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HCF DESIGN CURVES FOR HIGH STRENGTH STEEL WELDED JOINTS

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Abstract: The objective of this article is to present the newest results of our complex research work related to the high cycle fatigue (HCF) resistance of advanced high strength structural steels (HSSS). RUUKKI Optim 700QL and SSAB Weldox 700E steels were used for the investigations with 690 MPa yield strength. During the HCF tests base materials and their welded joints using gas metal arc welding as a joining process were tested at different mismatch conditions [matching (M), overmatching (OM), and matching/overmatching (M/OM)] for optimising welding process to achieve an improvement in the fatigue strength. Statistical approach was applied during the preparation and the evaluation of the investigations, which increased their reliability. The parameters of the determinable HCF design curves were calculated based on the philosophy of the Japanese method (JSME S 002-1981). During the investigations and the evaluation the results were compared with each other and with literary data.

Keywords: *high strength structural steel (HSSS), RUUKKI Optim 700QL, SSAB Weldox 700E, high cycle fatigue (HCF)*

1. INTRODUCTION

Welded joints have been used in the majority of engineering applications such as engineering structures, power generation, offshore structures, and transportation. Welded structures are very sensitive parts because the welded regions are in complex metallurgical and stress conditions. Before the Second World War, the design of all engineering structures was based on tensile strength and ductility. Mild steel was used as the structural material and the minimum yield strength of the weld metal was found to be around 340 MPa. The yield strength to tensile strength ratio of the weld metals that were used for welding the mild steel in early designs was very high and the designers did not pay much attention to the yield strength of the weld metals. It has been reported that the maximum yield strength of the filler metal that has been used for joining the mild steel plates was about 59% higher than the base material [1].

High strength structural steels (HSSS) with yield strengths from 690 MPa upwards are applied in growing amount industrial applications. Specific design solutions and economic aspects of modern steel constructions e.g. mobile cranes or hydro power plants, lead to an increasing trend in light-weight design. Steel producers currently provide a diversified spectrum of high-strength base materials and filler metals. Thus an extensive reduction in weight and production costs can be achieved with increasing material strength [2].

During the welding process the joining parts are affected by heat and force, which cause inhomogeneous microstructure and mechanical properties, and furthermore stress concentrator places can form. Both the inhomogeneity of the welded joints and the weld defects play important role in case of cyclic loading conditions. High cycle fatigue (HCF) phenomenon is a very common problem in welded structures; however there are a limited knowledge about the fatigue behaviour of HSSS base materials and welded joints up to now. In accordance with the welding challenges nowadays, the mismatch effect was examined. The aim of our present investigations was the determination of basic equations of the HCF design curves for base materials and their differently mismatched welded joints [3].

2. HSSS CLASSIFICATION AND TRENDS OF DEVELOPMENT

For years, metallurgists have been searching ways of producing structural steels which would have the highest (possible) mechanical properties and maintain satisfactory plastic properties at the same time. Due to an increase in yield point, it is now possible to manufacture structures consisting of elements of smaller wall thickness, thus lighter and less expensive to transport. A smaller wall thickness requires a smaller amount of filler metals and a shorter welding time, simultaneously. An increase in the mechanical properties of steels may be obtained by an appropriate selection of chemical composition through a classic process of toughening (hardening and tempering) or by means of thermo-mechanical treatment. However, no matter how high its mechanical properties might be, structural steel will only have practical application if it can be welded by means of commonly used arc methods; toughened steels offer such a possibility. Due to the appropriate selection of chemical composition and proper heat treatment, these steels are characterised by very good mechanical properties as well as good weldability.

The recent development of structural steels has involved on the one hand toughened steels such as S690Q, S890Q and S960Q and on the other hand thermo-mechanically rolled steels of lower mechanical properties but of a higher impact strength (S355M, S460M and S500M) [4].

Steels of 690 MPa yield have become commercial about three decades ago. They were, like today, essentially produced by water quenching and tempering. In the last years thermomechanical rolling followed by accelerated cooling has become an alternative production route [5].

Due to very high mechanical properties, steels of a yield point in excess of 1,100 MPa have found application in the production of high-loaded elements of car lifts, travelling cranes and special bridge structures. The advantages of using steels with high mechanical properties are visible as regards the costs of transport, plastic working, cutting, and welding [4].

By the use of normalizing process, the yield strength is maximized in 460 MPa, thus new methods have been developed since the seventies, when quenched and tempered (Q&T or Q+T) group appeared. With this heat treatment process, combined with alloying components, the maximal yield strength can reach 1,300 MPa. On the other hand, it should not be ignored that filler metals are not available, up to now, for this extreme strength, only if undermatching (approximately 15–20%) is allowed. It is important to note that applying undermatching during the selection of the filler metal may have some additional positive effects (residual stress, fatigue properties etc.). Due to the above mentioned causes, instead of S1100Q and S1300Q, the S960Q is more widespread, which can be welded by matched electrodes, as well. By the recent development of the thermomechanical (TM) process, the yield strength of TM steels have approached (Q&T) steels, thus it is worth examining this group by the upcoming welding researches [6]. *Figure 1* summarizes the chronology of structural steel developments [7], [8].

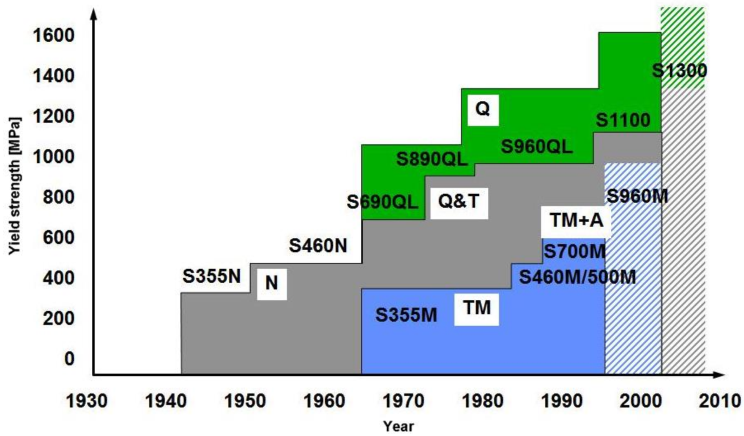

Figure 1. Chronology of structural steels developments [7], [8]

3. Production processes of toughened steels

The aim of quenching and tempering (Q+T) is to produce a microstructure consisting mainly in tempered martensite. Some amounts of lower bainite are also acceptable. Quenching of high strength steels is performed after austenitizing at temperatures of some 900 °C. In order to suppress during cooling, the formation of softer microstructure, such as ferrite, an accelerated cooling is necessary. The fastest cooling is obtained by exposing the plate surfaces to a rapid water stream. By such an operation the very surface is cooled to temperature below 300 °C within a few seconds. At the core of a plate cooling is essentially slower and the cooling rate decreases with increasing the plate thickness. At the core of thick plates the heat flow to the surface is the controlling parameter for the cooling rate. Closer to the surface and for thinner plates also parameters controlling the heat transfer, e.g. water temperature or flow rate are of importance [5]. The connection between yield strength and transition temperature ranges for different high strength steel types can be seen in *Figure 2* [5], [7], [9].

The development of steel metallurgical processes aims on the one hand the growing of efficiency (reduction of production costs), and on the other hand the decreasing of impurities in steels, which could cause disadvantages, e.g. lamellar tearing or hot cracking [4]. *Table 1* summarizes the characteristic metallurgical periods and the belonging values of the impurities [4].

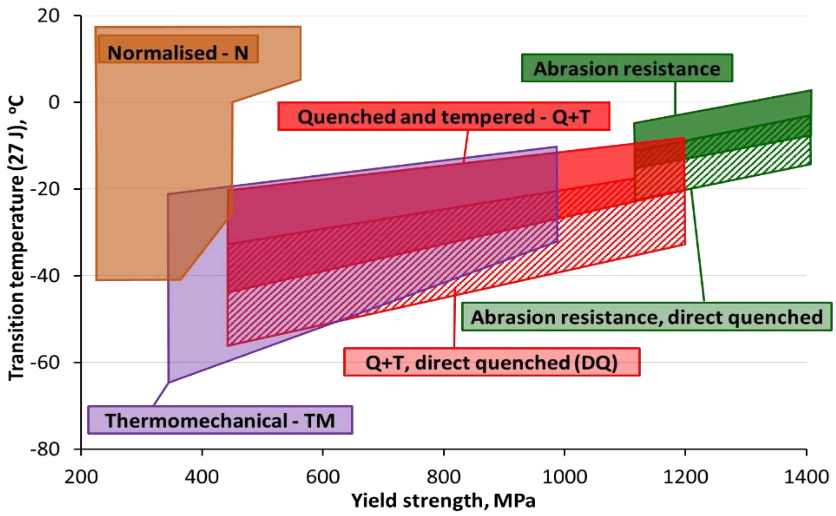

Figure 2. Combination of strength and toughness typical for commercial steels [5], [7], [9]

Table 1

Impact of development of metallurgical processes on the level of impurities in steel [4]

Element	**Metallurgical processes in the years**		
	1950/1960	**1980/1990**	**1990/2010[2)]**
	ppm		
Sulphur	100–300	50–80	60
Phosphorus	150–300	80–140	6
Hydrogen	4–6	3–5	–
Nitrogen	80–150	<60	–
Oxygen	60–80	<12[1)]	–

[1)] Technology made it possible to obtain the oxygen content at the amount <12 ppm however in practice, the oxygen content in steel was higher.

[2)] The manufacturers do not indicate the content of hydrogen, nitrogen and oxygen.

By applying this methods one can produce steels which have a carbon equivalent lower than approximately 0.05%. Such steels are characterised by better weldability in comparison with steels produced in a conventional way. Schematic diagrams of the production processes of toughened steels are shown in *Figure 3* [4].

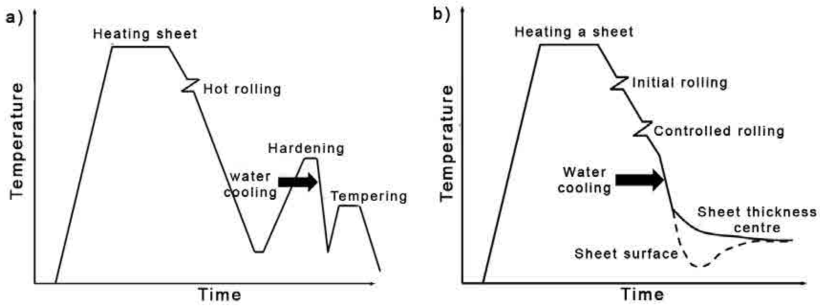

Figure 3. Diagrams of production processes of toughened steels
a) hardening and tempering processes, b) direct hardening process [4]

While developing a technology for welding of toughened steels characterised by high mechanical properties, one should also focused on apart from cold crack formation, such phenomena as follows: welding-induced HAZ softening ("soft layer issue"); failure to obtain a required toughness level in the weld and HAZ (brittleness caused by ageing and precipitation hardening). "Soft layer issue" during welding of toughened steels develops in their HAZ a softened microstructural area with worse mechanical properties. This phenomenon is particularly visible in steels after rolling and intensified cooling. *Figure 4* presents hardness changes in the cross-section of the welded joint made of toughened steel (Q+T). In the HAZ of toughened steel a hardness decrease is to a small extent caused by phase transitions; much greater in this case is the impact of tempering. Welding with limited linear energy makes the layer narrow. In this case, although the hardness of this layer is lower, this fact, due to a narrow softening zone, does not have to result in the deterioration of the mechanical properties of the joint, because of the "contact strengthening" phenomenon generated by plain strains induced in the soft layer [4].

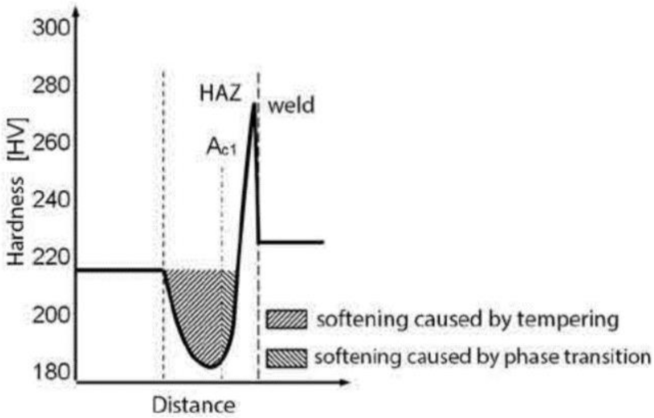

Figure 4. Hardness distribution in welded joint made of toughened steel (Q+T) where R_y > 500 MPa and $t_{8/5}$ = 30 s [4]

4. INFLUENCES OF MISMATCHING

The development of high strength low alloy steels, micro-alloyed steels and quenched and tempered steels as well as new fabrication techniques changed the engineers to design the structures on the basis of yield strength and fracture toughness instead of tensile strength. With the increased use of high strength base materials, it is very difficult to produce matching (M) and overmatching (OM) welding consumables because the strength and toughness cannot be increased simultaneously. Sometimes, the yield strength of the weld metal used for joining the plates is lower [undermatched (UM)] or higher (overmatched) than the yield strength of the base material.

Mismatched welded joints are joints in which the yield strength and/or the microstructure of the weld metal will be different from that of the base material and HAZ. The factors, which are responsible for heterogeneities, are welding process, consumables, joint design and weld thermal cycle. Undermatched joints are used in repair welding, welding of bridges, pressure vessels and penstocks, etc. They are used to prevent the cracks in the welds, for example an undermatched cap pass reduces the weld toe cracking from cyclic plastic bending during reeling. Similarly, overmatched joints are used in pipeline girth welds, welded offshore structures, cladding and hardfacing etc., for effectively preventing the weld metal failure by small cracks can be found in the weld metal.

In the base material, HAZ and weld metal combinations, the mismatch constraint is caused by both global mismatch and local mismatch. The global mismatch is defined as the ratio of yield strength of weld metal to that of the base material, whereas the local mis-match is defined as the ratio of yield strength of the weld metal to that of the HAZ. The mechanical factors responsible for producing global strength mismatch of weldments are base material yield strength, weld metal yield strength, base material tensile strength and weld metal tensile strength. The net section yielding occurs when plastic deformation is localized to the defective cross section. The gross section yielding occurs when the applied stress exceeds the material yield strength, i.e. when the yield strength of the weld metal exceeds that of the base material. In general, large defects trend to produce net section yielding, whereas small defects are beneficial for obtaining gross section yielding [1].

5. CIRCUMSTANCES OF INVESTIGATIONS

The investigated base materials, the selected filler metals and the pairing of the base materials and filler metals (mismatch conditions: M, OM and M/OM) for our investigations can be seen in *Table 2*.

Table 2

The base material-filler metal pairing during our experiments

Base material	Filler metal	Mismatch condition
RUUKKI Optim 700QL	INEFIL NiMoCr	matching (M)
SSAB Weldox 700E	Thyssen UNION X85	matching (M)
SSAB Weldox 700E	Thyssen UNION X90	overmatching (OM)
SSAB Weldox 700E	Thyssen UNION X85/UNION X90	matching/overmatching (M/OM)[1)]

[1)] M/OM = M root layers / OM filler layers

The chemical composition and the basic mechanical properties of the investigated base materials and used filler metals are summarized in *Table 3* and *Table 4*, respectively. Gas metal arc welding (GMAW) was selected for the welding experiments. Based on industrial experiences, M21 mixed gas with 18% CO_2 + 82% Ar content was chosen as shielding gas; in every cases 1.2 mm diameter solid filler wires were used. In the interest of the uniform stress distribution, X joint preparation was designed, with 80° opening angle and with 1.5 mm gap between the two plates. During the welding, the workpieces were rotated regularly.

Table 3

The chemical composition of the base materials and filler metals (weight %)

C	Si	Mn	Cr	Mo	Ni	S	P	Ti	V	Al	Cu
Base material: RUUKKI Optim 700QL											
0.14	0.30	0.96	0.60	0.19	–	0.002	0.009	0.020	0.005	0.05	–
Filler metal: INEFIL NiMoCr											
0.08	0.50	1.60	0.30	0.25	1.50	0.007	0.007	–	0.090	–	0.12
Base material: SSAB Weldox 700E											
0.14	0.30	1.13	0.30	0.17	–	0.001	0.007	0.009	0.010	0.03	–
Filler metal: Thyssen UNION X85											
0.07	0.68	0.61	0.29	0.61	1.73	0.010	0.006	0.080	0.010	0.01	0.06
Filler metal: Thyssen UNION X90											
0.10	0.80	1.80	0.35	0.60	2.30	–	–	–	–	–	–

Table 4

The mechanical properties of the examined base materials and filler metals

Base material and filler metal designation	**Yield strength**	**Tensile strength**	**Elongation**	**Charpy V impact energy (–40 °C)**
	MPa	**MPa**	**%**	**J**
RUUKKI Optim 700QL	783	826	19	54
INEFIL NiMoCr	≥ 750	≥ 820	≥ 19	≥ 60
SSAB Weldox 700E	791	836	17	165
Thyssen UNION X85	≥ 790	≥ 880	≥ 16	≥ 53
Thyssen UNION X90	≥ 890	≥ 950	≥ 15	≥ 58

The welding parameters were selected based on both theoretical considerations and real industrial applications (summarized in [8] and [10]) and those can be found in *Table 5*. The table shows the welding current (I), the voltage (U) and the welding speed (v_w), also the preheating (T_{pre}) and the interpass (T_{ip}) temperatures, with the calculated linear energy (E_v) and the calculated critical cooling time ($t_{8.5/5}$) values. The parameters of the root layers (1–2) and the filler layers (3–20/8) are shown separately. During the welding, eighteen filler layers (3–20) were used for RUUKKI

Optim 700QL base material, and six filler layers (3–8) were used for SSAB Weldox 700E base material.

Table 5
The applied welding parameters

Layer	T_{pre}, T_{ip}	I	U	v_w	E_v	$t_{8.5/5}$
	°C	A	V	cm/min	J/mm	s
Root (1–2)	150	130–140	19.0–20.5	20	700–750	7–8
Filler (3–20/8)	180	280–300	28.5–28.5	40	1000–1100	9–11

HCF experiments were performed on base materials and on their welded joints, with an MTS 810 type electro-hydraulic materials testing equipment, at room temperature and in laboratory environment. Flat test specimens and constant load amplitude were applied during the tests, with R = 0.1 stress ratio, f = 30 Hz loading frequency, and sinusoidal loading wave form. The geometry, the location, and the one group of the tested specimens in butt weld joint (BWJ) can be seen in *Figure 5*.

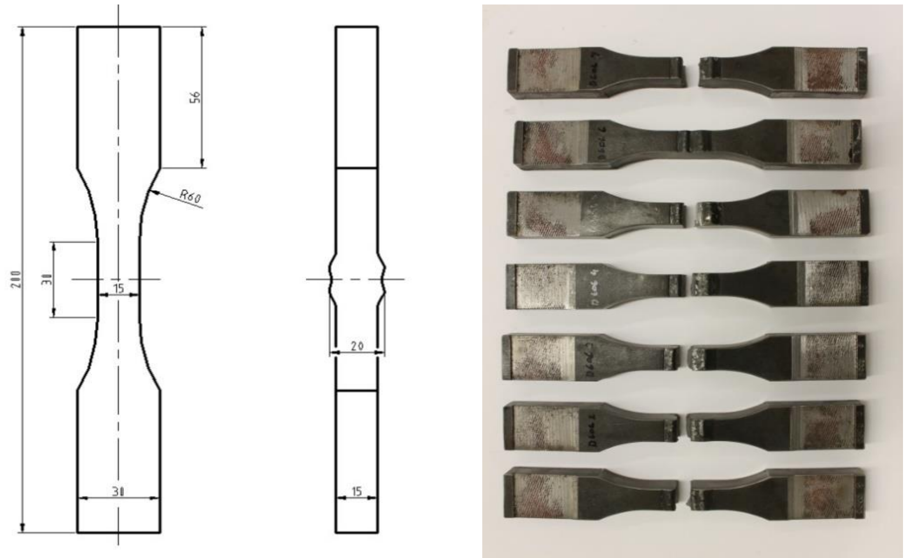

Figure 5. Configuration of the tested specimens (BWJ = butt welded joint)

6. HIGH CYCLE FATIGUE TEST RESULTS

Considering the large number of test specimen and striving after reliability, applying of a statistical approach was necessary. Staircase method was used during both the preparation and the evaluation of the HCF test, based on the JSME S 002-1981 prescription [11]. The results of our experiments were compared with some literature data [12]–[14]. The measured values and the basic lines of the determinable HCF design limit curves for the base materials (see [15] too) and their welded joints are presented in *Figures 6–7* (literary data) and *Figures 8–9* (own data). In the figures x/y = centre line of the specimen/crack growth direction, h = parallel to the rolling direction, k = perpendicular to the rolling direction, v = thickness direction, 1 W = centre line of the welded joint, 3 W = thickness direction in the welded joint.

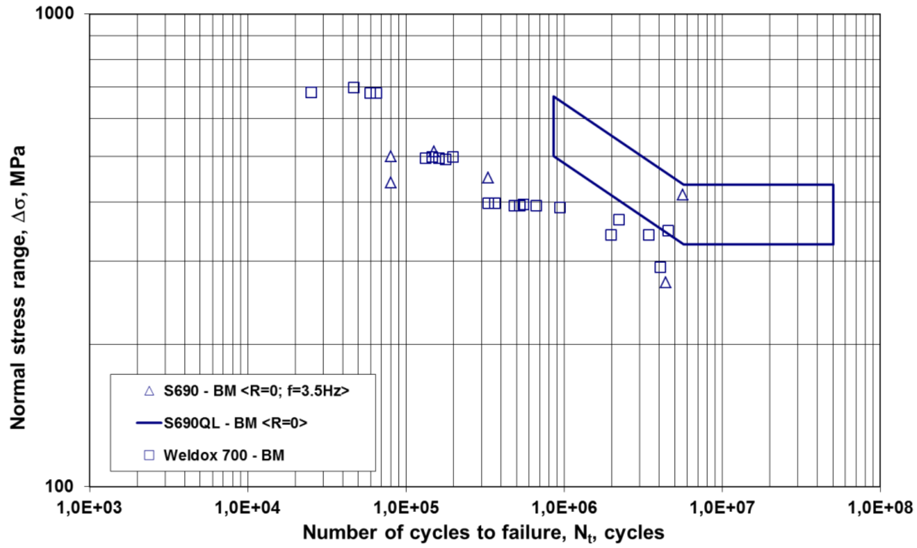

Figure 6. Measured values for S690 type base materials (BM) [12]–[14]

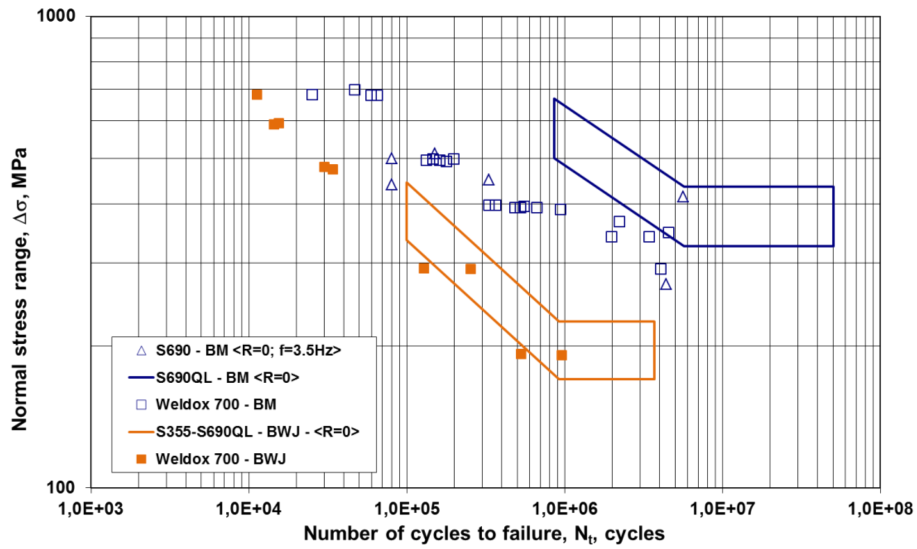

Figure 7. Measured values for S690 type base materials (BM) and butt welded joints (BWJ) [12]–[14]

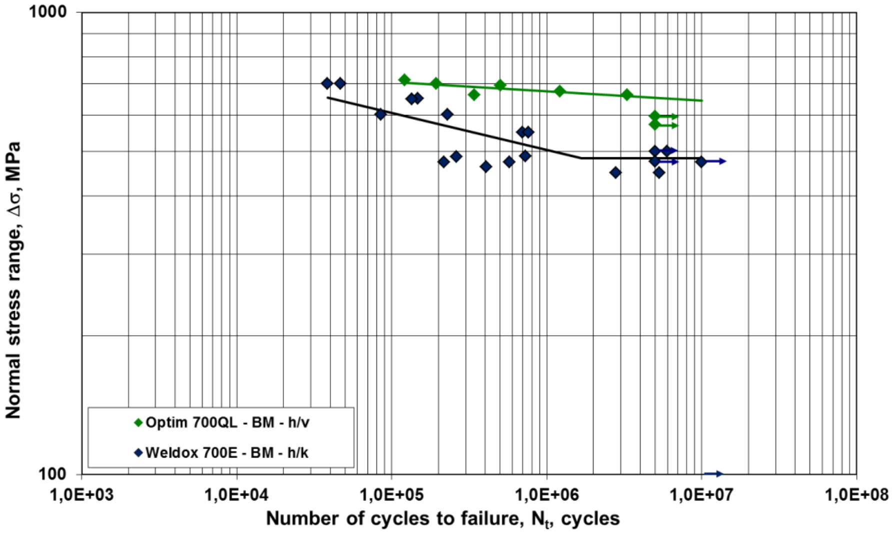

Figure 8. Measured values for S690 type base materials (BM) [own data]

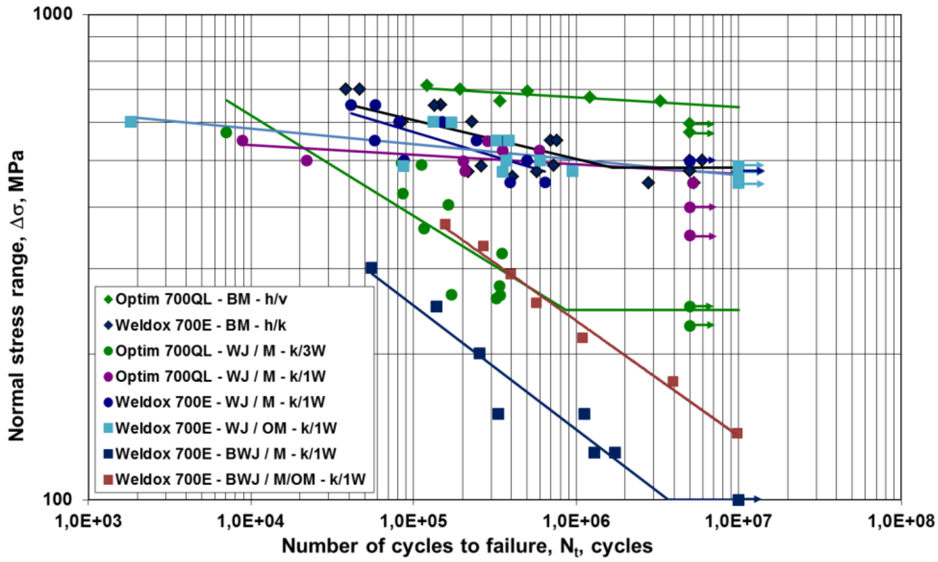

Figure 9. Measured values for S690 type base materials (BM), welded joints (WJ) and butt welded joints (BWJ) [own data]

Table 6 summarizes the basic parameters of the determinable HCF design curves, the N_k value is the number of cycles for the break point of the S-N curve, the $\Delta\sigma_D$ is the fatigue limit, and the $\Delta\sigma_{1E07}$ is the stress value belonging to 1×10^7 cycles in the cases, when the horizontal (endurance limit) part of the curves cannot be determined. The used equation is as follows:

$$N * \Delta\sigma^m = a,$$

and the HCF design limit curves can be calculated with the help of *–2SD* values.

Table 6

Basic parameters of the determinable HCF design limit curves

Mismatching and orientation	m	lg(a)	N_k	$\Delta\sigma_D$	$\Delta\sigma_{1E07}$
	–	–	cycle	MPa	MPa
Base material: RUUKKI Optim 700QL					
BM h/v	51.282	151.109	–	–	646
WJ/M k/3W	4.826	17.476	8.639E05	246	–
WJ/M k/1W	50.251	141.260	–	–	470
Base material: SSAB Weldox 700E					
BM h/k	12.453	39.650	1.677E06	483	–
WJ/M k/1W	9.960	32.469	–	–	–
WJ/OM k/1W	31.250	90.415	–	–	467
BWJ M k/1W	3.917	14.400	3.683E06	100	–
BWJ M/OM k/1W	4.207	15.966	–	–	–

7. SUMMARY AND CONCLUSIONS

Based on our investigations and their results the following conclusions can be drawn.

The results of the executed investigations justified the necessity of statistical approaches, especially referring to the directions of the base materials and the welded joints, and the determination of the number of the tested specimens.

Applying the developed welding technologies adequate welded joints can be produced, where the appropriate quality contains the eligible resistance to high cycle fatigue.

The resistance of the base materials to high cycle fatigue is more advantageous than the resistance of the welded joints; the mismatch phenomenon (matching, overmatching and matching/overmatching) has characteristic influence on the high cycle fatigue resistance.

Based on the Basquin equation, calculated curves can be used for the determination of high cycle fatigue design limit curves, applying *–2SD* philosophy

Further examinations required to draw statistically more establish conclusions, to calculate the parameters of the high cycle fatigue design limit curves reliably, to study the effects of the welding residual stress fields, and to determination of design limit curves for different type of whole welded joints.

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