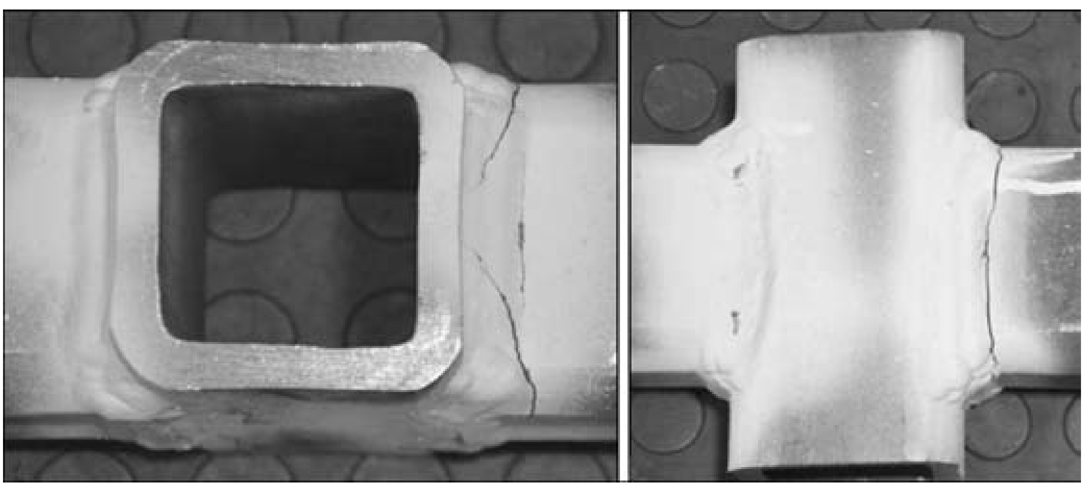


**Figure 11.** Cracks at weld transitions in section corners

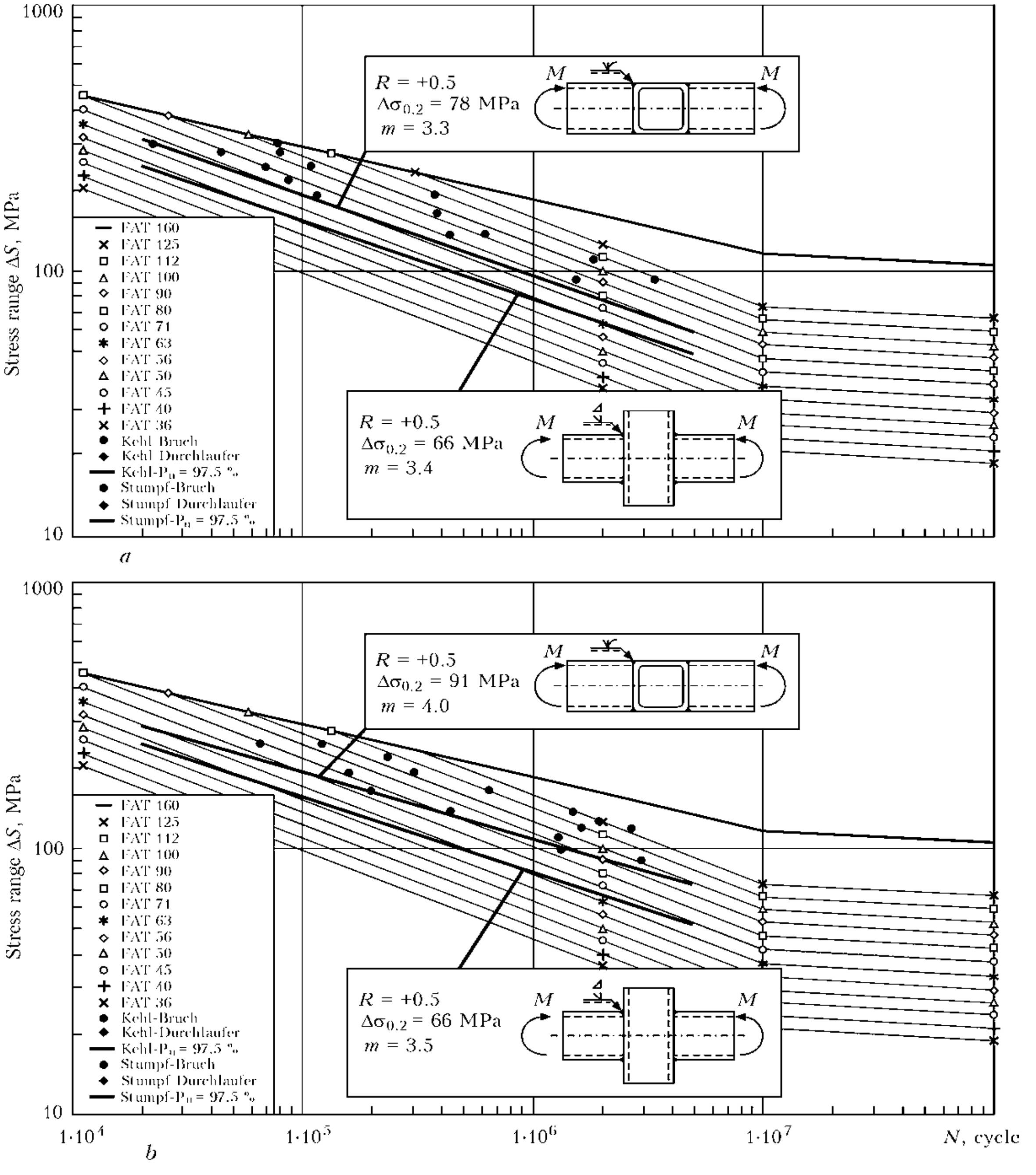



**Figure 12.** Fatigue curves for joints made with solid (*a*) and flux-cored wire (*b*)

During performance of butt weld (HV–R–M, HV–R–F) the HV-weld can be included into FAT 56 class, if we assume that NDT confirmed the appropriate quality of weld root (Table 4).

Table 5 gives comparison of NDT results with IIW data.

Although the slope of all the derived Woehler lines is flatter than in IIW recommendations,

**Table 4.** FAT 56 IIW classification [16] for HV-weld when making butt weld on sample No.234

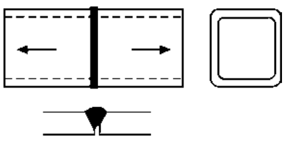
| Structural detail | Description | Fatigue class (FAT) | | Remark |
|---|---|---|---|---|
| | | Steel | Aluminium | |
|  | Transverse butt weld splice in rectangular hollow section, welded from one side, full penetration, root crack | | | Welded in flat position |
| | Root NDT | 56 | 25 | |
| | No NDT | 35 | 12 | |

**Table 5.** Comparison of experimental results with IIW data

| IIW requirements | $\Delta S$, MPa | $m$ | Sample marking | $\Delta S$, MPa | $m$ |
|---|---|---|---|---|---|
| FAT 50 | 50 | 3 | HV–K–M | 64 | 3.4 |
| | | | HV–K–F | 66 | 3.5 |
| FAT 56 | 56 | 3 | HV–R–M | 78 | 3.3 |
| | | | HV–R–F | 91 | 4.0 |

there is no point of crossing comparable Woehler FAT-lines, because of higher values of vibration strength at $N = 2\cdot10^6$ cycles.

Fatigue strength should not be overestimated either in the low-cycle region (cranes, gantry rails, pressure apparatuses), or in regions with high-cycle loads. It should, however, be borne in mind that in this case joints of hollow section assemblies (SG69Q) were evaluated, and calculation was performed according to FAT classes by IIW recommendations.

Therefore, application of high-strength improved fine-grained structural steels in many cases allows reducing wall thickness and, thus, lowering material and processing costs. A wide strength range enables limitation of the dimensions and weight of the part, allowing for the conditions of production and loads. Only application of these steels allows overcoming the established limits in some cases. Performed welding experiments are indicative of usability of the applied sections. With the respective edge preparation and observation of technological rules, it is possible to perform sound joints with good mechanical properties. Fatigue testing confirmed the applicability of the described sections also for structures with cyclic loads. Following the respective norms, instructions and recommendations is a necessary condition.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11. *EN ISO 14175*: Schweisszusaetze — Gase und Mischgase fuer das Lichtbogenschweissen und Verwandte Prozesse.
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13. *EN ISO 18276*: Schweisszusaetze — Fuelldrahtelektroden zum Metall-Lichtbogenschweissen Mit und Ohne Schutzgas von Hochfesten Staehlen.
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