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# THE INFLUENCE OF THE SHAPE OF WELD NOBS ON THE FATIGUE STRENGTH OF S540Q STEEL

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***Abstract***

*The development of weldable steels was discussed together with the methods of obtaining them. The influence of these methods on steel properties was explained. Research was performed on quenched weldable S540Q steel of high strength. Basic mechanical properties of this steel were determined. The results of a static tensile test and technological bending test were given. Next, steel sheets were welded by semi-automatic MAG method. The welds quality was examined and their future suitability was stated. Mechanical properties of the joints welded of this steel were determined. Mechanical properties of native material and welded joints were compared. Joints microstructure was examined in the weld axis, in the heat influence zone and in the native material. Fatigue tests were conducted in the cycle of nonsymmetrical tension – compression of welded joints. The analytical fatigue strength was obtained and it was compared with fatigue strength of welded joints. Tests results were elaborated with the static analysis of linear regression. Wohler diagrams were made after conducting fatigue tests. Finally, weldable joints were melted by TIG method without adding filler metal. The angle and radius of welds nobs entrance into the native material was measured. The increase of fatigue strength is related to the decrease of geometric notch on the edges of weld nobs.*

***Keywords:*** *weldability, high strength weldable steel, fatigue strength*

## 1. Introduction

The application range of materials that are treated by welding technology is considerably wide. Welded constructions are mainly made of:

– steel,
– aluminium alloys,
– magnesium alloys,
– plastics,
– titanium and its alloys,
– composite materials
– ceramic materials,
– multimaterials
– nanomaterials [9].

However today the most common material which is joined by means of welding is steel [3, 5, 9, 11]. This proves the fact that steel production exceeds the production of other structural materials four times. Fig. 1 presents the production of the main structural materials during the 1970 ties, in 2008 and in 2009.

The authors of publications dealing with contemporary welding and its perspectives highly appreciate the interest of constructors and technologists in steel of high and very high plasticity border [9].

The development of weldable steel of high and very high strength was observed during the last 50 years. Fig. 2 presents the development of structural steel of high strength.

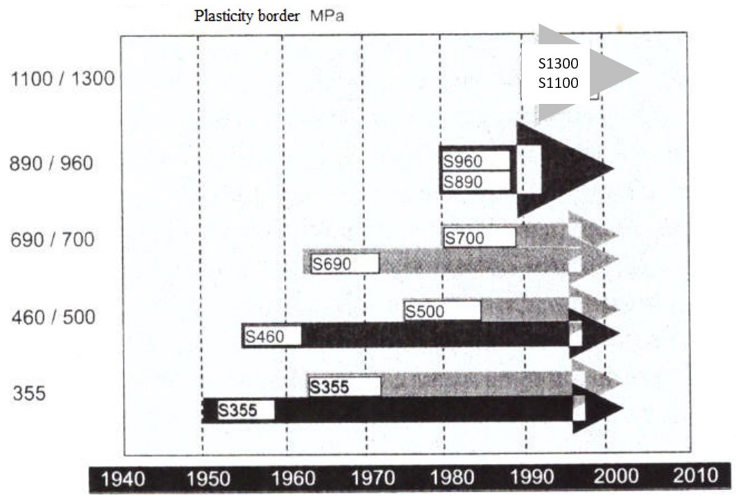


*Fig. 1. World production of main structural materials [9]*

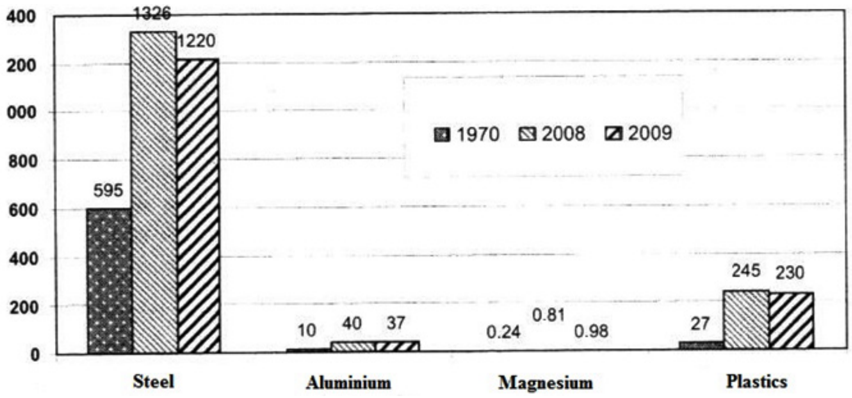


*Fig. 2. The development of low grain structural steels of high strength*

This steel is currently characterized by high strength, good plasticity and at the same time good weldability provided proper care be kept during the welding process. Such properties are obtained thanks to carefully selected chemical composition – alloy components and micro alloys, heat treatment and plastic working. The development of welding techniques also influenced the application of weldable steel of high and very high weldability.

The increase of strength and be achieved by:

- ferrite consolidation,
- refinement of ferrite grains by means of heat treatment or heat – mechanical treatment,
- ferrite consolidation and ferrite grains refinement by means of micro emissions of such alloy elements as carbides, nitrides and carbonitrides [3].

Welding steel of high strength can also cause some problems, for instance:

- there is a probability of cold cracking caused by martenzite occurrence,
- the decrease of ductility can occur in the heat influence zone,
- when welding with very high linear power of the arc, a binitic structure can appear which in turn can cause the decrease of strength.

The application of weldable steel of high and very high strength was also affected by the development of welding technology. Currently used technologies allowed to obtain welded joints which follow the requirements related to mechanical properties and which are also resistant to cold cracking ( without applying extra treatment) [5, 8, 11].

Welded constructions are also made of fine-grained structural steel which is obtained by:

- normalization,
- quenching,

– thermomechanical rolling,
– excretion hardening.

The application of fine-grained structural steel of high strength also influences economic aspects. It enables the utilization of steel sheets of lower thickness. This in turn is related to the decrease of construction weight while maintaining all the functional requirements. For instance it can lead to the decrease of ship weight which can consequently reach higher speed or increase load capacity. Limiting the mass of any construction causes the decrease of labour consumption needed for its production. Lower sheet thickness results in lowering the material costs of both the basic materials as well as additional materials for welding. Even the time necessary for making a given construction can be reduced. Tab. 1 shows the comparison of costs of single joints made of S235JR steel and S1100QL steel. Welded joint of S235JR steel was bevelled to X shape, while the welded joint of S1100QL steel was bevelled to V shape. The comparison shows clearly that the economic costs refer to the plasticity border relation of both steels and reach 80% [8].

Weldable steels of high strength are widely applied, for instance in shipping industry. So far they have been used for the following maritime constructions:

– ocean going vessels of high open deck space, for stringers and deck plates,
– LPG carriers for cargo tanks and double walls,
– special duty vessels,
– drilling rigs, search and mining vessels, for carrying elements of supports,
– underwater units for the strengthened hull.

The above considerations demonstrate that the interest in weldable steels of high strength is justified. If these steels are applied for constructions, working under variable load conditions it is necessary to point out parameters which may influence the level of their fatigue.

*Tab. 1. The comparison of costs of welded joint made of S235JR steel and S1100QL steel [8]*

| S235JR | Steel Grade | S110QL |
|---|---|---|
| 183 | Plasticity border [MPa] | 1100 |
| 72 | Sheet thickness [mm] | 12 |
| 11.527 | Weld weight [kg/m] | 0.726 |
| 40 | Labour cost [€/h] | 40 |
| 320 | Current intensity [A] | 220 |
| 6.5 | Fusion efficiency [kg/h] | 4 |
| SG2 | Type of wire Ø 1.2 mm | MF1100M |
| 0.8 | Cost of wire [€/kg] | 6.5 |
| 95 | Output [%] | 95 |
| 0.01 | Price of shield gas [€/l] | 0.01 |
| 15 | Flow of shield gas [l/min] | 15 |
| 118.87 | Cost of weld production [€/m] | 23.26 |
| 5.11 | Costs ratio [-] | 1 |

## 2. Research

The research was conducted on quenched steel sheets 12 mm thick made of S540Q steel. Tab. 2 presents chemical composition of the steel examined.

Welding was carried out by semi-automatic MAG method. The filler metal, the scheme and welding parameters were identical as in paper [4]. Butt welds were performed without preheating while keeping the interlayer temperature of 100°C and welding semi automatically in the low position in the shield of 80% Ar and 20% $CO_2$ mixture on the copper plate, with Y welds. Fig. 3 presents the scheme of welding.

*Tab. 2. Chemical composition of S543Q steel according to metallurgic certificates*

| Steel sign | Chemical composition, % of mass | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | P | S | Cr | Ni | Cu | Mo | V | Nb | Al |
| S540Q | 0.18 | 1.36 | 0.32 | 0.020 | 0.016 | 0.02 | 0.01 | 0.02 | – | 0.01 | 0.035 | 0.04 |

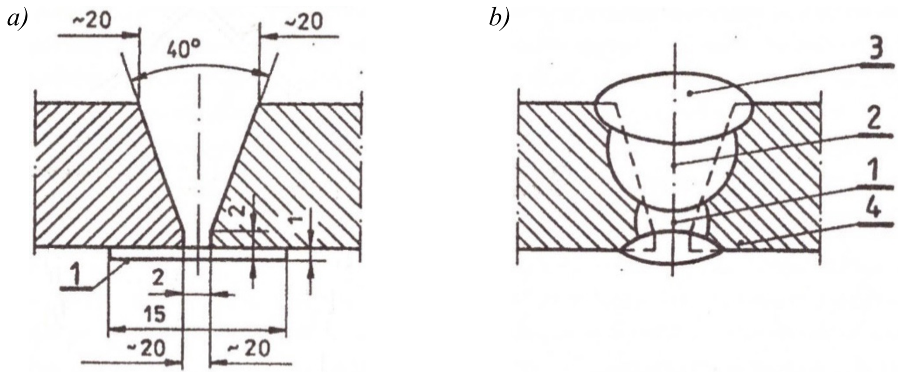


*Fig. 3. The scheme of welding: a) sheets edges preparation: 1 – copper pad, b) welding sequence: 1 – before penetration run, 2 – filling run, 3 – closing run*

In one weld, the nobs edges were penetrated by TIG method without adding filler metal. In order to penetrate the weld nobs a strip of native material 20 mm wide was cleaned to shining metal surface. Wolfram electrode of 3 mm in diameter was used. The distance of the electrode from the penetrated edge was kept in the range of 0.5-1.0 mm. Current intensity was 240 A, arc voltage was 14 V, the speed of penetration reached 160 mm/min, the linear energy was 12.6 kJ/cm, and the argon output was 9 dm$^3$/min. X ray tests confirmed the achievement of correct welds.

In order to assess the usefulness of the welded joints, a static tensile test was carried out as well as technological bend test. Mean values of the tensile strengths obtained for given welds are shown in Tab. 3.

*Tab. 3. Mechanical properties of quenched sheets of S540Q steel and their butt welded joints*

| Steel sign | Samples | YS [MPa] | UTS [MPa] | EL [%] | YS/UTS | $UTS_z/UTS_r$ |
|---|---|---|---|---|---|---|
| S540Q | Native mat. | 545 | 630 | 23.5 | 0.865 | – |
| | Welded joint. | – | 652 | – | – | 1.03 |

Bending tests were performed on flat transverse strips with the use of bending arbor 36 mm in diameter. The lengthened samples surfaces did not show any cracks exceeding 3 mm, on the back of weld and on the root of weld of welded joints of S540Q steel at the bending angle of 180°.

The welds microstructure was observed in the weld axis, in the heat influence zone and in the native material. Steel microstructure was classified as low carbon, tempered martensite of layered construction. The differences in microstructures of particular weld zones were observed. They appeared to be most clear in the observation line 1 mm distant from sheet weld surface. These were typical structures for welded joints such as dendric structure of weld, overgrown grains in the overheating zone, fine grain normalization zone and the zone of partial transformation at the entrance of SWC into the native material. No metal discontinuities were observed in the welded joint.

The computational fatigue strength was determined for welded joints of $UTS_Z$-165 MPa. The fatigue tests were carried out on strength machine in non-symmetrical cycle of lengthening – compressing, with the asymmetry coefficient of R = -0.3, at the load changes frequency of 16.7 Hz, with air-cooling in room temperature. Fig. 4 presents the Wöhler diagram for welded joints of quenched sheets of S540Q steel 12 mm thick. Fig. 5 depicts Wöhler diagram for welded joints after weld penetration by TIG method without adding filler metal.

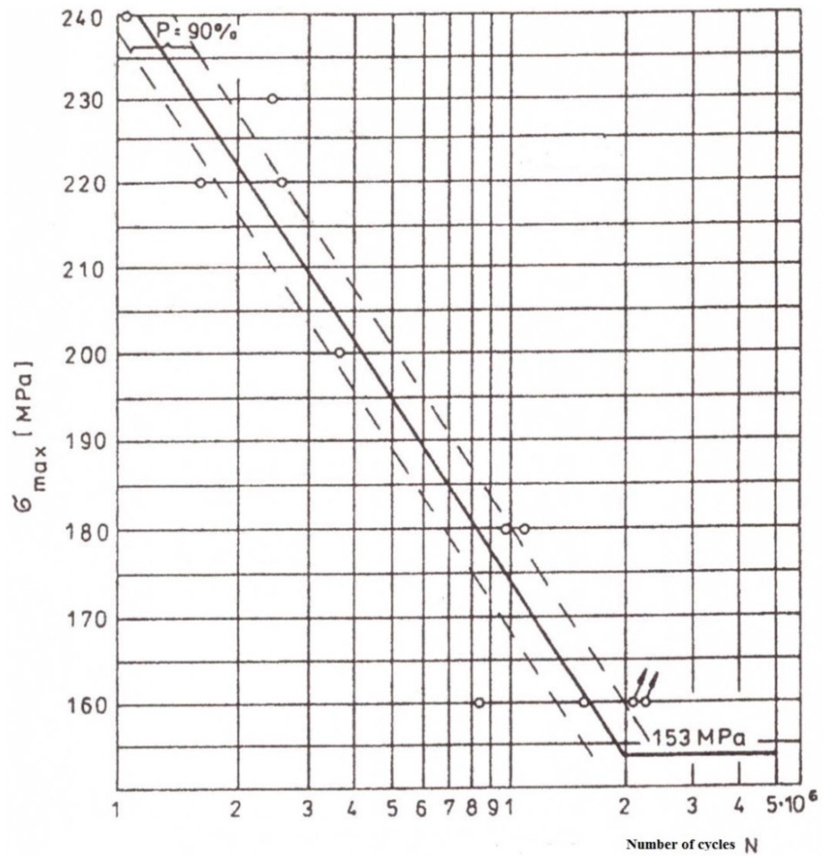


*Fig. 4. Wöhler diagram for welded joints of quenched sheets 12 mm thick of S540Q steel*

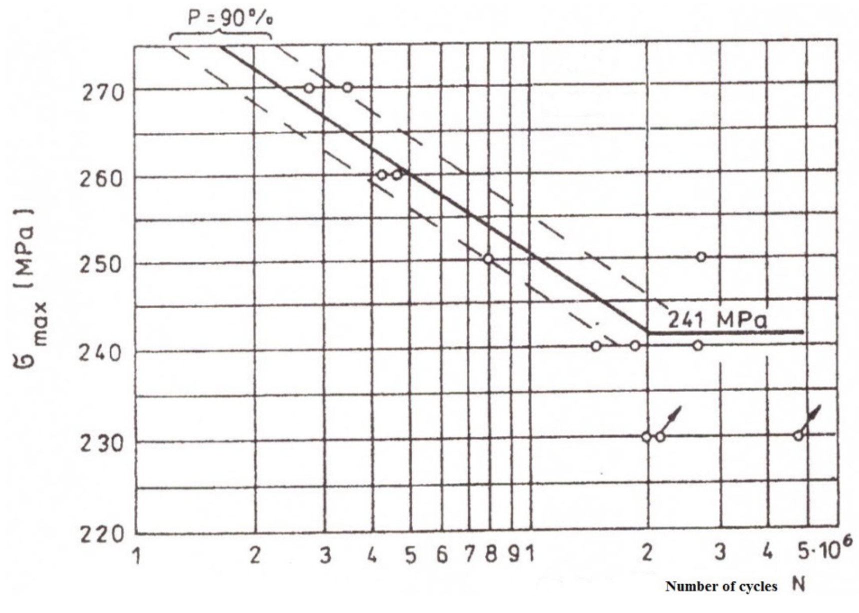


*Fig. 5. Wöhler diagram for welded joints of quenched sheets 12 mm thick of S540Q steel, where welds edges were penetrated by TIG method without adding filler metal*

Butt welded joints of S540Q steel showed fatigue strength of $Z_G$ = 153 MPa. While the fatigue strength of $Z_{Gp}$ = 241 MPa was obtained for welded joints after penetration.

Angles and radiuses of both weld nobs on both sides of the sample were measured (Fig. 6).

The average angle was 158° and the radius reached 6.0 mm for welded joints without penetration.

The average angle for the weld after penetration was 166°, while the radius reached 9.9 mm.

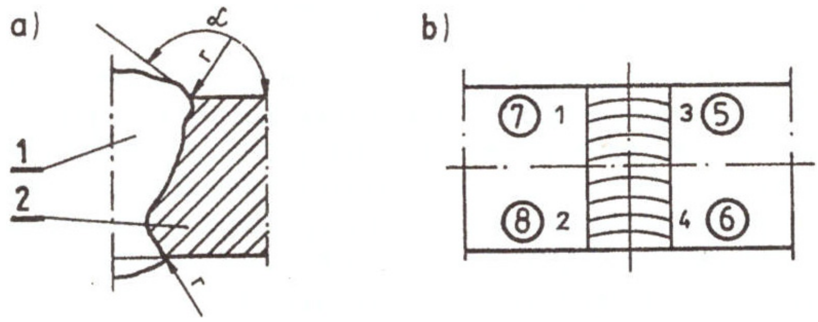


*Fig. 6. Measurements diagram of weld nobs edges: a) location of the angle and radius 1 – weld, 2 – native material, b) measurements spot 1-4 at the back of weld, 5-8 at the root of weld*

## 3. Remarks on research results

Literature [1, 2] assumes that quenched steel of high strength show lower weldability in comparison to steel of lower strength grade. During research, this thesis was not proved. S540Q steel is characterized by satisfactory welding quality. X-ray and metallographic examinations demonstrated that sample welds were metallically clean. These results were obtained without applying special welding conditions such as: preheating or linear energy limitation. The occurrence of microstructure differences in particular weld zones can affect the level of fatigue strength. Variable microstructure in welded joints forms a structural notch.

Tensile strength of the welds was better than that of native material. The ratio of plasticity border and tensile strength amounted to 0.865. It seems important to consider this fact when calculating permissible stresses for constructions made of these steels, which can increase the safety factor. When bending butt welds of S540Q steel, no cracks occurred at the bending angle of 180°. This result shows great plasticity capability, considering the regulations of classification societies [6, 10].

It was stated that fatigue strength of welded joints of S540Q steel is lower than the defined computational strength for this steel. Penetration of weld edges in S540Q steel resulted in the increase of fatigue strength by 58%. It also caused the increase of entrance angle of weld nobs by 5.1%, as well as the radius by 65%.

## 4. Conclusions

1. Welding sheets of quenched S540Q steel with semi-automatic MAG method without applying any special conditions allowed to achieve welds of metallic continuity and required utility.
2. Fatigue strength of welded joints was increased by 58% because of penetration of weld nobs edges with TIG method without adding filler metal.
3. The increase of fatigue strength is related to the decrease of geometric notch on the edges of weld nobs.

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