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Effect of heat treatment of S420MC steel joints on their mechanical properties and fatigue strength

Abstract: The article presents the results of tests focused on the effect of stress relief annealing on the mechanical properties and fatigue strength of joints made of S420MC steel grade belonging to a group of thermo-mechanically control processed steels. The article contains the description of the aforesaid tests and presents the results of the basic mechanical tests as well as of internal stress measurements. The text also presents information about fatigue categories experimentally determined for the four most popular types of welded joints at their initial state and after stress relief annealing. In addition, the article informs that the stress relief annealing process recommended by German guidelines SEW 088 does not result in an increase of the fatigue strength of S420MC steel welded joints.

Keywords: S420MC steel joints, heat treatment, stress relief annealing

Introduction

Today's steel industry sector dealing with the manufacture of welded structures sees the growing popularity of steels characterised by high mechanical properties and very good weldability. Such a group of steels includes thermo-mechanical control processed steels (TMCP). The Thermo-Mechanical Control Process carried out at a temperature lower than that used during normalising rolling, results in the refining of grains in the structure and high brittle crack resistance as well as high tensile strength with the carbon equivalent maintained at a low level [1]. Using this type of steel for welded structures has many advantages. Owing to its high strength, the cross-sections and the weight of welded structures can be decreased. In turn, the reduction of the structure weight enables the use of smaller, in terms of dimensions, equipment/technological fixtures such as cranes, heat treatment furnaces, structure-positioning devices etc. as well as allows the lower consumption of filler metals and electric power, e.g. for joint pre-heating prior to welding. TMCP steels find applications in many industries:

– production of oil and gas pipelines [2],
– production of pressure vessels [3],
– erection of off-shore structures,
– building of bridges [4],
– shipbuilding [2],
– production of machinery parts [5].

A very important issue in relation to the design of welded structures intended for operation under changeable loads is the fatigue strength of welded joints. Fatigue cracks are particularly hazardous as in many cases they may invisibly affect a structural element on a right-through basis [6]. The fatigue strength of welded joints is lower than that of other, i.e. non-welded, structural elements. This difference results from the

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high level of post-weld stresses [7] which adversely affect joints as they favour the generation and propagation of brittle cracks and increase the likelihood of stress corrosion-induced cracking. Internal stresses may reach the level close to the yield point of a material and in a welded structure exposed to changeable loads may cause cracks and quicken fatigue damage [8]. Methods for increasing the fatigue strength of welded joints are many and varied. The most popular is the reduction of internal stresses through stress relief annealing the purpose of which is to obtain the optimum level of stress relaxation and the recovery of ductility in the brittle areas of the joint HAZ.

Some heat treatment processes such as normalising annealing as well as hardening and tempering are not allowed in the case of TMCP steels. However, it is possible to subject welded joints made of the these steels to stress relief annealing. German guideline SEW 088 [9] related to welding of fine-grained steels orders carrying out stress relief annealing when the type of structure and/or expected operating stresses justify the reduction of internal stresses. Following the guidelines SEW 088 stress relief annealing should be carried out in the temperature range between 530°C and 580°C. The hold time (according to DIN 17014-1 [10]) should be at least 30 minutes and not longer than 150 minutes. When the hold time exceeds 90 minutes a temperature from the lower range should be applied. In turn, standard PN-EN 10028-5:2010P [17] referring to fine-grained weldable TMCP steels for pressure vessels warns that the improper conditions of the post-weld heat treatment may reduce the mechanical properties when the annealing temperature-time parameter (1) exceeds the critical value of $P_{crit.} = 17.3$:

$$P=T_s(20 + \lg t) \times 10^{-3} \tag{1}$$

where

T_s – annealing temperature, K;

t – hold time, h.

Part of the research work carried out at Instytut Spawalnictwa [19] required carrying out fatigue tests and determining fatigue categories FAT for selected types of welded joints made of TMCP steel after welding and stress relief annealing conducted in accordance with SEW 088 guidelines. The critical value of the this temperature-time parameter according to the standard [17] was not exceeded.

Subject of research

The research-related tests were carried out on welded joints made of 12 mm thick cold workable TMCP S420MC steel according to EN 10149-2:2000P [11]. The chemical composition of the steel was determined by means of emission spectrometry with spark excitation using a Spectro-made Spectrolab spectrometer. The analysis results are presented on Table 1.

Table 1. Chemical composition of S420MC steel [19]

Chemical element content,%								
C	Mn	Si	P	S	$Al_{tot.}$	Nb	Ti	V
0.06	0.97	0.03	0.011	0.006	0.043	0.046	0.004	0.007

The following types of welded joints were selected for the tests:

- butt joints,
- joints with a longitudinal rib with fillet welds,
- joints with a transverse rib with fillet welds,
- cruciform joints with fillet welds.

The test joints were made using the semi-automatic MAG welding (135). The filler metal used for making the joints was a solid wire G3Si1 having a diameter of 1.2 mm. The remaining types of joints were made using a flux-cored wire SG2 with a diameter of 1.2 mm.

Tests

Stress relief annealing

In order to compare the mechanical properties of S420MC steel welded joints subjected and not subjected to stress relief annealing, some of the welded joints underwent stress relief annealing prepared according to SEW 088. The process was carried out in a resistance furnace manufactured by the IZO-Gliwice company. The samples were heated along with the furnace at a rate of 150°C/h until they reached the heat treatment temperature of 550 ±5°C. The annealing at 550°C lasted 1 hour. Afterwards the samples were cooled along with the furnace to a temperature of 280°C (Fig.1). During annealing the temperature was monitored and recorded by means of thermocouples fixed in the area of the weld and the base metal. The direct reading and recording of the real temperature value enabled the precise monitoring of the heat treatment process.

Tensile test

The static tensile test of the base metal and S420MC steel welded joints was carried out in accordance with the requirements of standards PN-EN ISO 6892-1:2010E [12] and PN-EN ISO 4136:2013-05E [13] respectively. The tests were conducted on 2 series of samples, out of which one was subjected to stress relief annealing for 1h at 550±5°C, whereas the second series was composed of the joints not subjected to the post-weld heat treatment. In all the S420MC steel welded joints cracks were located outside the joint area. The tensile test results in the form of averaged values are presented in Figure 2.

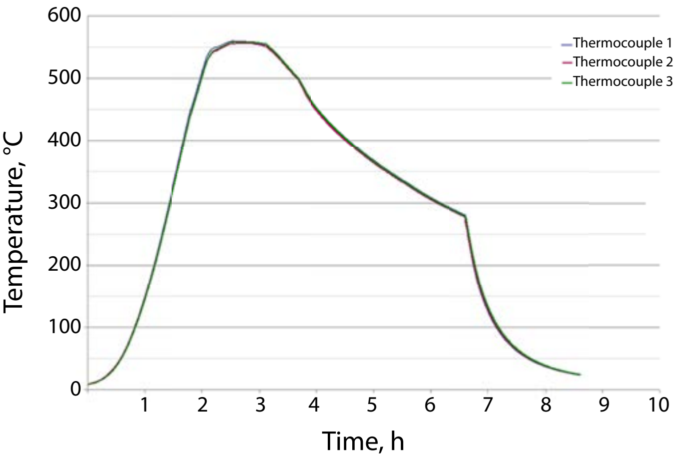


Fig. 1. Diagram of stress relief annealing process [19]

Impact test of S420MC steel welded joints

The impact test was carried out at +20°C and -20°C on Charpy V samples having the nominal dimensions of 10x10x55 mm in accordance with the requirements of standards PN-EN ISO 9016: 2013-05E [14] and PN-EN ISO 148:2010E [15]. The test involved a series of impact-test samples prepared from the S420MC steel joint. Impact notches were indented in the joint base metal, HAZ and in the weld. For each area tested the impact energy was determined on a series composed of 3 samples. The test results in the form of average values are presented in Figure 3.

The impact energy values for all the tested areas of the S420MC steel welded joint not subjected to stress relief annealing were higher than in the case of the same joint subjected to stress relief annealing. The impact energy determined at the sub-zero temperature (-20°C) for the area of the base metal and that of the weld, both in the joints subjected and not subjected to stress relief annealing, was lower than

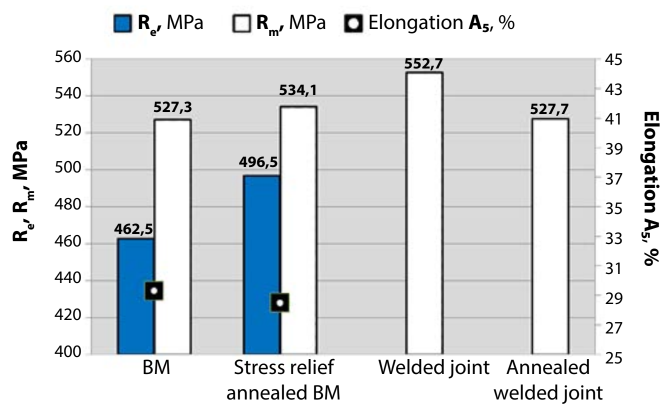


Fig. 2. Mechanical properties of base metal and of S420MC steel welded joints [19]

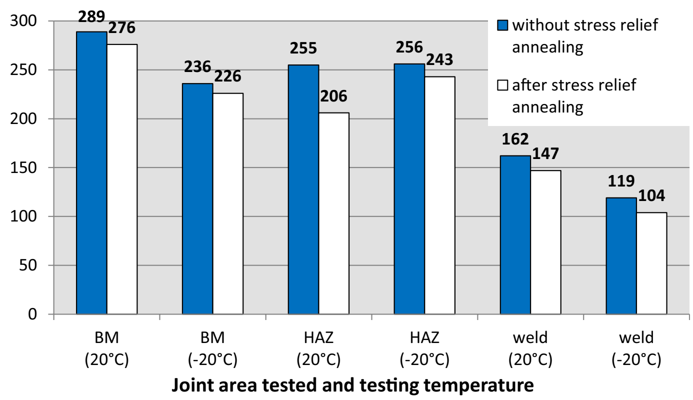


Fig.3. Impact energy test results for S420MC steel welded joints [19]

Table 2. Hardness measurement results of S420MC steel welded joints [19]

Joint condition	Meas. line	Hardness HV10 in measurement point (according to Fig. 4)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Joint without stress relief annealing	A	170	178	178	168	175	188	218	218	216	179	167	168	173	176	176
	B	-	-	-	169	169	181	213	215	215	173	168	168	-	-	-
Joint after stress relief annealing	A	178	178	178	169	185	199	228	219	218	199	185	170	173	172	170
	B	-	-	-	171	185	191	216	216	213	198	182	175	-	-	-

the values obtained at +20°C. In turn, the opposite tendency was revealed in the HAZ, where at the lowered temperature the impact energy for the joint not subjected to stress relief annealing remained almost identical, whilst in the case of the stress relief annealed joint an increase in the impact energy was observed. Such behaviour in the joint HAZ area, which is potentially the most crack-susceptible area, is very convenient as regards brittle crack resistance. Nonetheless, the verification whether such a tendency of changes can also be observed in joints made of other TMCP steel grades requires additional tests.

Hardness measurement of S420MC steel welded joints

The hardness measurements on the cross-sections of the welded joints were carried out using the Vickers method according to the requirements of standard PN-EN 1043-1:2011E [16] with the load of 98.1 N (HV10) applied on the indenter. The hardness tests were conducted on samples prepared from the cruciform joints (Fig. 4) subjected and not subjected to stress relief annealing. The test results are presented in Table 2. Figure 5 presents a diagram comparing

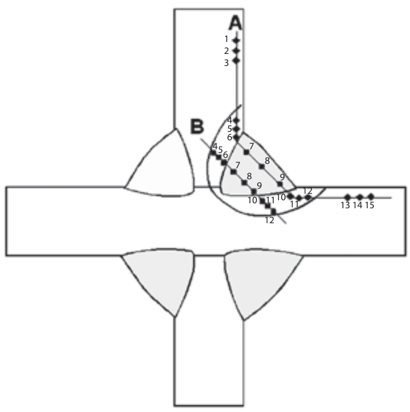


Fig. 4. Arrangement of hardness measurement points in S420MC steel cruciform joint with fillet welds [19]

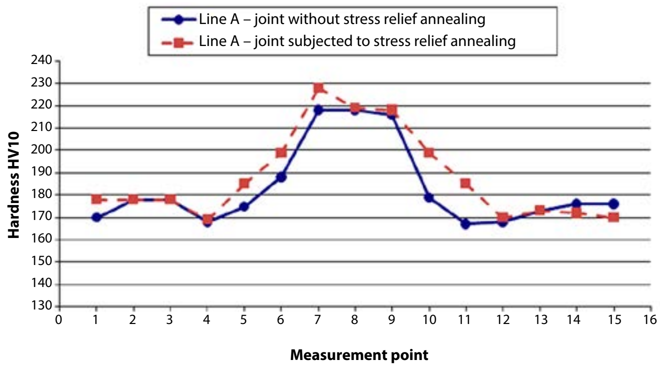


Fig. 5. Hardness distribution of S420MC steel welded joints without and after stress relief annealing [19]

the hardness of S420MC steel welded joints, in the measurement line A, subjected and not subjected to stress relief annealing.

Measurement of internal stresses using the trepanation method

The measurement of internal stresses generated during welding was carried out by means of a trepanation method utilising strain state changes in conducting measurements. The internal stresses were measured on two test butt joints. One of the joints was subjected to stress relief annealing in the same conditions as those to which the test joints for the fatigue tests were exposed. The measurement consisted in making 9 measurement bases, each 40 mm long, where metal balls pressed into the material were used as measurement points (Fig. 6). Next, using a

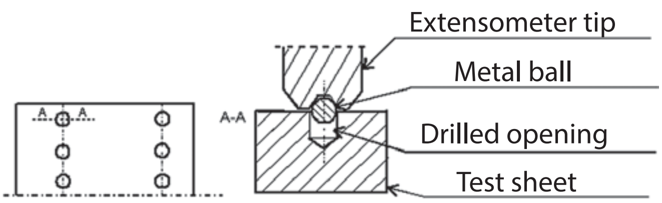


Fig. 6. Sketch of preparing measurement point in test sheet with welded joint [19]

mechanical extensometer the distances between the individual base measurement points were determined. In order to reveal internal stresses it was necessary to make notches between the measurement bases (Fig. 7). After making the notches another measurement of distances between the base points was carried out. The difference between inter-base distances before and after releasing stresses made it possible to determine their value and sense. Table 3 presents internal stresses determined for the individual measurement bases of the S420MC steel butt joints, whereas Figure 8 presents the distribution of stresses in the joints tested.

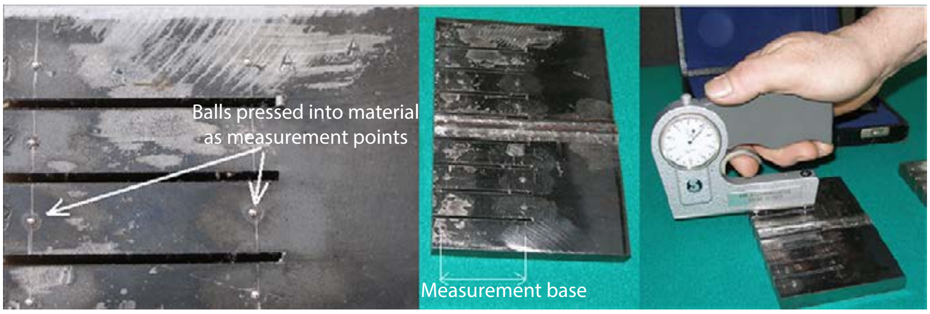


Fig. 7. Butt welded joint test elements for measuring internal stresses and manner of measurement with mechanical extensometer [19]

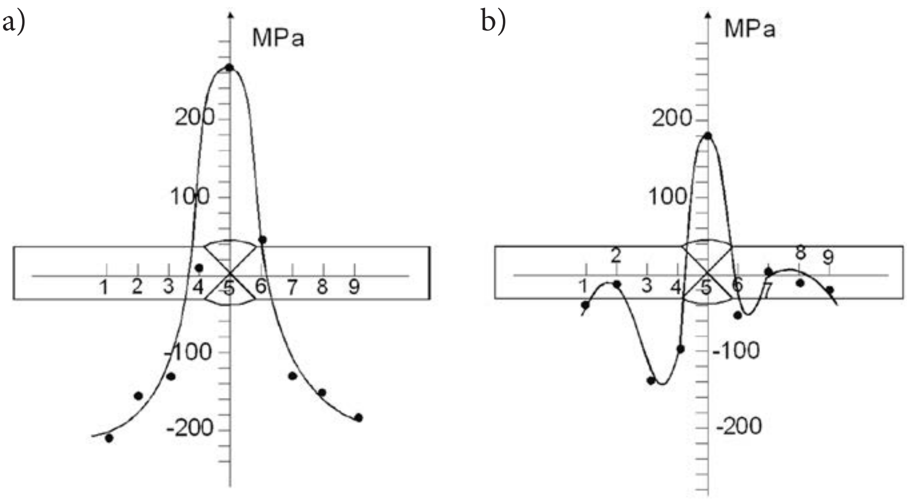


Fig. 8. Distribution of internal stresses in S420MC steel butt joint; a) without stress relief annealing, b) after stress relief annealing (stress values according to Table no. 3) [19]

Fatigue tests of welded joints made of S420MC steel

The fatigue tests of the welded joints subjected and not subjected to stress relief annealing were carried out using a MTS 810 testing machine. The fatigue tests involved making S420MC steel test joints out of which 4 types of samples were prepared (Table 4).

The fatigue tests of each sample series were carried out on several levels of the stress range $\Delta\sigma$ at the constant stress ratio R=0.2 ($R=\sigma_{min}/\sigma_{max}$) and the frequency of load changes in the 15-20 Hz range to the moment of sample destruction. The number of samples in each series amounted to 10-12, which enabled the determination of Wöhler lines and the calculation of fatigue categories FAT according to the guidelines of the International Institute of Welding (IIW) [18]. In accordance with the assumption of the procedure presented in the IIW document [18] the fatigue test results were presented in the form of a regression line (Fig. 9-12) calculated from the following dependence:

$$logN=logC-mlog\Delta\sigma \qquad (2)$$

Table 3. Measured values of internal stresses S420MC steel but joints [19]

Joint condition	Internal stresses, MPa								
	Successive points of measurement base								
	1	2	3	4	5	6	7	8	9
Joint without stress relief annealing	-216.5	-155.0	-128.0	10.0	262.5	57.5	-130.5	-148.0	-181.0
Joint after stress relief annealing	-46.0	-13.5	-140.0	-97.5	177.5	-54.0	3.0	*	-27.5

*- unreliable reading (improperly prepared measurement base)

Note: The negative values refer to compressive stresses and positive values refer to tensile stresses.

where:

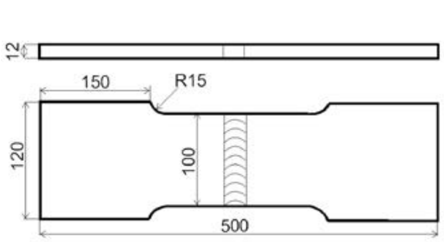
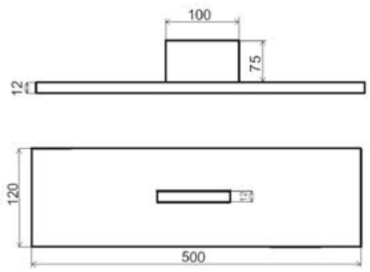
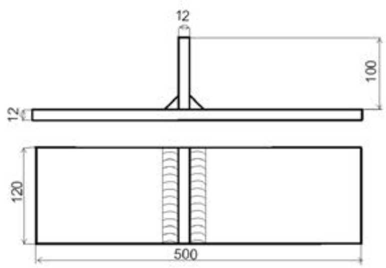
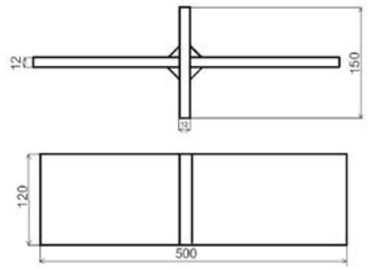
N – number of cycles to the sample destruction,

m – line inclination factor,

C - constant.

Statistical calculations made it possible to determine the permissible value of fatigue strength according to the instructions of the IIW document [18] also referred to as the fatigue category FAT. The comparison of the calculated fatigue categories FAT of the welded joints subjected and those not subjected to stress relief annealing are presented in Table 5.

Table 4. Samples prepared for fatigue tests

Samples from butt joint	Samples from joint with longitudinal rib with fillet welds
	
Samples from joint with transverse rib with fillet welds	**Samples from cruciform joint with fillet welds**
	

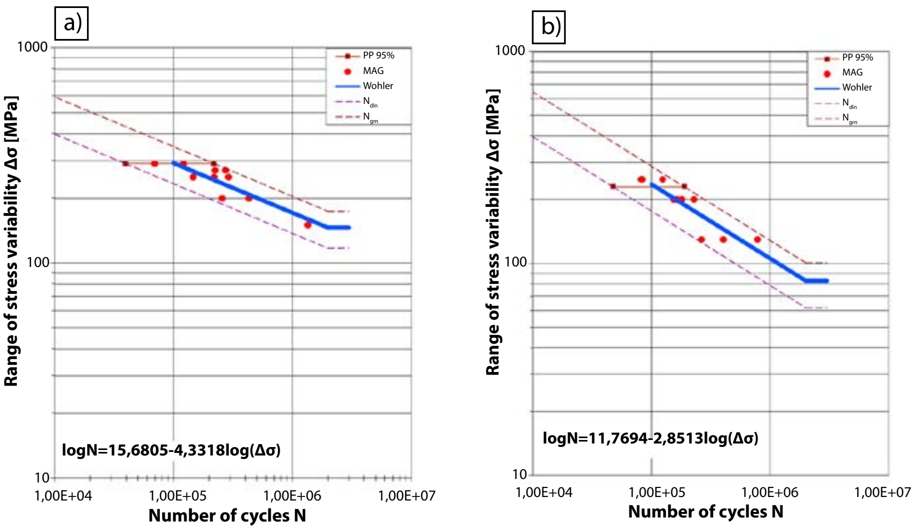


Fig. 9. Wöhler line for butt joint: a) without stress relief annealing, b) after stress relief annealing [19]

Summary of results

The experimental tests conducted enabled the determination of the influence of stress relief annealing at 550°C on the mechanical properties and the fatigue strength of the S420MC steel welded joints.

The tensile test of the stress relief annealed material samples revealed that both the yield point R_e and the tensile strength R_m of the samples increased, whilst their plastic properties decreased. The tensile test of the welded joint subjected to stress relief annealing revealed that the tensile strength R_m of the joint decreased by 25 MPa in comparison with the value R_m determined for the welded joint not subjected to stress relief annealing.

The impact energy KV determined for various areas of the welded joint subjected to stress relief annealing was in all the cases lower than the values obtained for the same welded joint areas in the initial state. The analysis of the impact energy test results related to the HAZ areas of the welded joints tested revealed that decreasing the testing temperature to -20°C did not cause a decrease in the brittle crack resistance of this joint area (Fig. 3). For the welded joint not subjected to stress relief annealing, irrespective of the testing temperature, the impact energy did not change reaching its average values of 255 J and 256 J at 20°C and -20°C respectively. In turn, the welded joints subjected to stress relief annealing revealed an increase in the average impact energy value from 206 J at 20°C to 243 J at -20°C.

The hardness measurement test results related to the welded joints revealed that stress relief annealing caused a hardness increase both in the HAZ areas and in the weld if compared to the analogical areas of the joint not subjected to the heat treatment. Relatively, the highest hardness increase could be observed in the joint weld after annealing (the highest hardness value was 228 HV10). As regards crack (particularly cold) resistance the hardness values obtained both for the joint not subjected and the one subjected to stress relief annealing were on the save level. However, there was a phenomenon observed which requires explanation, namely, a post-heat treatment hardness increase in the joint whose steel chemical composition does not imply the existence of precipitation hardening processes. This phenomenon can possibly be ascribed to the thermal conditions accompanying the welding process as well as to the effect of the chemical composition and the mechanical properties of the weld deposit of the filler

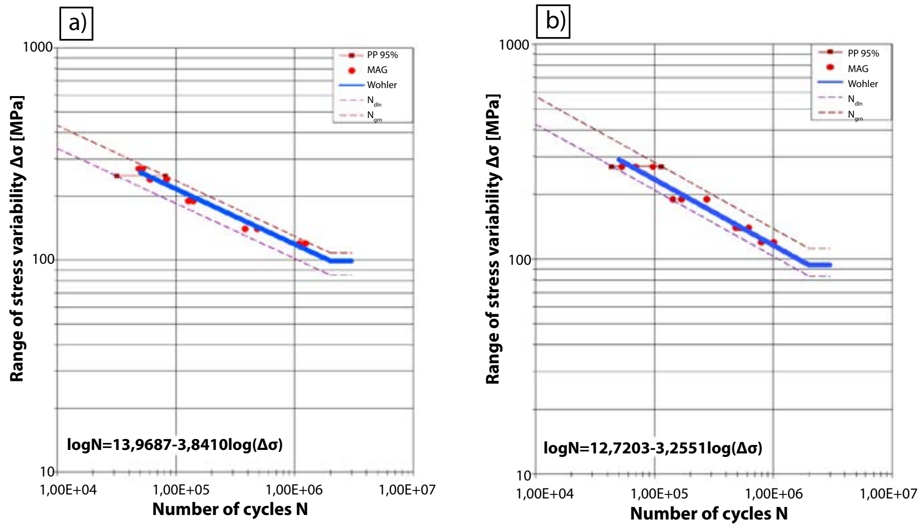


Fig. 10. Wöhler line for joint with longitudinal rib with fillet welds: a) without stress relief annealing, b) after stress relief annealing [19]

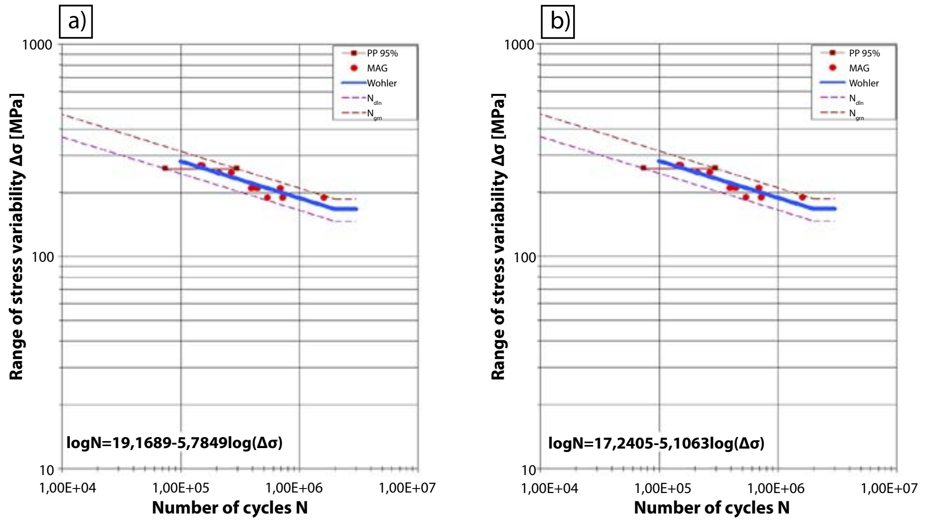


Fig. 11. Wöhler line for joint with transverse rib with fillet welds: a) without stress relief annealing, b) after stress relief annealing [19]

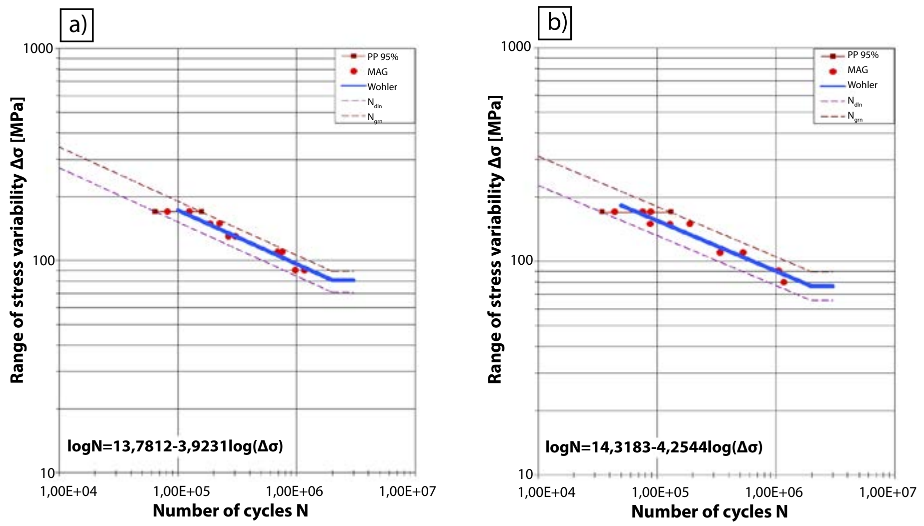
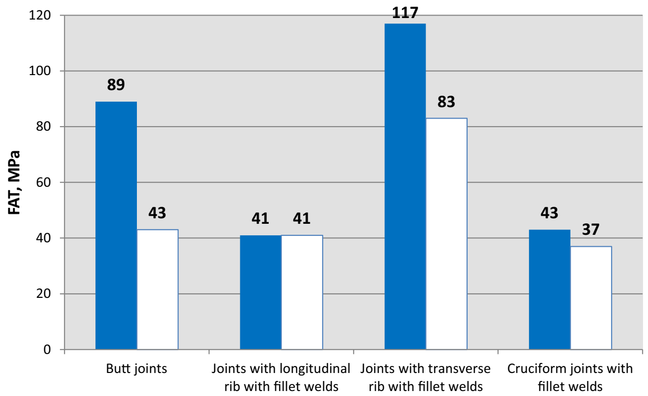


Fig. 12. Wöhler line for cruciform joint with fillet welds: a) without stress relief annealing, b) after stress relief annealing [19]

Table 5. Fatigue category FAT determined for joints tested [19]

Type of joint	Fatigue category FAT of welded join, MPa	
	Without stress relief annealing	After stress relief annealing
Butt joints	89	43
Joints with longitudinal rib with fillet welds	41	41
Joints with transverse rib with fillet welds	117	83
Cruciform joints with fillet welds	43	37



metal wire. According to the data provided by the manufacturer the filler metal wire weld deposit contained 1.25% Mn, which was considerably more than in S420MC steel tested (Mn=0.97%). At the same time the filler metal wire weld deposit was characterised by mechanical properties higher than those of the steel tested (R_e=580 MPa, R_m=600 MPa).

The measurement of internal stresses revealed that in the butt welded joint the greatest tensile stresses were present in the weld axis and amounted to 262 MPa, whereas in the welded joint which had been subjected stress relief annealing the internal tensile stresses in the same joint area were reduced by 85 MPa (Fig. 8). Stress relief annealing at 550°C caused only partial reduction of internal stresses in the S420MC steel welded joint.

The fatigue test results indicate that stress relief annealing of butt joints, joints with a transverse rib and cruciform joints with fillet welds not only failed to increase their fatigue strength but even resulted in decreasing it (FAT category below 6 MPa in the case of cruciform joints with fillet welds up to 46 MPa in the case of butt joints). For the longitudinal rib joints with the fillet weld, both after welding and after stress relief annealing the determined fatigue category FAT stayed the same. Therefore, it is possible to assume that stress relief annealing does not affect the fatigue strength of joints characterised by significant stress concentration. The test results indicate that stress relief annealing carried out at 550°C, i.e. restricted within the range of temperature recommended in SEW 088 guidelines increases mechanical properties at the cost of decreasing plastic properties (elongations and brittle crack resistance). Stress relief annealing at 550°C caused only partial internal stress relaxation but failed to increase the fatigue strength of the welded joints tested.

Concluding remarks

The tests conducted have led to the formulation of the following conclusions:

1. The process of stress relief annealing at 550°C causes only partial relaxation of internal stresses in S420MC steel welded joints.

2. The destructive testing results have revealed that stress relief annealing increases the mechanical properties (Re, Rm) and decreases the plastic properties (A5, KV) of S420MC steel as well as slightly decreases the impact energy (KV) of individual areas of the S420MC steel welded joint.

3. The HAZ in S420MC steels joints does not reveal decreased brittle crack resistance along with a decrease in temperature in the +20°C÷-20°C range.

4. The fatigue cracks in all the types of joints tested were initiated in the area where the weld face passed into the base metal, irrespective of the post-weld joint condition.

5. Although stress relief annealing in the temperature range 530-580°C is recommended

for welded joints made of TMCP steels, it should be noted that the process does not result in an increase in the fatigue strength of S420MC steel welded joints.

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