UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

FATIGUE STRENGTH AND FATIGUE CRACK PROPAGATION DESIGN CURVES FOR HIGH STRENGTH STEEL STRUCTURAL ELEMENTS

Booklet of PhD Theses

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1. INTRODUCTION

1.1 PRELUDE

In the vehicle industry, one of the fundamental trends in the environmental load reduction through weight reduction, which can be achieved by the application of high strength materials. In the case of various structures, the dominant joining technology is the welding, including fusion and pressure welding processes. During welding the joining parts are affected by heat and force, which cause inhomogeneous microstructure and mechanical properties, furthermore, stress concentrator places can form. In case of cyclic loading conditions, the inhomogeneity of the welded joints and the weld defects can have even a more important role. In welded structures the high cyclic fatigue (HCF) phenomena is a very common problem; however, there is limited knowledge about the fatigue behaviour of high strength steel welded joints up to now. In accordance with the welding challenges nowadays, the mismatch effect was examined [29].

During the welding the joining parts are affected by heat and force, which cause inhomogeneous microstructure and mechanical properties, furthermore stress concentrator places can form. In case of cyclic loading conditions, the inhomogeneity of the welded joints and the weld defects can have even a more important role. In welded structures the high cyclic fatigue (HCF) phenomena is a very common problem; however, there are a limited knowledge about the fatigue behaviour of high strength steel welded joints up to now. High cycle fatigue strength or limit curves can be found in numerous standards and prescriptions, such as Eurocode 3 [1], BS 7608 [2], BS 7910 [3], AASHO [4], and IIW [5] recommendations. The Eurocode 3 traditionally includes steels only with guaranteed yield strength up to 460 MPa, and with additional limitations it was extended up to 700 MPa. However, the IIW recommendation includes HCF properties of steels with yield strength up to 960 MPa. The fatigue design curves of these directives do not indicate differences between mild, conventional high and advanced high strength steels (HSS and AHSS, respectively), and do not consider the mismatch phenomenon between the base material and the filler metal.

RUUKKI Optim 700QL, SSAB Weldox 700E (S690QL type), SSAB Weldox 960E (S960QL type) and VOESTALPINE Alform 960M (S960M type) advanced high strength steels, and gas metal arc welding (GMAW) were chosen for the complex investigations. During our experiments, 15 mm and 30 mm (RUUKKI Optim 700QL) thick base materials were used. These steels are frequently used in mobile cranes, scrapers and bulldozers where the typical plate thickness is between 10 mm and 20 mm in the high strength structural elements.

Reliability of a structural element having crack or crack-like defect under cyclic loading conditions is determined by the geometrical features of the structural element and the flaws, the loading conditions, as well as the material resistance to fatigue crack propagation. There are different documents [6][7][8], standards and recommendations [3][9][10] containing fatigue crack propagation limit or design curves and rules for the prediction of the crack growth [3][11]. The background of the fatigue crack propagation limit curves and the calculations consist of two basic parts: statistical analysis of numerous investigations (fatigue crack propagation tests) and fatigue crack propagation law, frequently the Paris-Erdogan law [12].

In accordance with the welding challenges nowadays, the mismatch problem of the base material and the filler metal was examined.

1.2 THE PURPOSE OF DISSERTATION

The global aims of the research work are to study the influence of mismatch characteristics on cyclic loaded high strength steel welded joints and to determine high cycle fatigue strength and fatigue crack propagation design curves for different high strength steel base materials and their diversely mismatched welded joints, such as structural elements.

Because the research work is a significant continuation of previous researches, therefore builds upon their experience [13] and uses their measurement results [14][15]. It means that the previous results provide good and reliable basis for the comparison of the research results.

The specific aims of the research work are as follows.

- Carrying out high cycle fatigue investigations on differently mismatched butt welded joints with different crack paths made by different strength categories of high strength steels.
- Studying the influence of welding heat input on high cycle fatigue resistance of the thermomechanically rolled high strength steel type.
- Development a generally usable method for determination of fatigue strength curves, and determination of the curves for all investigated cases.
- Carrying out fatigue crack growth investigations on differently mismatched welded joints with different notch locations made by different strength categories of high strength steels.
- Studying the influence of welding heat input influence on fatigue crack growth resistance of the thermomechanically rolled high strength steel type.
- Analysing the usability of previously developed method for the determination of fatigue crack propagation design or limit curves for high strength steels and their welded joints, furthermore determination of the curves for all investigated cases.

During the research work I focused on the highest strength category, so-called quenched and tempered (Q+T) and thermomechanically treated (TM) groups of structural steels.

2. METHODOLOGY

In the first part of my dissertation research work I summarized the classification of high strength structural steels types and trends of development and production methods of these steels. 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) [16]. 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 [17]. Due to very high mechanical properties, steels of a yield point in excess of 1100 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 [16].

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) group appeared. With this heat treatment process, combined with alloying components, the maximal yield strength can reach 1300 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 [18]. Figure 1 summarizes the chronology of structural steel developments [19][20]. According to steel manufacturing companies' data the minimum yield strengths of (extra) high strength steel plates stated for Q+T steels 1300 MPa [21][22] and for TM steels 1100 MPa [23]. These mean that hatched areas in Figure 1 are nowadays available for users and development trends have shifted for higher strengths.

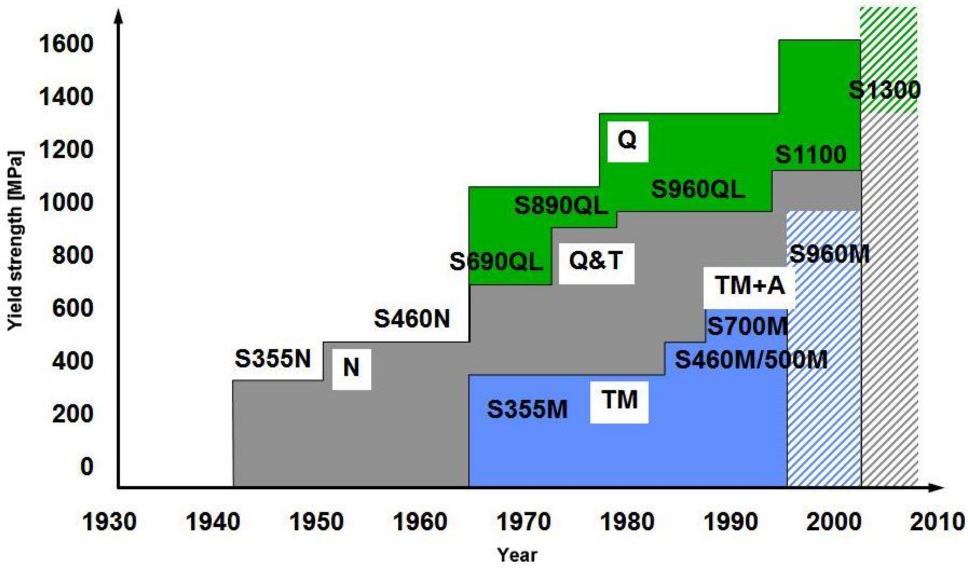

Figure 1. Chronology of structural steels developments [19][20].

During my first part I listed the production processes of toughened steels, where 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 [17]. The connection between yield strength and transition temperature ranges for different high strength steel types can be seen in Figure 2[15][16][18][30].

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 [16]. Table 1 summarizes the characteristic metallurgical periods and the belonging values of the impurities [16].

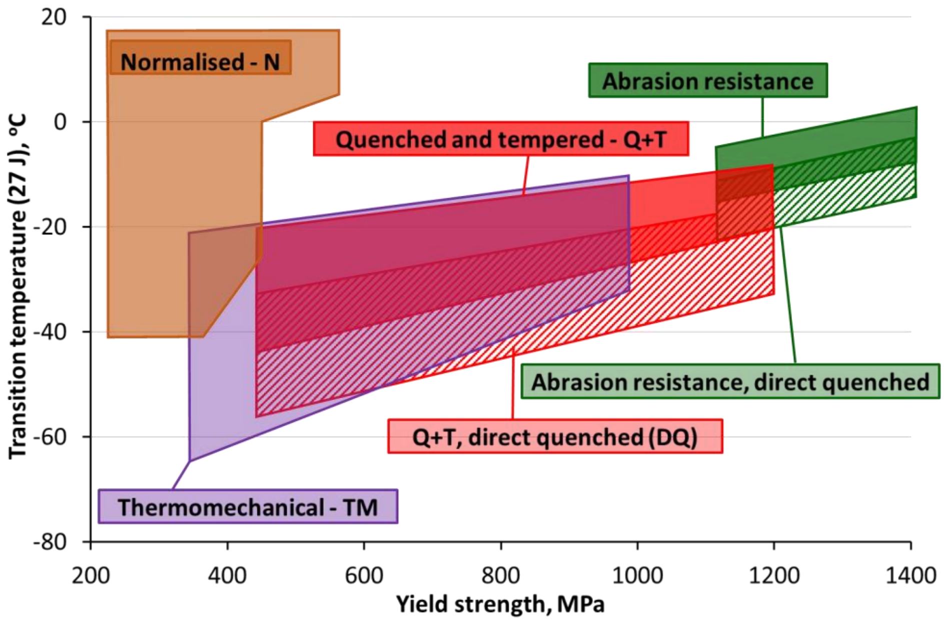

Figure 2. Combination of strength and toughness typical for commercial steels [15][16][18][30].

Table 1. Impact of development of metallurgical processes on the level of impurities in steel [16].

Element (ppm)	Metallurgical processes in the years		
	1950/1960	**1980/1990**	**1990/2010[2)]**
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 these 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 [16].

While the second part of my dissertation is related with the experimental work of the base materials specimens and their welded joints by two different experimental methods. The first method is the high cycle fatigue (HCF), where during this cycle we investigated the whole thickness (15 mm) of the butt welded joint (BWJ), as well as we interested from other flat and machining specimens with thickness of (5 mm) in both cases base materials (BM) and welded joints (WJ). During this task I investigated the weldability of both two types of high strength steels categories (690 MPa and 960 MPa) during different mismatching cases. The comparisons of the obtained results with previous experimented results collected by our colleagues have been performed [16].

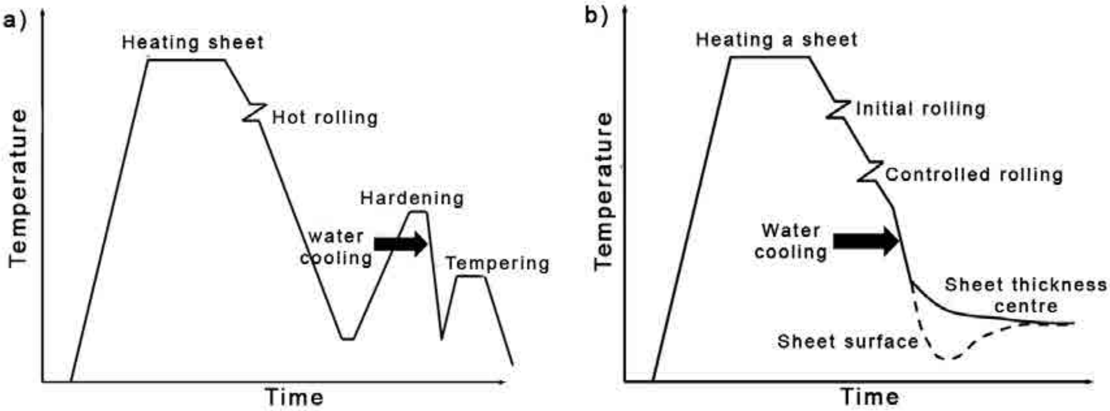

Figure 3. Diagrams of production processes of toughened steels a) hardening and tempering processes, b) direct hardening process [16].

To acquire the target of the research work we prepared a testing matrix to demonstrate the summary of the investigated groups and comparison possibilities (see Table 2.)

Table 2. The testing matrix: summary of the investigated groups and demonstration of the comparison possibilities.

Base material	**Matching condition and heat input**	**HCF tests**		**FCG tests**	
		Previous studies	**Own investigations**	**Previous studies**	**Own investigations**
Optim 700QL*	M – Medium	SP	–	SP	–
Weldox 700E	M – Medium	SP	BWJ	SP	–
	OM – Medium	SP	–	SP	–
	M / OM – Medium	–	BWJ	–	SP
Weldox 960E*	M – Medium	SP	–	–	–
	UM – Medium	SP	–	SP	–
Alform 960M	M – High	SP	BWJ	–	SP
	M – Medium	SP	BWJ	SP	–
	M – Low	SP	–	–	
	UM – High	–	–	–	SP
	UM – Medium	–	BWJ	SP	–

* Only for comparisons.

SP means that specimens were cat in full from the welded joint, all surfaces were cut (see Figure 4 and Figure 5), and will be designated as WJ.

BWJ means that only the side surfaces of the specimens were cut, the weld faces were not machined (see Figure 6).

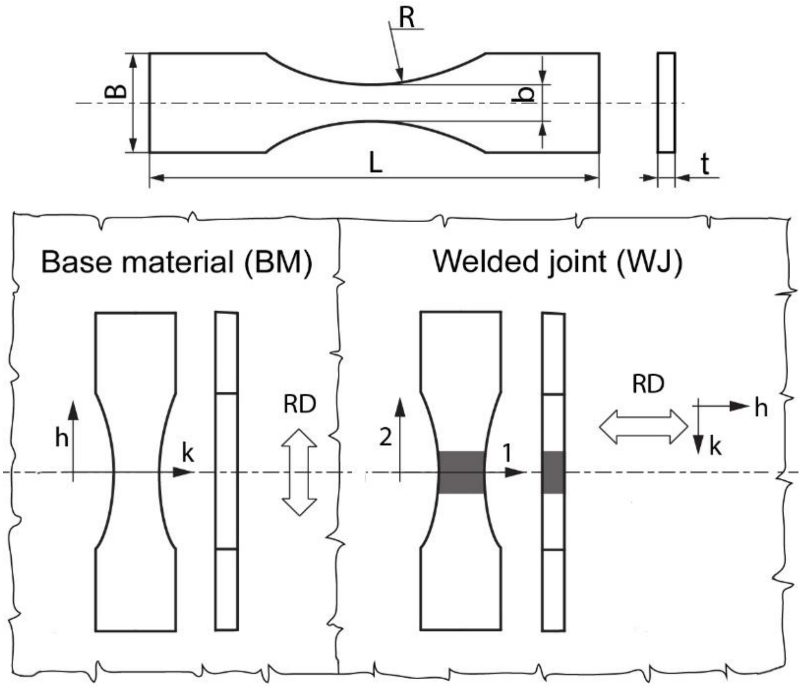

Figure. 4. The geometry, the location and the designation of the HCF test specimens for base materials (BM) and welded joints (WJ).

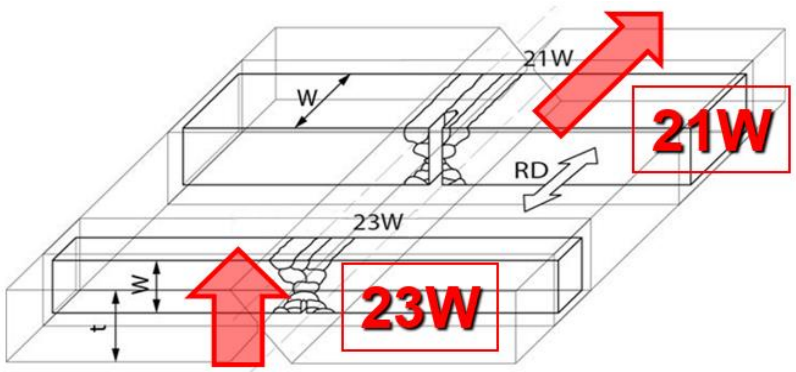

Figure 5. TPB specimen locations in welded joint with notch directions (RD = rolling direction).

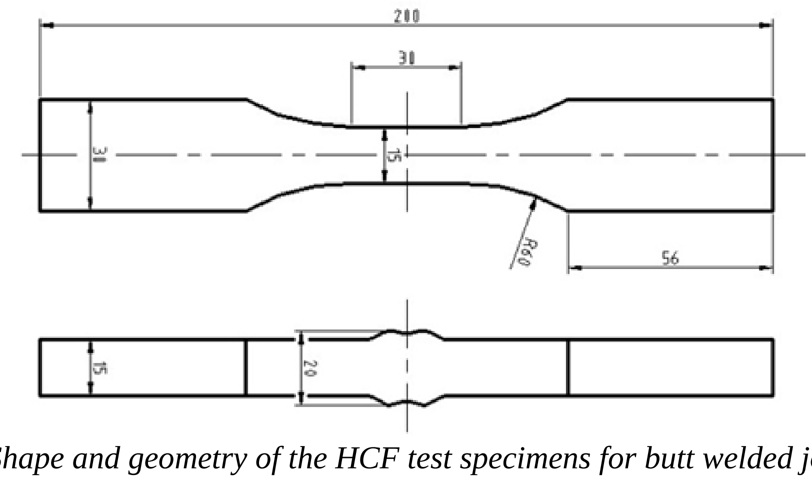

Figure 6. Shape and geometry of the HCF test specimens for butt welded joints (BWJ).

The "Mean" S-N curves determined based on JSME prescription [24] can be completed with standard deviation (*SD*) values and these curves ("Mean-2SD" S-N curves) can be used as high cycle fatigue strength curves, in other words high cycle fatigue design or limit curves (see Figure 7).

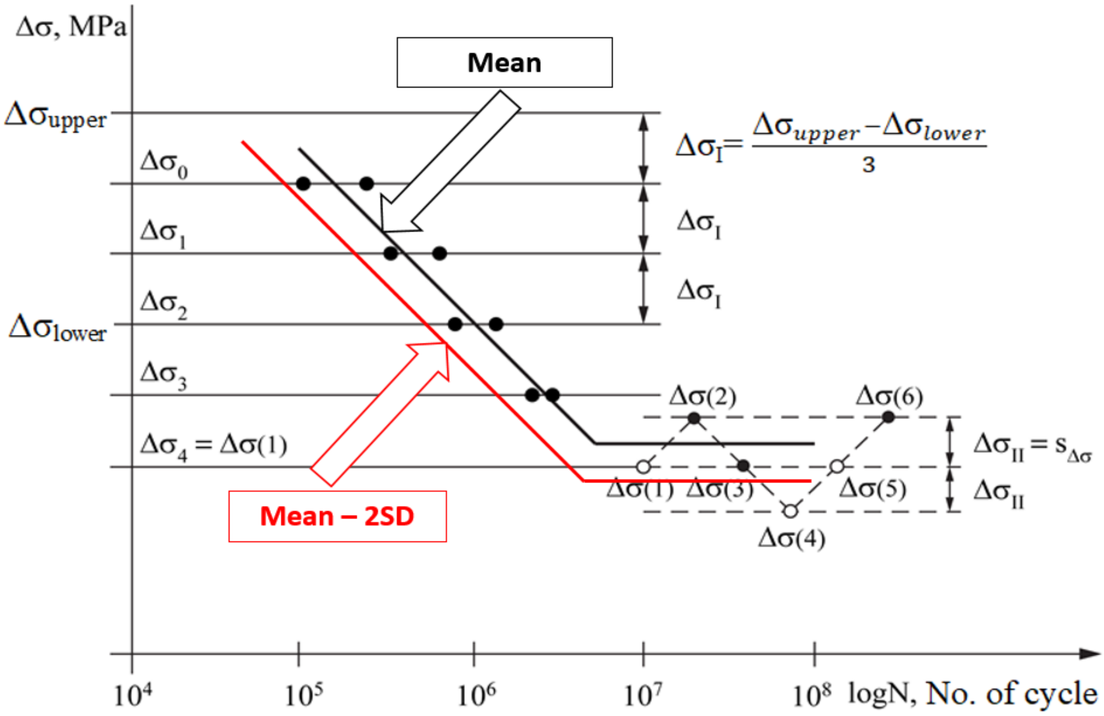

Figure 7. Determination of high cycle fatigue strength curves, „Mean-2SD" S-N curves.

On the one hand, it is known that HCF test results have greater uncertainty, standard deviation and lower reliability than static test results, therefore "Mean" values and "Mean" S-N curves reflect unacceptable risks. On the other hand, the application of 3SD value – based on the three-sigma (3σ) rule – is unjustified because the excessively low allowable strength values. It means that 2SD and "Mean-2SD" S-N curves result in a good compromise between the acceptable risk and the required reliability.

The calculated parameters of the "Mean-2SD" S-N curves for both steel categories (690 MPa and 960 MPa) and for all types (base material, welded joint, butt welded joint) investigated are presented in Table 3.

The m and lg(a) values are the parameters of the Basquin equation, the N_k value is the number of cycles for the knee 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.

Table 3. Parameters of high cycle fatigue (HCF) strength curves: "Mean-2SD" S-N curves.

Base material	**Manufacturing, orientation and heat input***	**m**	**log(a)**	**N_k**	**$\Delta\sigma_D$**	**$\Delta\sigma_{1E07}$**
		(–)	**(–)**	**(cycle)**	**(MPa)**	**(MPa)**
Optim 700QL	BM-h/v	51.282	150.186	–	–	620
	WJ/M-k/3W	4.826	16.762	9.893 E05	170	–
	WJ/M-k/1W	50.251	138.732	–	–	418
Weldox 700E	BM-h/k	12.453	38.557	1.677 E06	395	–
	WJ/M-k/1W	9.960	31.739	–	–	–
	WJ/OM-k/1W	31.250	88.311	–	–	400
	BWJ/M-k/1W	3.831	13.752	2.660 E06	82	–
	BWJ/M/OM-k/1W	4.207	15.822	–	–	126
Weldox 960E	BM-h/k	10.288	33.473	1.014 E06	467	–
	WJ/M-k/3W	16.722	49.063	8.535 E06	331	–
	WJ/UM-k/1W	12.594	39.173	4.944 E06	379	–
Alform 960M	BM-h/k	11.494	37.207	5.122 E06	450	–
	WJ/M-k/1W lhi	8.130	26.723	4.270 E06	296	–
	WJ/M-k/1W	16.129	48.012	2.681 E06	379	–
	WJ/M-k/1W hhi	15.385	47.226	9.693 E05	479	–
	WJ/UM-k/1W	41.667	116.389	–	–	422
	BWJ/M-k/1W	1.984	9.175	1.099 E06	38	–
	BWJ/M-k/1W	2.392	11.103	2.336 E06	95	–
	BWJ/M-k/1W hhi	2.123	9.107	9.307 E05	30	–
	BWJ/UM-k/1W	3.891	13.957	8.701 E05	115	–

* Only low and high heat inputs (collective of linear energy and interpass temperature) were designated, lhi and hhi, respectively.

The FCG tests were executed on three-point bending (TPB) specimens, nominal W values were 26 mm (t = 15 mm), and 28 mm (t = 30 mm) and 13 mm (t = 15 mm) for the base materials and the welded joints, in the 21 and 23 directions, respectively. The position of the notches correlated with the rolling direction (T-L, L-T and T-S). The positions of the cut specimens from the welded joints are shown in Figure 5, where 21 and 23 directions (21W and 23W) were used.

Kinetic diagrams of fatigue crack growth can be simplified and described using both simple and two-stage crack growth relationships, as it can be seen in Figure 8, based on BS 7910 [3]. According to the main aim of the research work, the simple crack growth relationship was selected and used.

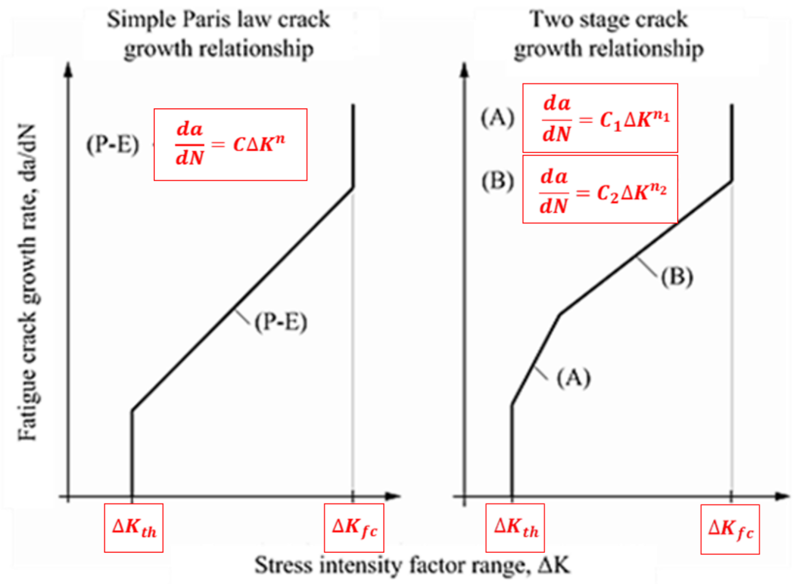

Figure 8. Simple and two-stage fatigue crack growth relationships, based on [3].

Based on the experimental data and results, fatigue crack propagation limit curves can be determined, which consists of six steps [25]. First step: determination of measuring values; second step: classification of measured values into statistical samples; third step: selection of the distribution function type; fourth step: calculation of the parameters of the three parameter Weibull-distribution functions; fifth step: selection of the characteristic values of the distribution function; sixth step: calculation of the parameters of the fatigue crack propagation design or limit curves. The fifth step can be seen in Figure 9, schematically.

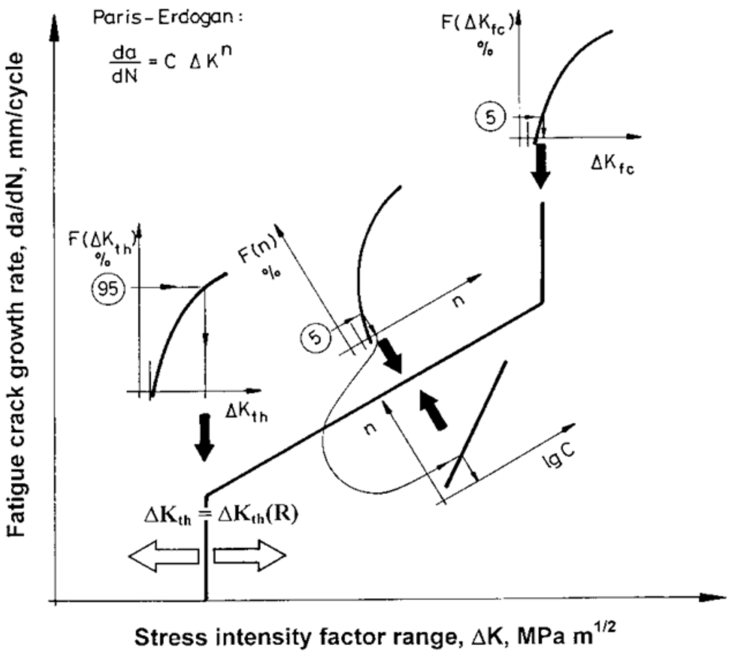

Figure 9. The previously proposed method for determination of fatigue crack propagation limit curves [25].

The main characteristics of the determined fatigue crack propagation design or limit curves can be found in Table 4. In those cases, when the orientation and/or the path of the propagating crack is known, the values in Table 4 can be directly used. In those cases, when n and ΔK_{fc} values calculated in different directions (T-L and L-T vs. T-S, or 21W vs. 23W) are significantly different, and the orientation and/or the growing crack path is not known, the lowest value should be considered from the related ones.

Table 4. Characteristics of the determined fatigue crack propagation design or limit curves.

Base material	**Mismatch type and heat input***	**Orientation**	**n**	**C**	**ΔK$_{fc}$**	**Source**
			(MPam$^{1/2}$, mm/cycle)		**(MPam$^{1/2}$)**	
Optim 700QL	M	T-S	1.20	6.52E-06	93	[20]
Weldox 700E	BM	T-L and L-T	1.70	8.09E-07	101	[13]
		T-S	1.50	2.06E-06	75	
	M	T-L/21W	4.10	1.12E-11	105	[13]
		T-S/23W	2.30	4.93E-08	80	
	OM	T-L/21W	1.85	4.02E-07	96	[13]
		T-S/23W	1.90	3.19E-07	61	
	M/OM	T-L/21W	2.67	8.88E-09	90	OWN
		T-S/23W	2.85	3.87E-09	67	
Weldox 960E	BM	T-S, L-S and T-L	1.80	3.50E-07	94	[26]
	M	T-L/21W and T-S/23W	2.75	1.03E-08	93	[27]
Alform 960M	BM	T-L and L-T	1.82	4.63E-07	116	[13]
		T-S	1.75	6.41E-07	87	
	UM	T-L/21W	2.40	3.10E-08	115	[28]
		T-S/23W	2.15	9.93E-08	67	
	UM – hhi	T-L/21W and T-S/23W	2.65	1.65E-08	81	OWN
	M	T-L/21W	1.90	3.19E-07	114	[13]
		T-S/23W	2.75	6.06E-09	82	
	M – hhi	T-L/21W and T-S/23W	2.25	9.45E-08	65	OWN

* Only high heat input (collective of linear energy and interpass temperature) was designated, hhi.

3. NEW SCIENTIFIC RESULTS – THESES

T1. For reliable assessment of high cycle fatigue and fatigue crack growth resistance of high strength steels and their welded joints statistical approaches must be used. On the one hand, different crack paths and notch locations must be applied; on the other hand, sufficient number of specimens must be tested in order the correct applications of evaluation methods. I have proved this statement with executed and/or analysed high cycle fatigue and fatigue crack growth tests. (2) (3) (7) (10) (11) and (9)

T2. Both the high cycle fatigue and the fatigue crack growth resistance of the investigated high strength steels and their welded joints characteristically depend on the crack growth directions; the thickness direction is more unfavourable than the other directions. I have proved this statement with executed and/or analysed high cycle fatigue and fatigue crack growth tests. (4) (6) (10) (12) and (9)

T3. The linear energy and the interpass temperature during the welding of the thermomechanically rolled Alform 960M steel have collectively characteristic influence on the high cycle fatigue resistance of butt welded joints and the fatigue crack growth resistance of welded joints, which have to take into consideration during the specification of welding technology. I have proved this statement with executed and/or analysed high cycle fatigue and fatigue crack growth tests. (8) (10)

T4. With common application of the JSME investigation method resulting “Mean” S-N curves and “-2SD” philosophy, “Mean-2SD” S-N curves can be calculated, which can be used as high cycle fatigue strength curves. I have proved this statement with executed and/or analysed high cycle fatigue tests and with calculated “Mean” and “Mean-2SD” S-N curves. (7)

T5. The matching phenomenon has characteristic influence on the high cycle fatigue resistance of both Weldox 700E and Alform 960M high strength steel butt welded joints, depending on the strength category. In case of Weldox 700E the matching/overmatching (M/OM) condition is better than matching (M), while in the case of the Alform 960M the undermatching (UM) is better than matching (M). The statement justifies the specific role of the 690 MPa strength category in the mismatch phenomenon. I have proved this statement with executed and analysed high cycle fatigue tests. (2) (3) (4) (11)

T6. The mismatch phenomenon (matching (M), undermatching (UM), matching/overmatching (M/OM) and overmatching (OM)) has characteristic influence on the fatigue crack growth resistance of investigated high strength steel welded joints. The average values of Paris-Erdogan exponents (n) of mismatch conditions of the investigated welded joints were statistically higher (Weldox 700E, Alform 960M thickness direction) or lower (Alform 960M longitudinal and transversal direction) than the exponents of the concerning base materials. I have proved this statement with executed and analysed fatigue crack growth tests. (6) (7) (8) (10) (12) and (9)

T7. The average value of the Paris-Erdogan exponent (n) of the matching/overmatching (M/OM) welded joint of Weldox 700E is lower than the exponent of both the overmatching (OM) and the matching (M) conditions; the matching (M) mismatch type is more efficient than both the overmatching (OM) and the matching/overmatching (M/OM) types. The average value of Paris-Erdogan exponent (n) of the matching (M) welded joint of Alform 960M is lower than the exponent of the undermatching (UM) condition and independent of the collective of linear energy and interpass temperature; the undermatching (UM) mismatch type is more efficient than the matching (M) type, independently of the collective of linear energy and interpass temperature. The statement justifies the specific role of the 690 MPa strength category in the mismatch phenomenon, too. I have proved this statement with executed and/or analysed fatigue crack growth tests. (5) (6) (10)

4. INDUSTRIAL UTILIZATION AND FURTHER DEVELOPMENT

Nowadays, the reliability of a structural element or a structure is one of the most important, if not the most important feature of the structural element or the structure itself. This is a requirement on the one hand; on the other hand, this is a task for the structural and technological designers, manufacturers, operators and maintainers of the structure. The regrettable accidents always draw attention to this fact, and summary studies about these form global messages from which all stakeholders can learn.

At the same time, the behaviour of HSSS differs fundamentally from that of conventional steels, both as a result of manufacturing technologies and in static and dynamic stresses. As a result, it is not possible to make general recommendations for all high strength steels. Therefore, one of the basic aims of this dissertation is to summarize knowledge that provides useful information to industry professionals by experimenting multi (mismatching and heat input) with different characteristics of BM and FM. The data and case studies presented in the sections on the determination of welding working ranges can provide useful insights for engineers manufacturing welded structures.

There are different characteristics of HSSS friend of the environment and then achieve sustainable development, as follows. Economy: by increasing the strength of steel, then the structural section can be reduced by 20 to 30%. Architecture: by reducing the size of structural elements with higher-performing steel products, strong, thin and lightweight. Environment (resources): by construction with less steel, reduced consumption of our world’s scarce resources. Safety: by ensured high safety of the structures both in the fabrication and application.

Significant reduction of the structure’s dead weight, material and labour consumption are the main advantages of using these steels. They influence economic and operational efficiency by reducing the costs of production, operating and maintenance. Further development of the innovative HSSS, determination of their performance and improvement joining technology are associated with the necessity to perform further studies.

Survive of structures against different hard weather conditions without or less repairing process it's also achieved by obtained results which will also help for conservative raw materials in nature and decrease production cost.

High performance is obtained of these new generations of high strength steel categories of welded joints in many application fields than these previous applications of lower steel categories. Also continuous and survival HSSS applications for the long term than the previous other applications. Thus the results increased performance of applications i.e. ships, offshore, heavy vehicle equipment and machinery now are better than old applications.

In predominantly cases, service loads have variable characteristics. For this reason, it is necessary to perform numerous investigations of the HSSS welded joints determining their mechanical properties, especially fatigue characteristics and behaviour. During the research, despite a large number of experiments and specimens, it was not possible to fully investigate the steels. Fatigue strength and limit curves were determined for the conditions of HCF and FCG, for both investigated base materials and welded joints, and for each mismatch. Fatigue strength curves were calculated for comparative materials, too. These boundary curves, in their specific or generic form, can be used to evaluate the integrity of welded structures, estimate lifetime and/or residual lifetime, and perform comparative calculations. These curves carry important data and information for the interested researchers, manufacturing companies and so on.

The materials from the grade of HSSS are increasingly used in welded structures e.g. telescopic jibs and chassis of mobile cranes, gantries frames, pressure vessels, offshore platforms or bridge structures including the military mobile bridges. For example, in the vehicle industry, one of the fundamental trends in the environmental load reduction through weight reduction, this can be achieved by the application of high strength materials.

The publishing results via articles of researchers, dissertations of both masters and PhD students as well as different of other studies have a contributing role to start a new generation of manufacturing with new joining welding technology applied on higher steel categories these make our life more pleasant and easier.

The importance of investigation and then the results obtaining for welded joints specimens what was studied in two different categories and comparison with previous investigated work is necessary during mismatch phenomenon of welded joints which characteristic influence both on the HCF and on the FCG resistance. Thus in case of different matching conditions, the reliability of the test results will be different, and this justifies the necessity of applying many experimental investigation works to collect more reliable results which will serve the people who are interested with this science area, and finally developing of application field and enhance the products.

Welding technology is improved by supporting these results which applied for joining HSSs in different types of applications and by developing the characteristics of welding aspect and testing methodology so the results of researchers or manufacturing products will be in higher level in the near future. Applying the developed welding technologies adequate with HSSS base materials produced, appropriate quality contains the eligible resistance to HCF and FCG.

The results of researcher help reduce the number of pieces of equipment working in the projects like the increase in the capacity of the loader, shovel and cranes using higher steel categories with developed welding process help decreasing the number of them in the working land.

Increasing productivity of buildings and towers by the increasing number of floors and length of towers using the new results of welded of high strength steel categories in construction of these buildings and towers and then increases green land and supporting sustainable development issue.

5. LIST OF PUPLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

IN ENGLISH

(1) H. F. H. Mobark, Á. Dobosy, J. Lukács: *Mismatch effect influence on the HCF resistance of high strength steels and their GMA welded joints*, Vehicle and Automotive Engineering 2 (VAE 2), pp. 755-767, 2018.

(2) H. F. H. Mobark, J. Lukács: *Mismatch effect influence on the high cycle fatigue resistance of S690QL type high strength steels*, 2nd International Conference on Structural Integrity and Durability, Dubrovnik, Croatia, October 2-5, pp. 1-4, 2018.

(3) H. F. H. Mobark, J. Lukács: *HCF design curves for high strength steel welded joints,* Design of Machines and Structures, Vol. 8, No. 2, pp. 39-51, 2018.

(4) H. F. H Mobark, J. Lukács: *HCF resistance characteristics of S690QL type high strength steels and their welded joints*, PhD Doctoral Forum, Faculty of Mechanical Engineering and Informatics, István Sályi Doctoral School, University of Miskolc, November 2018.

(5) H. F. H. Mobark, J. Lukács: *Connection among the parameters of the Manson-Coffin, the Basquin and the Paris-Erdogan equations*, MultiScience - XXXIII. microCAD International Multidisciplinary Scientific Conference, University of Miskolc, 23-24 May 2019, ISBN 978-963-358-177-3.

(6) J. Lukács, H. F. H. Mobark: *Mismatch effect on fatigue crack propagation limit curves of S690QL, S960QL and S960TM type base materials and their gas metal arc welded joints*, 72nd IIW Annual Assembly and International Conference 7-12 July 2019 Conference Proceedings, Bratislava Slovakia 2019.

(7) H. F. H. Mobark, J. Lukács: *Efficient application of S690QL type high strength steel for cyclic loaded welded structures,* Solutions for Sustainable Development, Proceedings of the 1st International Conference on Engineering Solutions for Sustainable Development (ICESSD 2019), October 3-4, 2019, Klára Szita Tóthné, Károly Jármay, Katalin Voith, Miskolc, Hungary.

(8) H. F. H. Mobark, J. Lukács: *Heat input influence on fatigue crack growth characteristics of high strength steel GMAW joints*, PhD Doctoral Forum, Faculty of Mechanical Engineering and Informatics, István Sályi Doctoral School, University of Miskolc, November 2019.

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(10) H. F. H. Mobark, J. Lukács: *Mismatch effect on fatigue crack propagation limit curves of GMAW joints made of S960QL and S960TM type base materials*, Design of Machines and Structures, Vol. 10, No. 1, pp. 28-38, 2020.

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(11) H. F. H. Mobark, J. Lukács: *High cycle fatigue resistance characteristics of S690QL type high strength steels and their welded joints*, GépGyártás, Vol. LVIII, No. 1-2, pp. 71-75, 2019.

(12) H. F. H. Mobark, J. Lukács: *Base material - filler metal pairing influence on fatigue crack propagation resistance of high strength steels and their welded*, GépGyártás, Vol. LVIII, No. 1-2, pp. 76-80, 2019.

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