A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 54 2009 Issue 4

K. KRASNOWSKI*

# INFLUENCE OF STRESS RELIEF ANNEALING ON MECHANICAL PROPERTIES AND FATIGUE STRENGTH OF WELDED JOINTS OF THERMO-MECHANICALLY ROLLED STRUCTURAL STEEL GRADE S420MC

# WPŁYW WYŻARZANIA ODPRĘŻAJĄCEGO NA WŁASNOŚCI MECHANICZNE I WYTRZYMAŁOŚĆ ZMĘCZENIOWĄ ZŁĄCZY SPAWANYCH STALI KONSTRUKCYJNEJ WALCOWANEJ TERMOMECHANICZNIE W GATUNKU S420MC

Due to a number of advantages characterising thermo-mechanically rolled steels, they are often used in construction of such welded structures as bridges, pressure vessels, elements of ships, pipelines, machinery parts etc. From the viewpoint of design of welded structures exposed to changing load during their operation, critical importance is attached to fatigue strength of welded joints, which is lower than that of other i.e. non-welded structural elements. This fact is caused by significant post-weld stresses which can be reduced in several ways e.g. by stress relief annealing. German design guidelines SEW 088 concerned with welding of fine-grained steels recommend stress relief annealing to be conducted within temperature range 530-580°C for between 30-150 minutes. This article contains description of impact of stress relief annealing on mechanical properties and fatigue strength of welded joints of S420MC steel belonging to a group of thermo-mechanically rolled steels. The description includes the course of tests, results of basic mechanical tests, results of measurements of internal stresses and fatigue categories for four most popular types of welded joints in their initial states and after being subject to stress relief annealing. It was determined that the process of stress relief annealing recommended by German guidelines SEW 088 does not lead to an increase in fatigue strength of S420MC steel welded joints. The test results can be useful for designers of steel structures.

Stale walcowane termomechanicznie, ze względu na szereg zalet jakimi się charakteryzują, są często wykorzystywane do budowy takich konstrukcji spawanych jak mosty, zbiorniki ciśnieniowe, elementy statków, rurociągi, części maszyn i inne. Z punktu widzenia projektowania konstrukcji spawanych, które podczas eksploatacji będą pracowały pod obciążeniem zmiennym, bardzo ważna jest wytrzymałość zmęczeniowa połączeń spawanych, która jest mniejsza niż innych niespawanych elementów konstrukcji. Dzieje się tak ze względu na wysoki stan naprężeń pozostających po spawaniu, które mogą być zredukowane kilkoma sposobami jak np. wyżarzanie odprężające. Niemieckie wytyczne projektowe SEW 088 dotyczące spawania stali drobnoziarnistych zalecają przeprowadzenie wyżarzania odprężającego w zakresie temperatury między 530-580°C przez okres od 30-150 min. W artykule opisano wpływ wyżarzania odprężającego na własności mechaniczne oraz na wytrzymałość zmęczeniową złączy stali w gatunku S420MC należącej do grupy stali walcowanych termomechanicznie. Opisano przebieg badań i przedstawiono wyniki podstawowych badań mechanicznych, podano wyniki pomiarów naprężeń własnych oraz wyznaczono kategorie zmęczeniowe dla czterech najpopularniejszych rodzajów złączy spawanych w stanie wyjściowym oraz po wyżarzaniu odprężającym. Stwierdzono, że proces wyżarzania odprężającego zalecanego przez niemieckie wytyczne SEW 088, nie wpływa na wzrost wytrzymałości zmęczeniowej złączy spawanych stali S420MC. Wyniki badań mogą być przydatne projektantom konstrukcji stalowych.

## 1. Introduction

Observing today's steel industry and its sectors dealing with manufacturing of welded structures one may notice growing popularity of steels characterised by high mechanical properties and very good weldability such as, for instance, thermo-mechanically rolled steels also referred to as TMCP steels (TMCP – Thermo-Mechanical Control Process) Thermo-mechanical rolling performed at a temperature significantly lower than that of standardisation rolling results in grain size reduction in the structure, high resistance to cold cracking as well as high strength while maintaining low carbon equivalent [1]. The application of the said type of steel proves very advantageous. Thanks to high strength of these readily welded steels it is possible to reduce cross-sections and weight of welded structures. In turn, the reduction

* INSTITUT OF WELDING, 44-100 GLIWICE, 16-18 BŁ. CZESŁAWA STR. POLAND

of weight makes it possible to apply smaller, from dimensions' point of view, technological machinery and equipment such as cranes, furnaces for heat treatment, devices for structural positioning etc. Another advantage is a smaller demand for filler metals and lower consumption of electric energy used for e.g. weld pre-heating prior to welding. TMCP steels are used in numerous branches of industry e.g.:
– production of pipelines for oil and gas industries [2],
– production of pressure vessels [3],
– marine constructions,
– building of bridges [4],
– manufacturing of ships [2],
– production of machinery parts [5].

From the viewpoint of design of welded structures exposed to changing load during their operation, the key issue is that of the fatigue strength of welded joints. Fatigue cracks are regarded as particularly hazardous as in many cases they may thoroughly and invisibly penetrate the whole structural element [6]. Fatigue strength of welded joints is lower than that of other non-welded structural elements; this being so due to significant post-weld stresses [7]. The presence of stresses in a joint is a disadvantageous phenomenon favouring generation and propagation of brittle cracks as well as increasing the probability of cracking triggered by stress corrosion. Internal stresses may reach values close to that of yield stress; in a welded structure subject to changing load they may lead to cracking and cause faster fatigue failure [8]. Methods for increasing fatigue strength are many and various; the most commonly applied is elimination of internal stresses through stress relief annealing aimed at obtaining optimum value of stress relaxation and restoration of continuity in brittle areas of HAZ of the joint.

Some of heat treatment processes such as standardisation annealing or hardening and tempering are not allowed in case of thermo-mechanically rolled steels. However, joints made of TMCP steels may be subject to stress relief annealing. German guidelines SEW 088 [9] concerned with welding of fine-grained steels require stress relief annealing to be performed whenever the type of structure and/or forecasted operating loads require the reduction of internal stresses.
Under SEW 088 guidelines stress relief annealing should be conducted within the temperature range 530-580°C; hold time (pursuant to DIN 17014-1 [10]) should be longer than 30 minutes and should not exceed 150 minutes. If hold time is in excess of 90 minutes, one should try to apply temperature closer to the lower value of the aforementioned range. In turn, standard PN-EN 10028-5 [17] related to welding of thermo-mechanically rolled fine-grained steels used for production of pressure vessels states that unfavourable post-weld heat treatment conditions may reduce mechanical properties when time-temperature parameter of stress relief annealing (1) exceeds the critical value $P_{ctit.} = 17.3$

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

where:
$T_s$ – temperature of stress relief annealing [K],
$t$ – hold time [h].

The research work [19] carried out at Instytut Spawalnictwa involved fatigue tests and determination of fatigue categories (FAT) for selected types of welded joints of thermo-mechanically rolled steel after being subject to welding and stress relief annealing conducted in accordance with recommendations contained in SEW 088 guidelines. The critical value of the aforesaid time-temperature parameter acc. to the aforesaid standard [17] was not exceeded.

## 2. Material used for tests and types of welded joints

Welded joints were produced with 12mm-thick thermo-mechanically rolled steel S420MC used for cold working and pursuant to EN 10149-2:2000 [11]. The chemical composition of the steel was determined by means of spark-excited emission spectrometry with Spectro-manufactured Spectrolab-type spectrometer. The analysis results are presented in Table 1.

TABLE 1
Chemical composition of S420MC steel [19]

| Elemental content [%] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| C | Mn | Si | P | S | $Al_{\|rmtot.}$ | Nb | Ti | V |
| 0.06 | 0.97 | 0.03 | 0.011 | 0.006 | 0.043 | 0.046 | 0.004 | 0.007 |

Types of welded joints selected for tests:
– butt joints,
– joints with longitudinal rib with fillet welds,
– joints with crosswise rib with fillet welds,
– cruciform joint with fillet welds.

The test joints were produced by means of semi-automatic MAG welding method (135). Butt joints were made with 1.2 mm-diameter solid filler wire G3Si1, whereas the remaining types of joints were made with 1.2 mm-diameter flux-cored wire SG2.

## 3. Description of tests

### 3.1. Stress relief annealing

In order to compare mechanical properties of welded joints made of S420MC steel, some of them underwent stress relief annealing pursuant to SEW 088 guidelines whereas some remained unprocessed. The annealing process was conducted in an IZO-manufactured resistance furnace. The samples were heated along with the furnace at a speed of 150°C/h until reaching a temperature of 550 ±5°C. The hold time at 550°C amounted to 1 hour (Fig.1); afterwards the sample was cooled along with the furnace to a temperature of 280°C. During stress relief annealing temperature was monitored and registered by means of thermocouples fixed in the weld and parent metal area. Real-time readings and registration of actual temperature enabled precise monitoring of the heat treatment process.

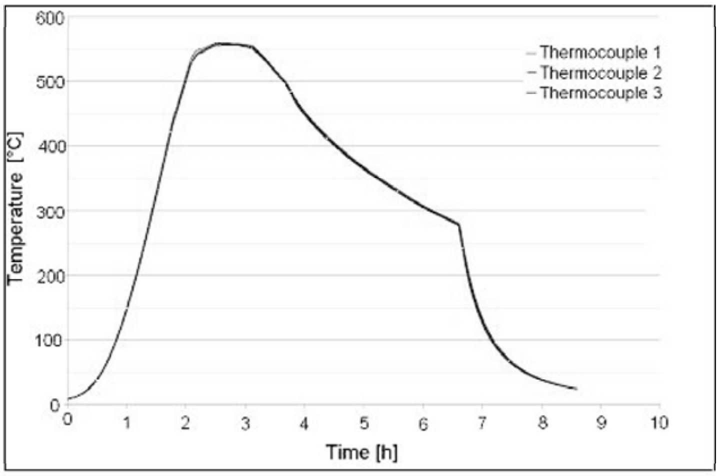



Fig. 1. Stress relief annealing diagram [19]

### 3.2. Static tensile test

The static tensile test incorporating the parent metal (S420MC steel) and welded joints of S420MC steel was conducted pursuant to the requirements of standards PN-EN 10002-1:2004 [12] and PN-EN 895:1997 [13] accordingly. The tests involved 2 lots of samples, out of which one was subject to stress relief annealing at 550±5°C for 1 hour while the other remained unprocessed. In case of S420MC steel welded joints ruptures were located outside the welded joint area. The averaged results of the static tensile test are presented in Figure 2.

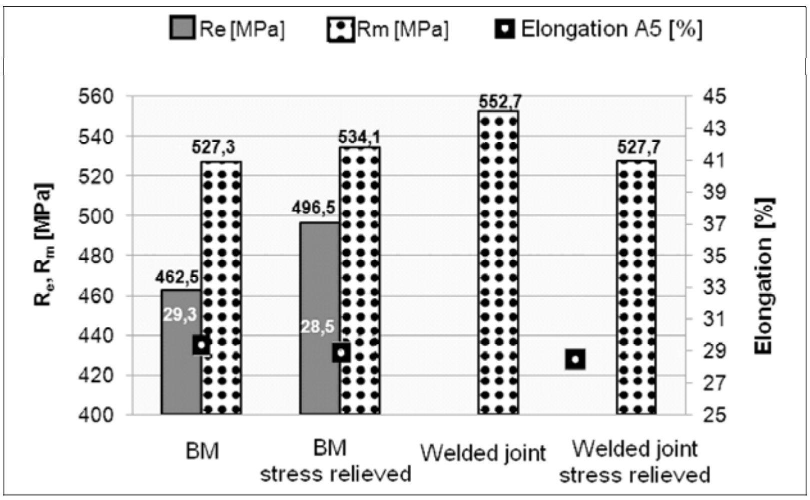



Fig. 2. Mechanical properties of parent metal and welded joints made of S420MC steel. BM=Base Metal [19]

### 3.3. Impact test of S420MC steel welded joints

The impact test was performed at +20°C and -20°C using Charpy V samples of the nominal dimensions 10x10x55 mm in accordance with the requirement of standards PN-EN 875:1999 [14] and PN-EN 10045-1:1994 [15]. The test involved lots of test pieces sampled from S420MC steel. Impact notches were prepared in the parent metal of the joint, HAZ and in the weld. In case of each of the examined areas the impact absorbed energy was determined using a lot of three impact test samples. The averaged results are presented in Figure 3.

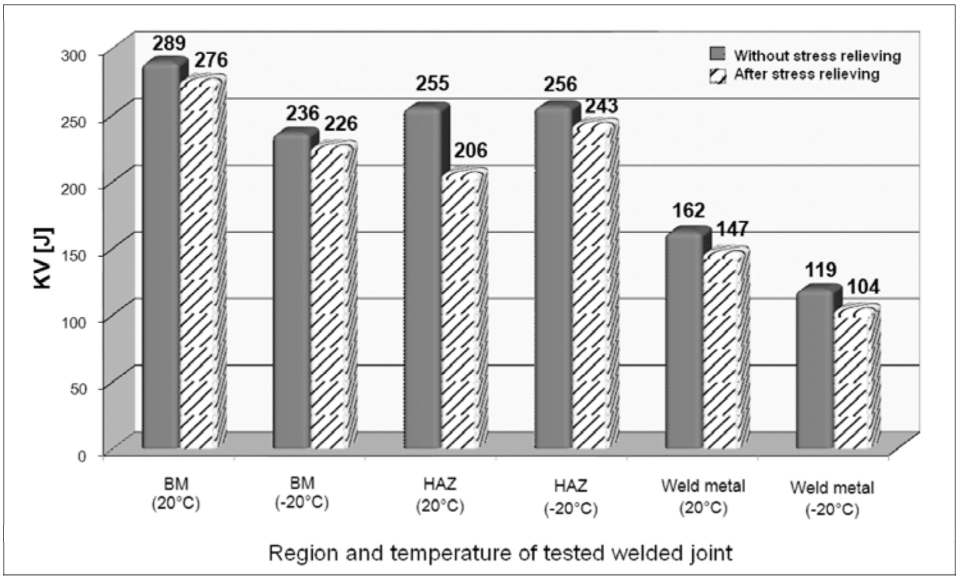



Fig. 3. Test results of impact absorbed energy of S420MC steel welded joints. HAZ=Heat Affected Zone [19]

The impact absorbed energy values for all tested areas of the S420MC steel welded joint not subject to stress relief annealing are higher than those for the areas of the S420MC steel welded joint subject to annealing. Both in case of the joints which were subject to stress relief annealing and those which were not, the impact absorbed energy determined at the negative temperature (-20°C) for the area of the parent metal and the weld was lower than that obtained at the positive temperature (+20°C). An utterly different tendency could be observed in the heat affected zone, where at the lower temperature, the impact absorbed energy for the joint not subject to stress relief annealing remained almost unchanged. In case of the joint subject to stress relief annealing it was possible to observe an increase in impact absorbed energy value. From brittle cracking point of view, such a phenomenon in HAZ of the joint (i.e. the area potentially most susceptible to cracking) is highly advantageous. Nevertheless, the verification whether the aforesaid tendency can be observed also in case of welded joints produced from other grades of thermo-mechanically rolled steels requires further research.

### 3.4. Measurement of hardness of S420MC steel welded joints

Measurement of hardness in the cross-section of welded joints was carried out by means of Vickers method pursuant to the requirements of standard PN-EN 1043-1:2000 [16], where the weight imposed on the indenter amounted to 10 kg (HV10). Hardness tests involved specimens sampled from cruciform joints (Fig. 4) subject and not subject to stress relief annealing. The test results are presented in Table 2. Figure 5 presents a diagram comparing hardness values of S420MC steel welded joints subject and not subject to stress relief annealing; the test reference line being measurement line A.

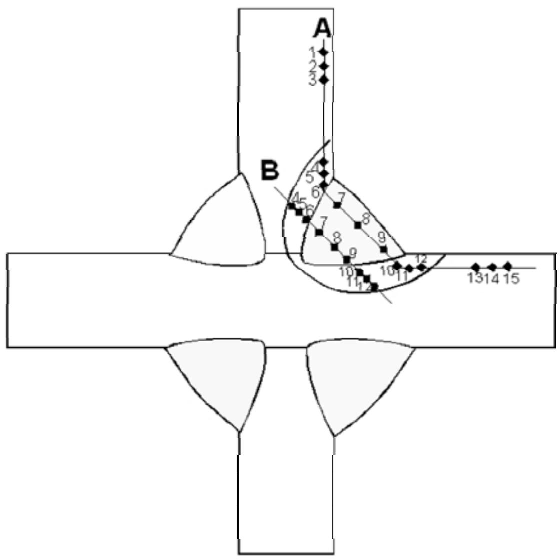



Fig. 4. Diagram of hardness measurement lines of cruciform joint with fillet welds of S420MC steel [19]

TABLE 2

Hardness measurement results of S420MC steel welded joints [19]

| State of joint | Measurement line | Hardness HV10 in measurement point (acc. to 4) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Joint not subject to 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 subject to 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 | – | – | – |

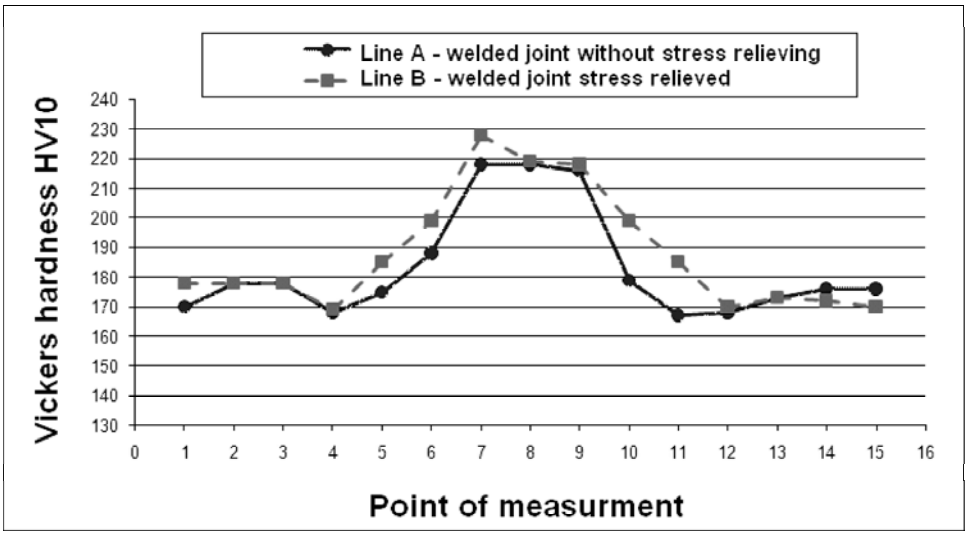



Fig. 5. Diagram of hardness of S420MC steel welded joints subject and not subject to stress relief annealing [19]

### 3.5. Measurement of internal stresses by means of trepanation method

The measurement of internal stresses resulting from the welding process was conducted by means of the trepanation method using transformation of strains. Internal stresses were measured on two test butt welded joints. One of the joints was subject to stress relief annealing under the same conditions as those applied during stress relief annealing of test elements used for fatigue tests. The measurement consisted in preparing nine 40 mm-long measurement bases where metal balls mechanically pressed in the material served as measurement points (Fig. 6). Next, a mechanical extensometer was used in order to measure the distances between individual measurement points of the bases. In order to reveal internal stresses it was necessary to prepare notches between the measurement bases (Fig. 7). Preparation of the notches was followed by another measurement of the distances between the base points. The difference in distances between the bases before and after relief of stresses enabled the determination of their value and sense. Table 3 presents internal stresses determined for individual measurement bases of S420MC steel welded joints; Figures 8-9 present the distribution of stresses in tested joints.

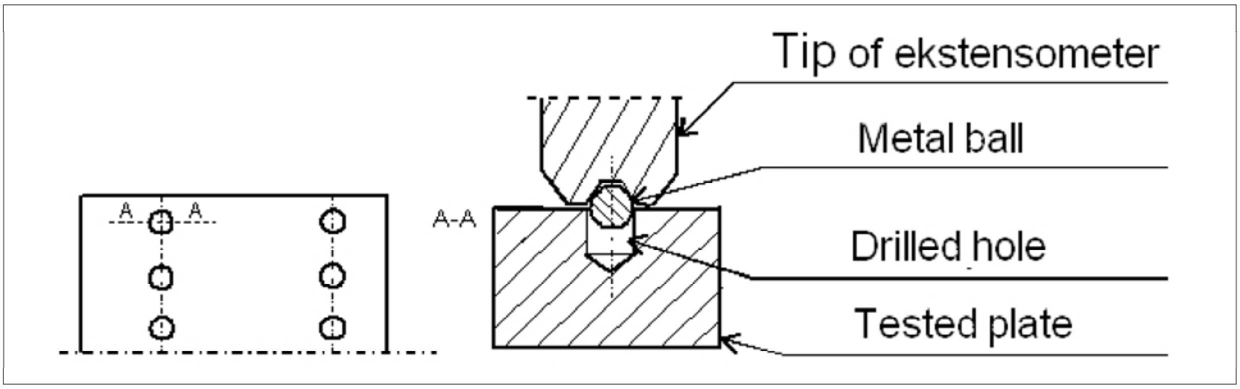



Fig. 6. Sketch of preparation of measurement point in tested sheet with welded joint [19]

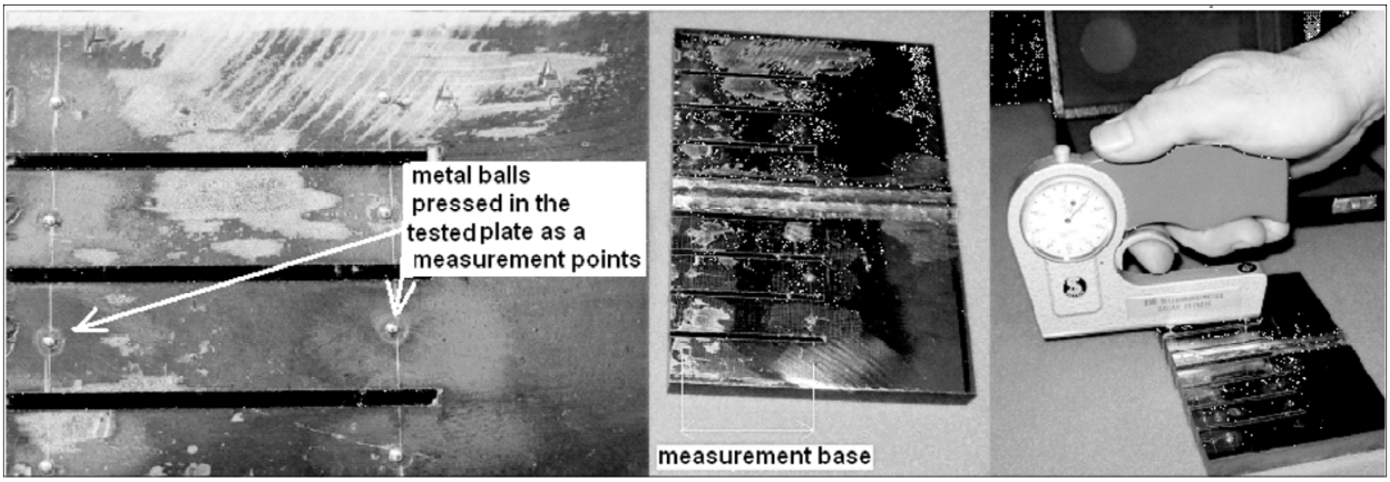



Fig. 7. Test elements of butt welded joint for measurement of internal stresses and method of measurement using mechanical extensometer [19]

TABLE 3

Measured values of internal stresses in S420MC steel butt welded joints [19]

| State of joint | Internal stresses [MPa] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Successive points of measurement base | | | | | | | | |
| | 1 | 2 | 3 | ,4 | 5 | 6 | 7 | 8 | 9 |
| Joint not subject to stress relief annealing | – 216.5 | -155 | -128 | 10 | 262.5 | 57.5 | -130.5 | -148 | -181 |
| Joint subject to stress relief annealing | -46 | -13.5 | -140 | -97.5 | 177.5 | -54 | 3 | * | -27.5 |

* – unreliable readout (incorrectly prepared measurement base)

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

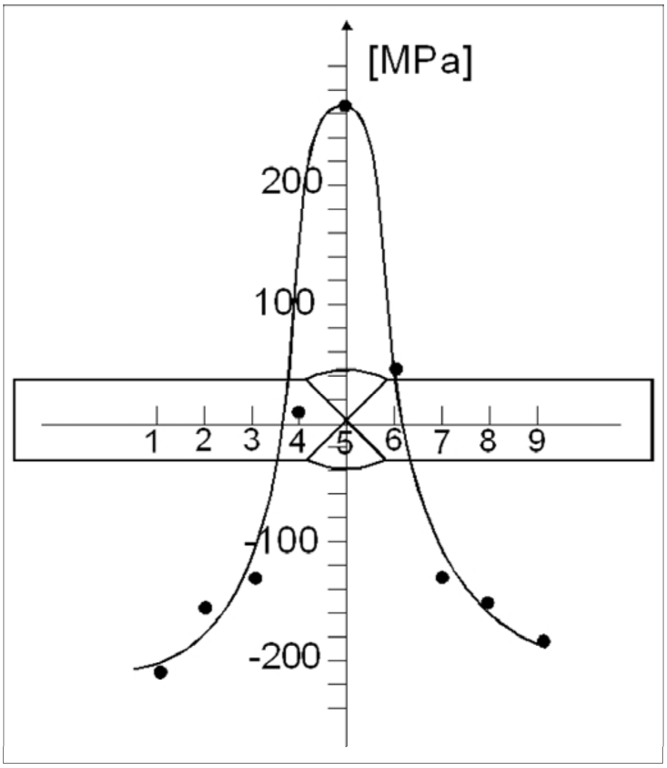



Fig. 8. Distribution of internal stresses in S420MC steel butt welded joint not subject to stress relief annealing (stress values acc. to Table 3) [19]

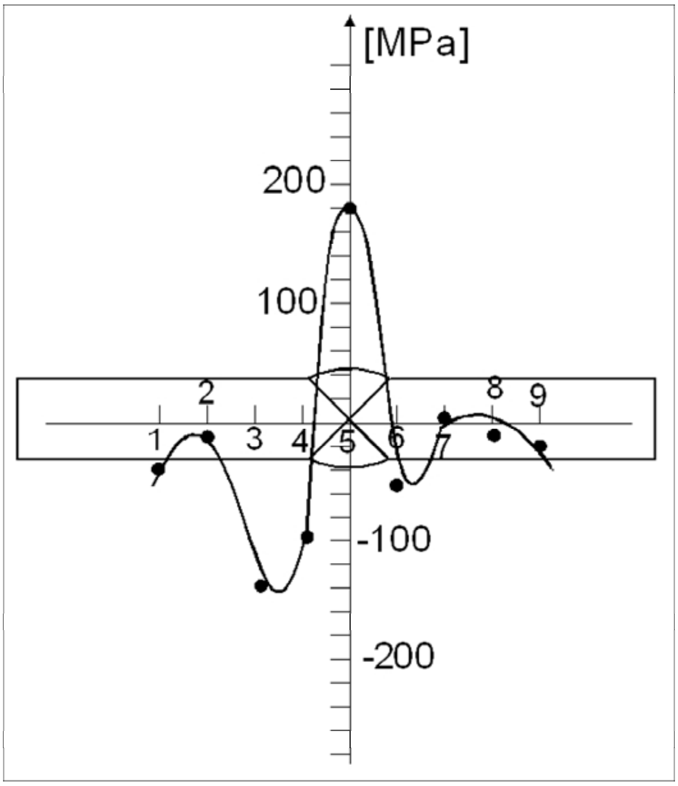



Fig. 9. Distribution of internal stresses in S420MC steel butt welded joint subject to stress relief annealing (stress values acc. to Table 3) [19]

### 3.6. Fatigue tests of S420MC steel welded joints

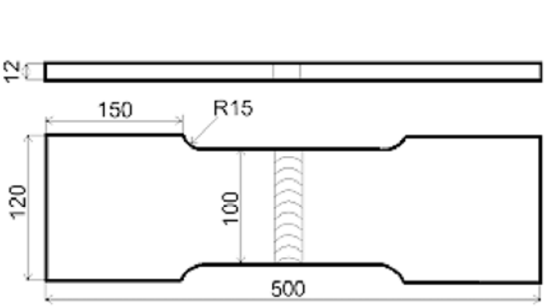
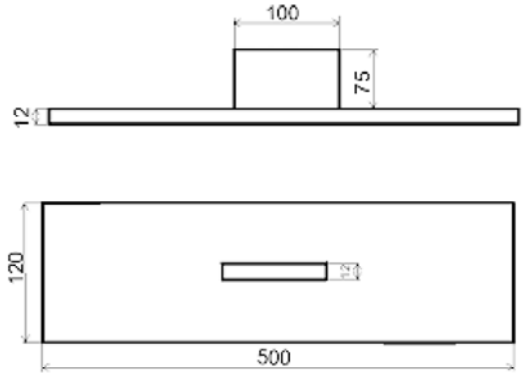
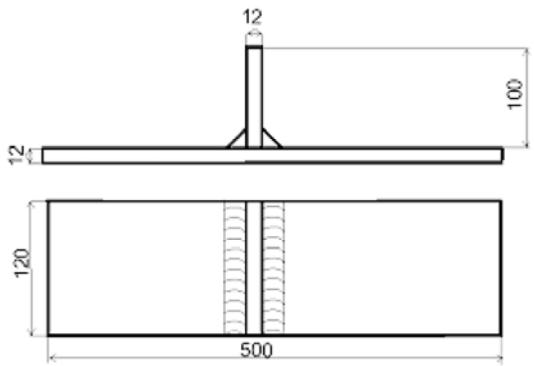
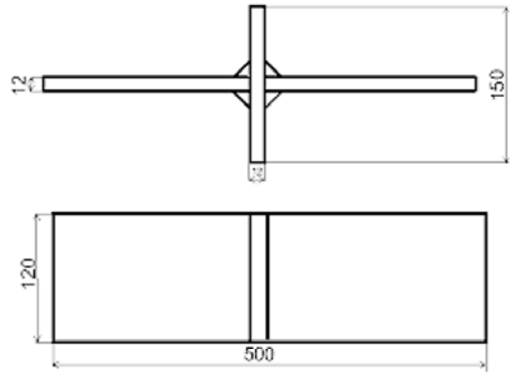
Fatigue tests of welded joints subject and not subject to stress relief annealing were conducted with testing machine MTS 810 (Fig.10).

Fig. 10. Fatigue testing machine MTS 810 at Instytut Spawalnictwa in Gliwice

Fatigue tests involved 4 types of specimens sampled from S420MC steel test welded joints (Table. 4).

TABLE 4

Types of samples for fatigue tests

| Samples from butt welded joint | Samples from joint with longitudinal rib with fillet welds |
|---|---|
|  |  |
| **Samples from joint with crosswise rib with fillet welds** | **Samples from joint with cruciform rib with fillet welds** |
|  |  |

Fatigue tests of each lot of samples were performed for several ranges of stresses $\Delta\sigma$ with constant cycle asymmetry coefficient R=0.2 ($R=\sigma_{min}/\sigma_{max}$) and changing load frequency in the range 15-20 Hz until reaching the moment of the test sample failure. The number of samples in each lot amounted to 10-12, which enabled the determination of Wöhler curve and calculation of fatigue category FAT pursuant to the guidelines of the International Institute of Welding (IIW) [18]. The results of tests in the form of a number of cycles (N) preceding the failure of the test sample were registered by means of MTS-developed software Multi Purpose Test Ware and subject to successive statistical calculation. According to the assumption of the procedure presented in the IIW document [18], the fatigue test results were presented as regression line (Fig. 11-14) calculated on the basis of the relation :

$$\log N = \log C - m \log \Delta\sigma, \tag{2}$$

where:

N – number of cycles preceding failure of sample,

m – straight line slope coefficient,

C – constant.

The statistical calculation enabled the determination of the value of allowed fatigue strength also referred to as fatigue category FAT. Table 5 presents the comparison of calculated fatigue categories FAT of welded joints subject and not subject to stress relief annealing.

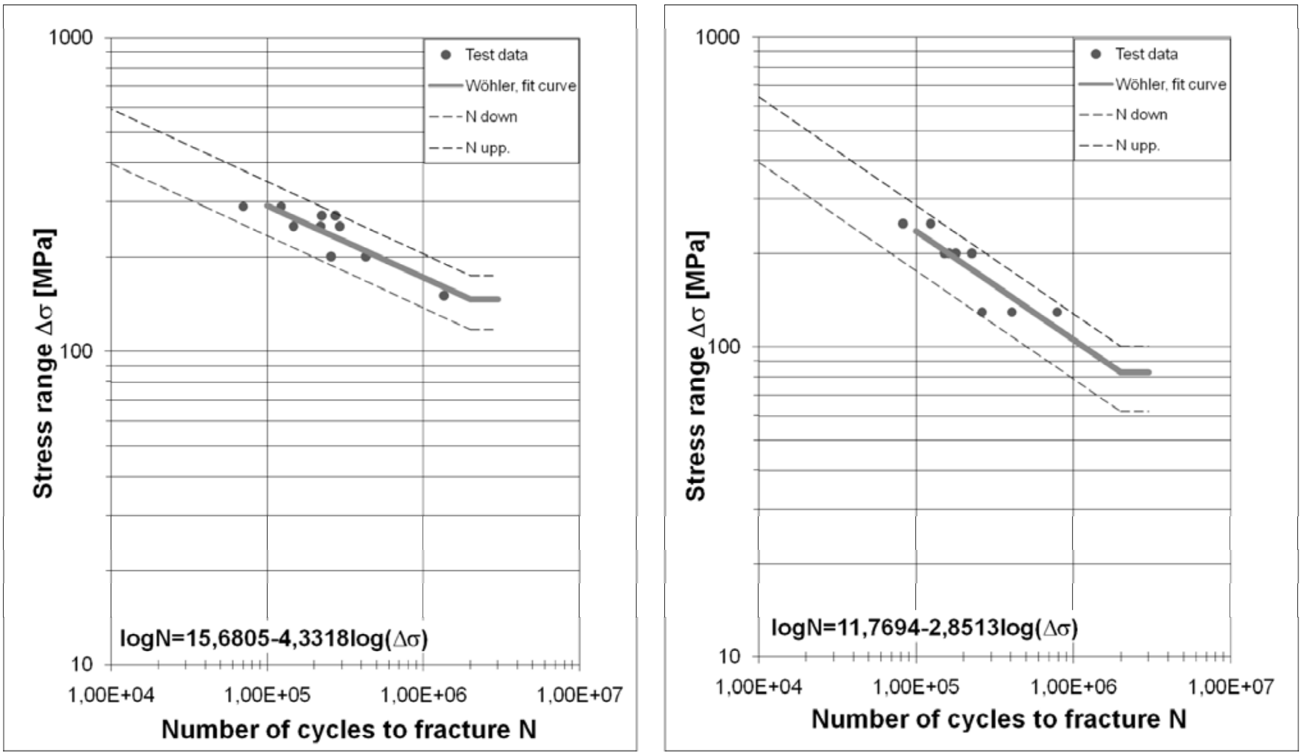



Fig. 11. Wöhler curve for butt welded joint: a) not subject to stress relief annealing, b) subject to stress relief annealing [19]

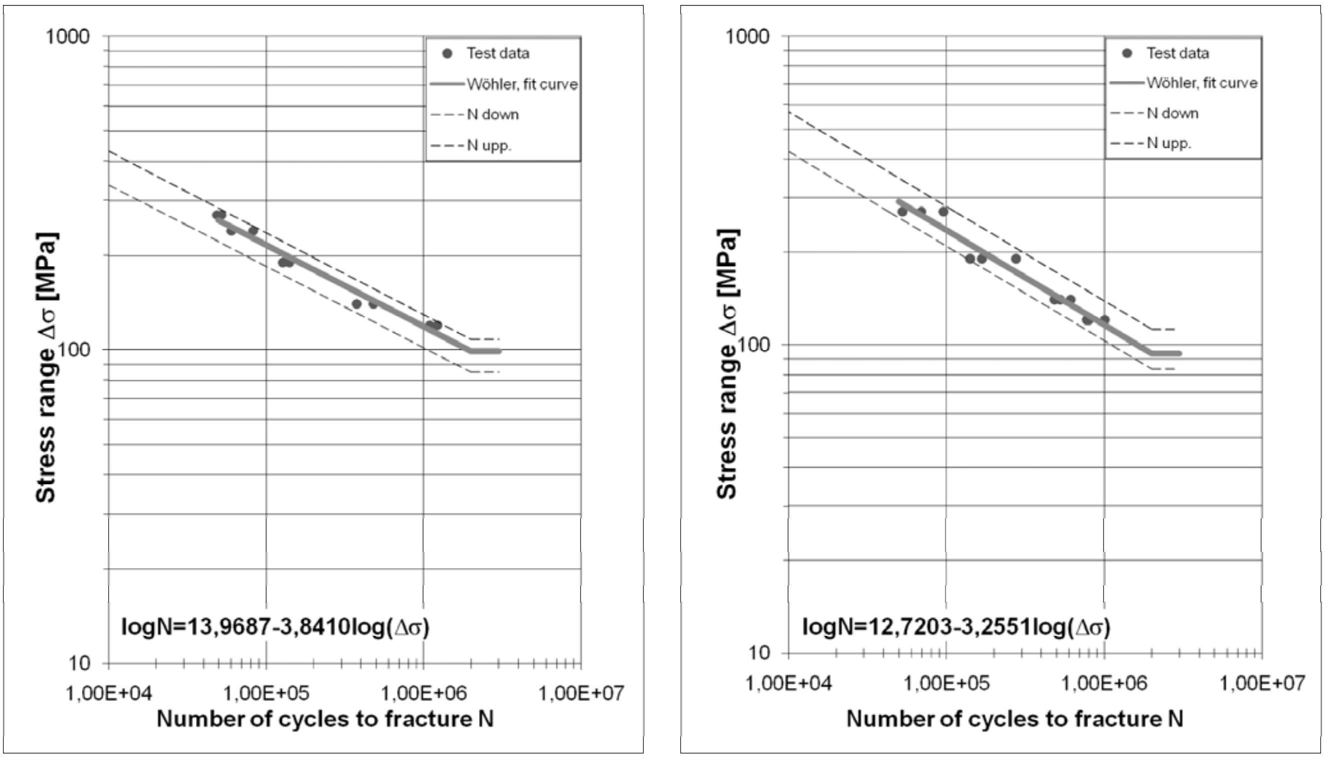
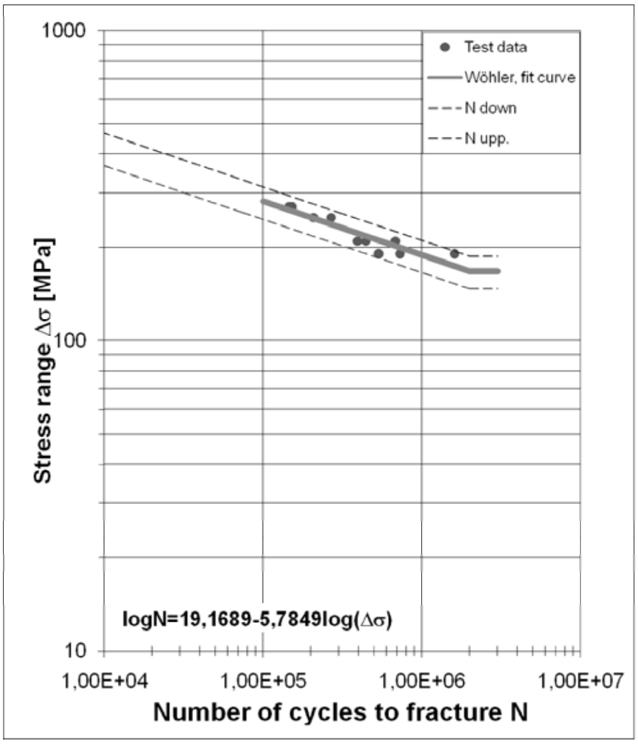



Fig. 12. Wöhler curve for joint with longitudinal rib with fillet welds: a) not subject to stress relief annealing, b) subject to stress relief annealing [19]



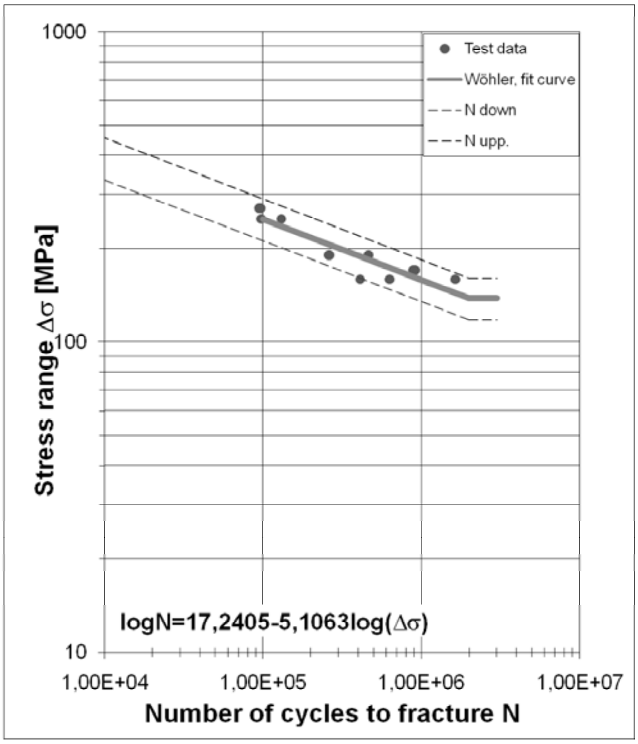
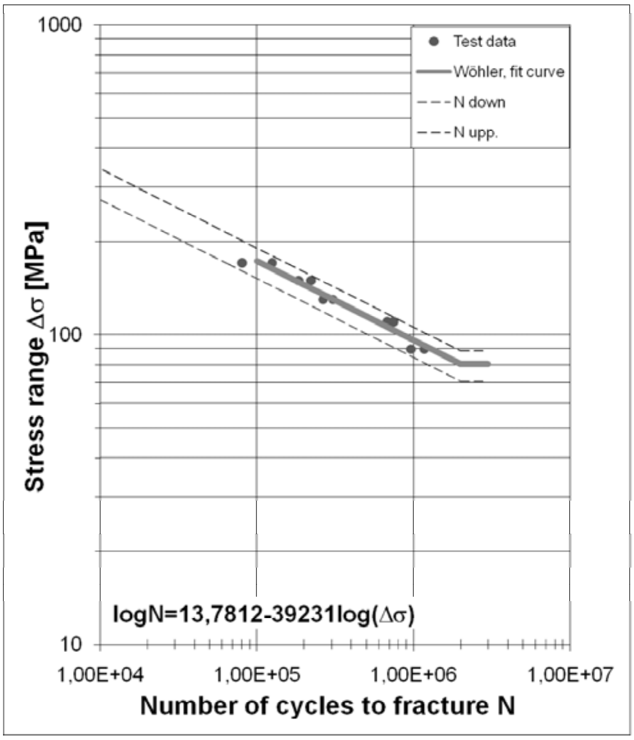




Fig. 13. Wöhler curve for joint with crosswise rib with fillet welds: a) not subject to stress relief annealing, b) subject to stress relief annealing [19]



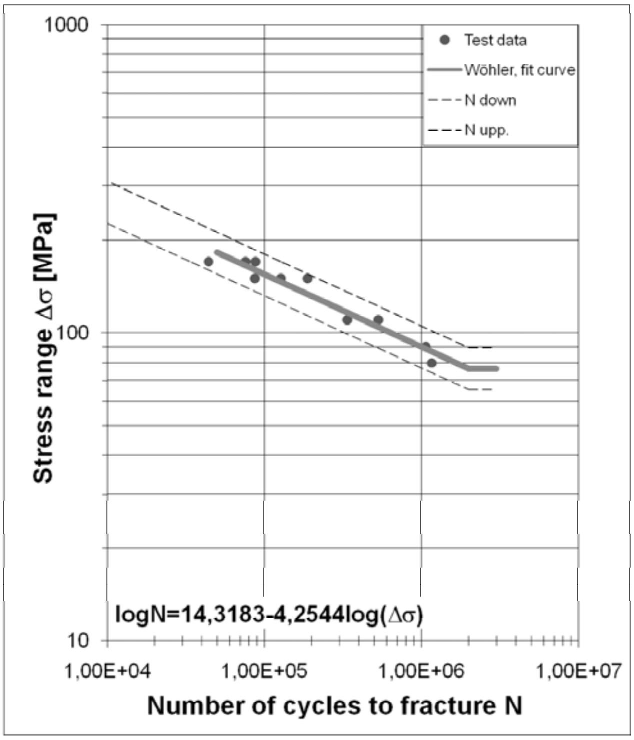
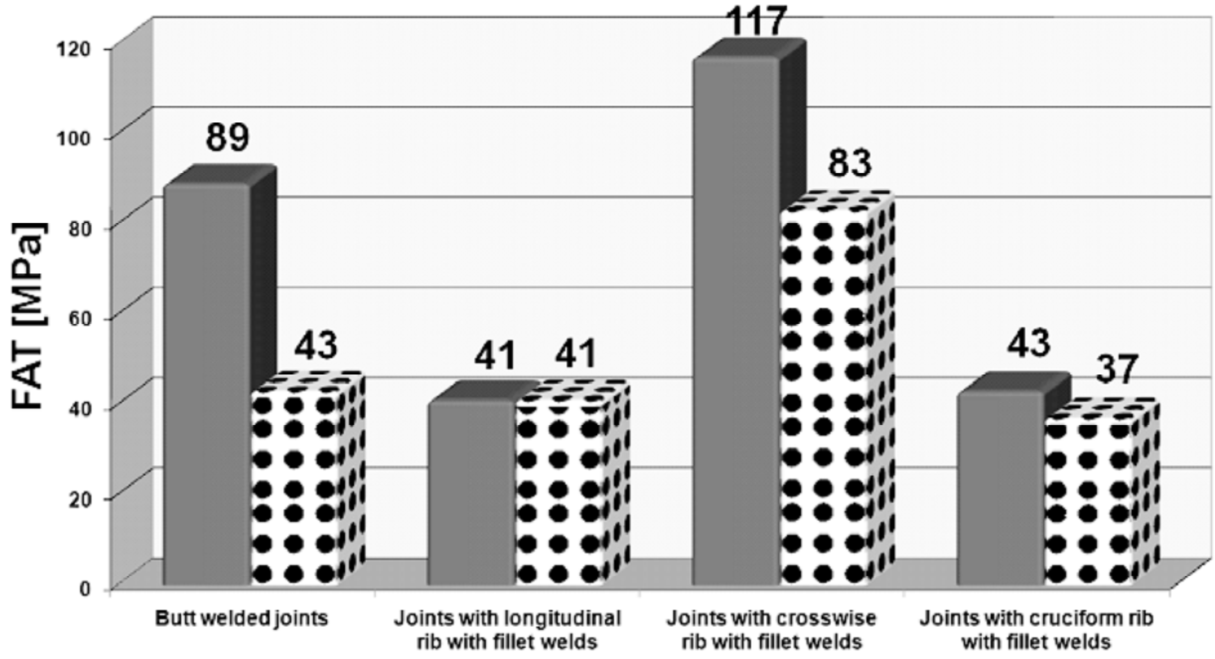




Fig. 14. Wöhler curve for joint with cruciform rib with fillet welds: a) not subject to stress relief annealing, b) subject to stress relief annealing [19]

TABLE 5

Fatigue categories FAT determined for tested joints [19]

| Type of joint | Fatigue category FAT of welded joint [MPa] | |
|---|---|---|
| | not subject to stress relief annealing | subject to stress relief annealing |
| Butt welded joints | 89 | 43 |
| Joints with longitudinal rib with fillet welds | 41 | 41 |
| Joints with crosswise rib with fillet welds | 117 | 83 |
| Joints with cruciform rib with fillet welds | 43 | 37 |




## 4. Summary of test results

The experimental results described above made it possible to determine the impact of stress relief annealing at 550°C on strength-related properties and fatigue strength of S420MC steel welded joints.

The static tensile test revealed that both the yield point $R_e$ and tensile strength $R_m$ increased in the samples subject to stress relief annealing. At the same time it was possible to observe a decrease in the plastic properties of the samples. In the static tensile test of the welded joint subject to stress relief annealing it was possible to observe a 25 MPa decrease in the tensile strength $R_m$ if compared to the tensile strength $R_m$ of the welded joint not subject to stress relief annealing.

In all cases the impact absorbed energy KV determined for various areas of the welded joint subject to stress relief annealing was lower than that determined for the same areas of the welded joint not subject to stress relief annealing. The analysis of the results related to the impact absorbed energy of HAZ of tested welded joints reveals that a decrease in the test temperature does not lead to a decrease in brittle crack resistance of the joint area (see Fig. 3). For the welded joint not subject to stress relief annealing, irrespective of the test temperature, impact absorbed energy remains unchanged with its average value being 255 J and 256 J at 20°C and -20°C accordingly. In turn, in case of the welded joints subject to stress relief annealing it is possible to observe an increase in the average value of impact absorbed energy from 206 J at 20°C up to 243 J at -20°C.

The results of hardness measurements of tested welded joints revealed that stress relief annealing caused an increase in hardness values both in HAZ and the weld if compared to the same areas of welded joint not subject to stress relief annealing. The highest relative increase in hardness can be observed in the weld of the joint subject to stress relief annealing; the highest hardness value being 228 HV10. From crack resistance point of view (especially cold cracking), both types of joints (i.e. subject and not subject to stress relief cracking) reveal safe hardness values. Nevertheless, it appears necessary to clarify the phenomenon of hardness increase following heat treatment of a joint whose chemical composition reveals no occurrence of strengthening liberation processes. Apparently, the said phenomenon could be attributed to thermal conditions accompanying welding process and heat treatment (significant cooling speeds). Additionally, the phenomenon could be associated with the chemical composition and mechanical properties of filler wire deposited metal. According to the manufacturer's data, the filler wire deposited metal contained 1.25% of manganese – significantly more than Mn content in tested S420MC steel (Mn= 0.97 %). At the same time, the filler wire deposited metal was characterised by higher strength properties than those characterising the tested steel ($R_e$ = 580 MPa, $R_m$ = 600 MPa).

The measurement of internal stresses showed that in the butt welded joint the highest tensile stresses were present in the weld axis and amounted to 262 MPa. In turn, in the same area in the welded joint subject to stress relief annealing it was possible to observe a decrease in internal tensile stresses of 85 MPa (32%) (see Fig. 8 and 9). In the welded joint of S420MC steel stress relief annealing caused only partial reduction of internal stresses.

The results of fatigue tests show that the stress relief process of butt welded joints, joints with crosswise rib with fillet welds and joints with cruciform rib with fillet welds did not result in increasing their fatigue strength, but conversely, led to decreasing thereof (from 6 MPa in case of joints with cruciform rib with fillet welds up to 46 MPa in case of butt welded joints). For the joints with longitudinal rib with fillet weld, both after welding and after stress relief annealing, the determined fatigue category FAT stayed the same. Therefore it can be assumed that stress relief annealing does not modify the fatigue strength of joints with significant concentration of stresses. The research results indicate that stress relief annealing conducted at 550°C i.e. within the temperature range recommended by SEW 088 guidelines results in increasing strength properties at the cost of reduction of plastic properties (elongation and brittle crack resistance). Stress relief annealing conducted at 550°C caused only partial relaxation of internal stresses but did not contribute to an increase in fatigue strength of tested welded joints.

## 5. Conclusions

On grounds of conducted tests it was possible to formulate the following conclusions:

1. Stress relief annealing conducted at 550°C causes only partial relaxation of internal stresses in welded joints of S420MC steel.
2. The results of destructive tests revealed that stress relief annealing increased strength properties ($R_e$, $R_m$) and reduced plastic properties ($A_5$, KV) of S420MC steel as well as reduced the impact absorbed energy (KV) of the individual areas of S420MC steel welded joint.
3. HAZ in S420MC steel welded joints reveals no decrease in brittle crack resistance along with a decrease in temperature within the range from +20°C to -20°C.
4. In all types of tested joints, irrespective of the post-weld state of the joint, fatigue cracking was initiated in the area between the face of the weld and the parent metal.
5. Although stress relief annealing within the temperature range of 530-580°C is recommended for welded joints of thermomechanically-rolled steels, it should be noted that this process does not result in increasing the fatigue strength of S420MC steel welded joints.

REFERENCES

[1] K. Ferenc, J. Ferenc, Welded structures; WNT; (2006),(in Polish).

[2] N. Yurioka, TMCP steels and their welding; Welding in the World **35**, 6, 375-390 (1995).

[3] D. Porter, A. Laukkanen, P. Nevasamaa, K. Rahka, K. Wallin, Performance of TMCP steel with respect to mechanical properties after cold forming and post-forming heat treatment; International Journal of Pressure Vessels and Piping **81**, 867-877 (2004).

[4] C. Miki, K. Homma, C. Tominaga, High strength and high performance steels and their use in bridge structures; Journal of Constructional Steel Research **58**, 3-20 (2002).

[5] T. Varga, Safety of welded modern high strength steel constructions, in particular bridges; Welding in the World **38**, 1-22 (1996).

[6] T. R. Gurney, Fatigue of welded structures WNT, (1973), (in Polish).
[7] M. Szubryt, Technological ways of enhancing fatigue strength of welded structures, Seminar Aspects of fatigue strength of welded structures – projecting, developing, testing. Instytut Spawalnictwa; (2007) (in Polish).
[8] A. G. Olabi, M. S. J. Hashmi, Stress relief procedures for low carbon steel welded components, Journal of Materials Processing Technology **56**, 552-562 (1996).
[9] SEW 088:1993 Schwei*SS*geeignete Feinkornbaustähle; Richtlinien für die Verarbeitung, besonders für das Schmelzschwei*SS*en.
[10] DIN 17014-1 Heat treatment of ferrous materials. Terminology.
[11] EN 10149-2:2000 Specification for hot-rolled flat products made of high yield strength steels for cold forming. Delivery conditions for thermomechanically rolled steels.
[12] PN-EN 10002-1:2004 Metale. Tensile testing of metallic materials. Method of test at ambient temperature.
[13] PN-EN 895:1997 Destructive tests on welds in metallic materials. Transverse tensile test.
[14] PN-EN 875:1999 Destructive tests on welds in metallic materials. Impact tests. Test specimen location, notch orientation and examination.
[15] PN-EN 10045-1:1994 Charpy impact test on metallic materials. Test metod.
[16] PN-EN1043-1:2000 Destructive tests on welds in metallic materials. Hardness testing. Hardness test on arc welded joints.
[17] PN-EN 10028-5:2005 Flat products made of steels for pressure purposes. Weldable fine grain steels, thermomechanically rolled.
[18] A. Hobbacher, Recommendation for fatigue design of welded joints and components; IIW Doc. XIII-2151-07 / XV-1254-07; (2007).
[19] K. Krasnowski and others Fatigue strength of welded joints made of thermomechanicaly rolled steel with and without post weld heat treatment; Research work number Id-131, Institute of Welding (2008) (in Polish).

*Received: 7 April 2009.*