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Research on the impact of the heat input of GMAW processes on ultrahigh strength steels properties

Booklet of PhD Theses

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Miskolc
2024

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1. INTRODUCTION, THE AIM OF THE RESEARCH WORK

1.1 INTRODUCTION

High strength steels are playing an increasingly important role in various engineering applications, especially in the automotive and transportation industries. In the last decades, in addition to the conscious design of alloying and micro-alloying combined with rolling and heat treatment processes, various high strength steels have been developed, resulting in the availability of thick plates with yield strengths above 1300 MPa [1-7]. The use of high strength steels has several advantages. These steels can be used to build thinner, lighter but stronger components, which is beneficial in moving structures. Smaller cross-sections result lower material requirements in terms of both base materials and filler materials, thus reducing production time and costs. Finally, the operation of a structure with a smaller weight leads to energy savings [8-12]. However, achieving a balance between the increased strength and the toughness required by the operation of the structure, and ensuring resistance to fatigue loads [13], requires a complex approach in order to provide structural integrity [14-15].

Despite the good mechanical properties and potential benefits, welding of high strength steels still has challenges, mainly in the selection of the right welding technology and process parameters. Heat input and cooling time are two of the most important parameters that influence the load capacity, ductility, and toughness of the joint. As different parts of the welded joint are exposed to different thermal effects, the different parts of the heat affected zone have different properties. In the case of high strength steels, the softening and toughness reduction in the heat affected zone is the most significant. Cold cracking (susceptibility) can also be a problem during welding of these steels. In addition, the high yield strength creates the problem of filler material selection, as matching filler materials are only available for materials with yield strengths up to 1100 MPa [1, 8, 9, 16-20].

The weakest part of welded joints is usually the heat affected zone; therefore, it is also very important to investigate it. In the case of real welded joints, the different parts of the heat affected zone have small extent thus their investigation is limited. Physical simulation provides a solution to test specimens made of a given base material, to produce defined heat affected zones in an adequate size range for further investigations. With the Gleeble physical simulator, various simulations can be performed using thermocouple measurements or mathematical models with defined thermal cycles. The processes are carried out under conditions and with parameters as realistic as possible, in real time, and therefore provide reliable results. In addition, a wide range of programmable heat cycle models can be used to accurately analyse the properties of the microstructure under different welding parameters [21-28].

During operation, many components or structural elements are subjected to cyclic loading and therefore fatigue failure is often observed [29, 30], which can occur in the ultra-high cycle fatigue range even below the conventional fatigue limit at relatively low stress [31]. Therefore, for safe operation, one of the main design considerations for steel structures subjected to cyclic loading should be the provision of adequate fatigue strength [30]. It is well known that the fatigue strength of welded joints is lower than that of the base material, and therefore their lifetime during service is even more limited. The main reasons are changes in the microstructure due to welding, the residual stresses formed, and the stress accumulation sites caused by the joint [32]. Fatigue strength is one of the most important mechanical parameters in the engineering application of steels. For low(er) strength steel grades, the fatigue strength can be determined by the fatigue limit, which can be clearly identified from the knee point of the S-N curve. However, for higher strength steel grades, there is not always a corresponding knee point. In such cases, the fatigue strength is defined as, for example, the maximum stress amplitude at which the specimens will not fail for a prescribed number of cycles, which is often 10^7 cycles [33]. During the high cycle fatigue, the specimens undergo macroscopic elastic deformation only, their cross-section is considered constant, and the calculated stress is in fact a real stress. However, the crack initiation and crack propagation, and hence the resulting measurements, are influenced by several factors, both internal and external. Therefore, due to the expected standard deviation of the results, a larger number of specimens must be tested under the same conditions and the measured data must be evaluated by mathematical-statistical methods [34].

For structures (mainly welded structures) subjected to cyclic loading, it is also important to investigate the fatigue crack propagation rate. Crack growth can be divided into three phases: slow growth, stable growth, and unstable crack propagation. Once the crack enters the unstable range, the damage is irreversible. Fatigue crack propagation is highly dependent on the structural properties of the material and the test conditions. Microstructural characteristics influence the crack propagation path and velocity, and hence the fracture morphology. Since different materials have different microstructure and mechanical properties, and therefore different crack propagation behaviour, before application this should also be investigated [35-37].

1.2 THE AIM OF THE RESEARCH WORK

As can be seen in the introduction, there are still a number of challenges and unknown factors in the field of high strength steels, all of which require extensive research. In the field of structural steels, thick plates with yield strengths of up to 1100 MPa or 1300 MPa are available, depending on the production method, but their application is still very limited at present, and my research is therefore focused on these steel types.

I focus my research on two main research fields. Since welding is very common in the application and there are many difficulties in welding of high strength steels, the first field is related to the development of welding technology for the chosen materials. The second field is the investigation of the resistance of the chosen materials and their welded joints to cyclic loading.

In case of fusion welding of high strength steels, one of the most important aspects of the design is the determination of the appropriate welding (parameter) range. This is supported by the determination of the optimal $t_{8/5}$ cooling time, which can be used to define the different welding parameters. One of the best devices for testing the $t_{8/5}$ cooling time is the physical simulator, which can be used to generate the critical parts of the heat affected zone at a suitable size for further material testing. A useful additional advantage of physical simulation is that a wide range of process variants can be investigated in a relatively fast and easily reproducible way. Based on the results of the material tests, welding parameters can be determined in an optimised way. As a first step, physical simulations are carried out in the critical parts of the heat affected zone in terms of toughness reduction, using different $t_{8/5}$ cooling times. For welding high strength steels, the selection of filler material is also a problem, as matching filler materials are only available for materials with yield strengths up to 1100 MPa and these filler materials are also considered as new, therefore welded joints are prepared with this filler material and a widely used undermatching filler material during welding experiments. Thus, by further material testing, the mechanical properties of the different joints can be investigated.

In the case of resistance to cyclic loading, I examine the resistance to high cycle fatigue loading and fatigue crack propagation for both selected materials and their welded joints. As the filler material also influences the different fatigue behaviour, I will also analyse the effect of the chosen filler materials on the fatigue properties. Finally, based on the results of the experiments, I determine the design limit curves for the tested base materials and for the welded joints prepared with different filler materials.

2. METHODOLOGY

My PhD thesis is focused on the welding and weldability of thermomechanically (TM) rolled and quenched and tempered (QT) high strength structural steels (S1100M and S1300Q, respectively) and their behaviour under cyclic loading conditions.

The first part of my thesis is provided a comprehensive literature overview on the characteristics, manufacturing technology and welding of high strength steels, the theoretical background of physical simulation studies, including the used Rykalin 3D model, and the high cycle fatigue and fatigue crack propagation tests in case of cyclic loading. Based on the literature overview, it can be stated that both TM rolled, and QT steels require complex manufacturing technology. TM rolled steels have advantageous mechanical and toughness properties due to their lower alloying content and finer grain structure, but the manufacturing technology results in a lower producible plate thickness and strength than that of QT steels. In the field of welding, the main problems identified in the relevant literature for high strength steels are cold cracking, softening of the heat affected zone (HAZ) and the selection of the filler material. Therefore, during welding, special attention must be paid to the regulation of the heat input and the $t_{8/5}$ cooling time, as the risk of cold cracking increases if the heat input is too low and the risk of softening of the HAZ increases with a too high value of the heat input and increased cooling time. This suggests that, to ensure the good mechanical properties of high strength steels after welding, the heat input should be reduced to the lowest possible value, while avoiding cold cracking. In the case of cyclic loading, since high strength steels are often used in welded structures, the disadvantageous effects of welding may not lead to favourable fatigue properties. Furthermore, most of the standards and specifications do not include these materials yet, therefore more testing and background information are required before their application.

In the second part of my thesis two structural steels of different strength categories, produced by different manufacturing methods were examined, which currently have the highest strength of all available structural steels in the case of thick plates. One of the steels investigated is TM rolled with 1100 MPa yield strength (Alform 1100M x-treme), and the other is QT with 1300 MPa yield strength. Before preparing the welded joints, the first step was to determine the appropriate welding parameters based on the optimal $t_{8/5}$ cooling time for the chosen gas metal arc welding process. For this purpose, HAZ simulations were carried out in zones considered to be the most critical in terms of toughness reduction, namely the coarse-grain, intercritical and intercritically reheated coarse-grain zones. During the simulations, in order to simulate a low, a medium and a high heat input gas metal arc welding process, three different cooling times were set, which were 5 s, 15 s and 30 s. The parameters of the HAZ simulations carried out are shown in **Table 1**.

Table 1. Parameters for the HAZ simulations

HAZ area	Peak temperature, [°C]		$t_{8/5}$ cooling time, [s]
	T_{max1}	T_{max2}	
Coarse-grain	1350	-	5, 15, 30
Intercritical	775	-	5, 15, 30
Intercritically reheated coarse-grain	1350	775	5, 15, 30

The simulation programs for the performed heat affected zone investigations were generated by manual programming of the physical simulator, using time-temperature data calculated by taking into account the temperature-dependent physical properties. An example of the programmed thermal cycles is shown in **Figure 1.**

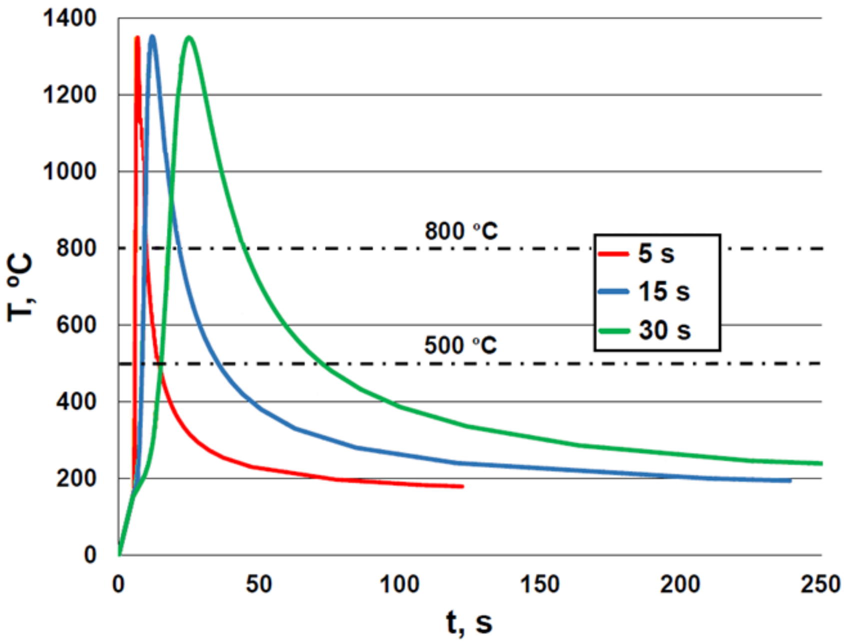

Figure 1. Coarse-grained heat affected zone thermal cycles

After the simulations, optical microscopy, hardness, and instrumented impact tests were performed. The obtained results suggest that, taking into account the strength and toughness properties of the investigated high strength steels, using a shorter cooling time close to 5 s is recommended.

After the physical simulation experiments, welded joints were prepared on the investigated high strength steels with two different strength grades of filler materials, Böhler Union X96 (Ø 1,2 mm) and Böhler alform 1100 L-MC (Ø 1,2 mm). The parameters for welding were determined according to the chosen $t_{8/5}$ cooling time. The welding parameters determined are given in **Table 2** and **Table 3**.

Table 2. Welding parameters in case of S1100M

Welding pass number	Welding current [A]	Welding voltage [V]	Welding speed [cm/min]	$t_{8/5}$ cooling time [s]	Heat input [J/mm]
1	180	19,1	24	5	688
2	190	19,7	27		666
3-4	260	25,1	50		624
5-8	280	28,7	61		632

Table 3. Welding parameters in case of S1300Q

Welding pass number	Welding current [A]	Welding voltage [V]	Welding speed [cm/min]	$t_{8/5}$ cooling time [s]	Heat input [J/mm]
1-2	180	19,1	31	5	562
3-4	240	22,7	53		493

The process chosen to produce the joints was gas metal arc welding, using a Daihen WB-P500L power source. The 350 mm · 150 mm · 10/15 mm plates with X-groove were welded in PA position. To ensure a uniform welding speed and weld seam (except for the first pass), the torch was moved by an ESAB B5001 welding tractor. The applied preheating temperature was 100 °C, taking into account previous own experiments and literature recommendations, and the interpass temperature was approximately 130 °C. Shielding gas mixture of 80% Ar + 20% CO_2 (M21) with a flow rate of 18 l/min was used.

Optical microscopy, hardness, instrumented impact, high cycle fatigue (HCF) and fatigue crack propagation (FCP) tests were performed on the prepared welded joints.

Cyclic loading tests were carried out on the base materials and welded joints with the two different filler materials.

High cycle fatigue tests are carried out on MTS universal electro-hydraulic material testing systems (MTS 312 and MTS 810) in accordance with the requirements of JSME S 002 [38, 39]. A constant load amplitude control mode and a constant stress ratio of R = 0.1 were applied throughout the test series. The tests were performed at room temperature with the use of a sinuous load curve. The load frequency was in the range of 15-25 Hz, with a typical value of f = 25 Hz, from which it was only changed to lower values when the stability of the test required it. Varying the load frequency in this range had no significant effect on the test results [34]. During the evaluation of the results, the equation for the lifetime section of the limit curves was determined by using the Basquin relation. After logarithmizing and rearranging the equation, we receive the following (1):

$$\log(\Delta\sigma) = \frac{\log(a)}{m} - \frac{1}{m}\log(N). \tag{1}$$

which in a double logarithmic system is the equation of a line, in our case the endurance limit section of the limit curve.

The equation of the fatigue limit section of the limit curve, i.e., the value of the fatigue limit, was calculated using the average values of the surviving specimens in cases where there were surviving specimens. These limit curves are the curves for the 50% probability, called "Mean" curves in some specifications. From the limit curves, a fatigue strength curve is obtained by shifting the limit curve downwards by two standard deviations ("2SD") ("Mean - 2SD"), taking into account the technically required safety. This methodology is illustrated in **Figure 2**, which also shows the logic for performing the fatigue tests. The stress levels of the fatigue life and fatigue limit sections should be determined in connection with each other, but with a different philosophy.

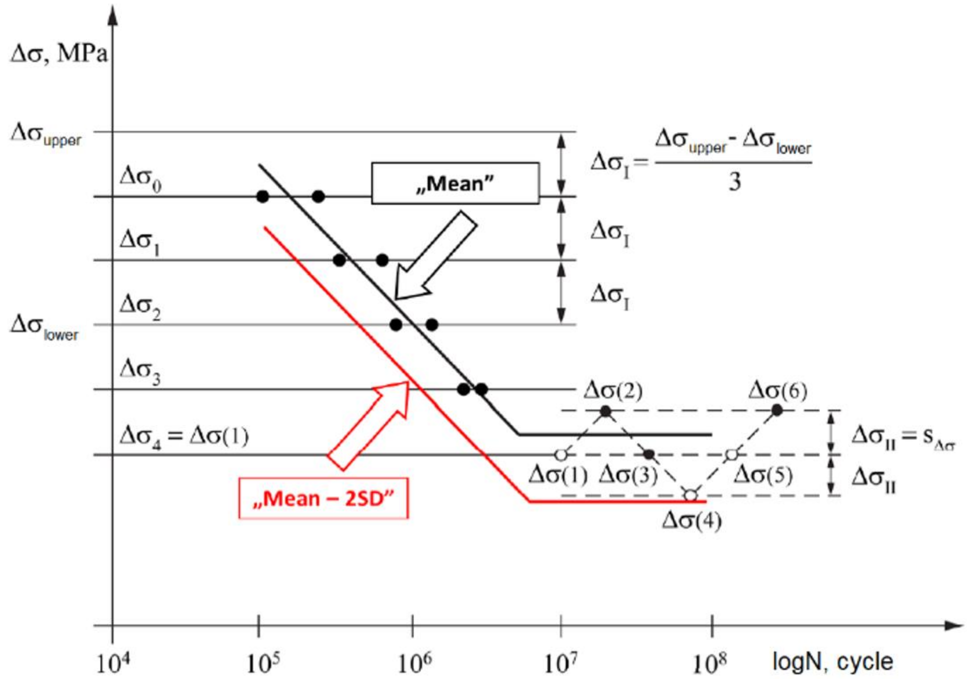

Figure 2. The logic for performing fatigue tests, the limit curves ("Mean") and the fatigue strength curves obtained from the limit curves ("Mean - 2SD") [34]

The fatigue crack propagation tests were performed using the MTS universal electro-hydraulic material testing system (MTS 312), which was also used for the high cycle fatigue tests. In order to evaluate the resistance to crack propagation, three-point bending specimens (TPB) were prepared from the tested materials and their welded joints with different filler materials. From the welded joints, the specimens were prepared as shown in **Figure 3.**

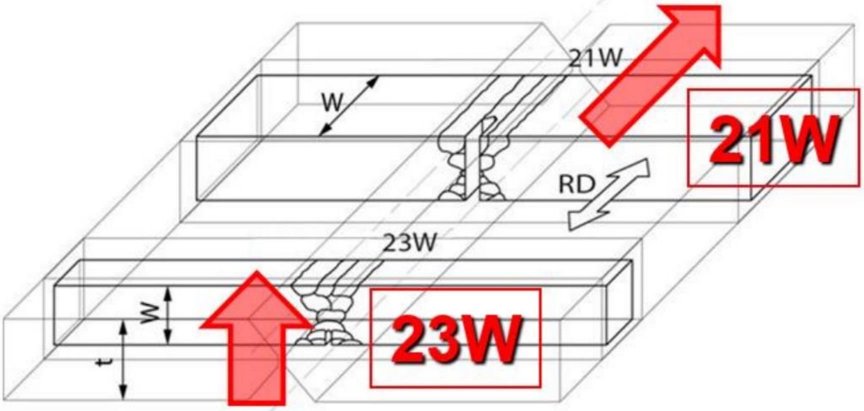

Figure 3. Design of three-point bending specimens from welded joints, with marked notch directions [40]

Specimens with T-L and T-S orientations were prepared from the two base materials, while specimens with 21 and 23 orientations [41] were prepared from the welded joints. An example of the location of the notches for welded joints is illustrated in **Figure 4.**

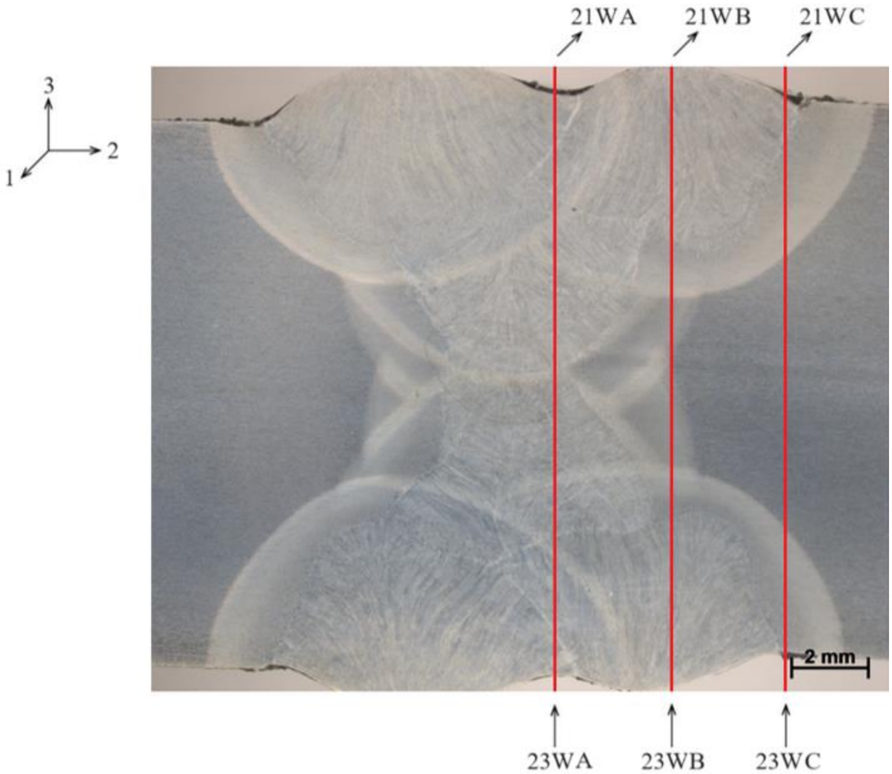

Figure 4. Notch orientation of TPB specimens used for fatigue crack propagation tests for welded joints of S1100M

The locations of the notches varied throughout the tests; thus, the crack propagation provided a comprehensive understanding of the behaviour of the welded joints. The control mode used during the tests was load reduction (preload) or constant load amplitude (crack propagation) with a load asymmetry factor of R = 0.1 and a sinuous load curve. All tests were performed in a laboratory environment at room temperature. At the beginning of the tests, the load frequency was f = 20 Hz, which was reduced to f = 5 Hz in the final phase. To ensure proper comparability of the results, the specimen preparation was uniform in all cases and the nominal value of the characteristic specimen size (W), which is relevant for the tests, was the same for each orientation.

After the tests, the crack size - number of cycle (a-N) curves were drawn from the recorded data, and the fatigue kinetic diagrams were determined using the a-N curves. Afterwards, the values of the Paris-Erdogan constant (C) and the exponent (n) of the Paris-Erdogan relation [42] were determined - from the kinetic diagrams using the method of least squares- with the correlation indexes and with the values of the fatigue fracture toughness (ΔK_{fc}). To evaluate the results, the data obtained in each test group (n and ΔK_{fc}) were considered as statistical samples and - where it was possible due to the number of samples - the similarity and dissimilarity of each sample was examined. For this purpose, a Wilcoxon test was used [43, 44] with a two-sided significance level of $\varepsilon = 0.1$.

First, the different material orientations (T-L and T-S) were examined, and it was found that the difference was significant, and the samples should be treated separately. Secondly, for the welded joints of S1100M, the undermatching and matching combinations by orientation (21W and 23W) were analysed and it was found that the differences are not significant - except for the ΔK_{fc} samples of the 23W orientation - and the samples can be grouped into a single sample - except for the ΔK_{fc} samples of the 23W orientation. With this knowledge, it was also examined whether the samples grouped by welded joint orientation (21W and 23W) could be considered similar or not. The result obtained is that these samples are significantly different in all cases. In the case of S1300Q, the different base material orientations (T-L and T-S) were firstly examined, and it was found that the difference was significant, and the samples should be treated separately. Subsequently, for the 21W welded joint orientation, the two undermatching combinations were analysed and it was found that the differences are not significant - for either the n or ΔK_{fc} samples - and the samples can be grouped into a single sample. The same analysis could not be performed for the 23W welded joint orientation due to limited numbers of samples. In a third step, assuming that the 23W orientation would lead to the same result as the 21W orientation, it was also examined whether or not the samples grouped by weld orientation (21W and 23W) could be considered as similar. The result was that these samples would be significantly different in all cases.

3. NEW SCIENTIFIC RESULTS – THESES

T1. The different parts of the heat affected zones of the tested 1100 MPa and 1300 MPa steel grades (thermomechanical and quenched and tempered), which are critical in terms of toughness reduction, show different tendencies of strength and toughness changes as a function of the typical cooling time ($t_{8/5}$). These conclusions were proved by the results of hardness measurements and instrumented impact tests on the different parts of the heat affected zone produced by physical simulation. (1)(4)(5)(7)(9)(10)(11)(19)(21)

T2. The strength and toughness properties of the welded joints produced by gas metal arc welding are better with the use of the undermatching filler material for the tested 1100 MPa strength grade steel, and with the use of the undermatching filler material with a higher strength difference for the tested 1300 MPa strength grade steel. These conclusions have been confirmed by the results of hardness measurements and instrumented impact tests on welded joints under industrial circumstances. (2)(6)(15)(18)(20)

T3. The fatigue limit/tensile strength ratio of the tested thermomechanically rolled steel is higher than that of the tested quenched and tempered steel; furthermore, this higher ratio is suitable for the fatigue limit/tensile strength relationship of different strength steels. These conclusions have been confirmed by the results of high cycle fatigue tests carried out on the base materials. (3)(8)

T4. The resistance to high cycle fatigue of the gas metal arc welded joints of both investigated steels is more favourable when the joint is welded with the higher strength filler material. For steel with 1100 MPa strength grade this is matching, for steel with 1300 MPa strength grade this is undermatching with a lower strength difference. These conclusions have been confirmed by the results of high cycle fatigue tests carried out on welded joints under industrial conditions. (3)(8)

T5. The fatigue crack propagation resistance of both tested base materials and gas metal arc welded joints is significantly different in the rolling direction (T-L and 21, respectively) and in the thickness direction (T-S and 23, respectively); the base materials and their welded joints are more susceptible to cracks propagation in the thickness direction. The significant difference is demonstrated by both the Paris-Erdogan correlation exponent (n) and fatigue fracture toughness (ΔK_{fc}) values determined from the performed fatigue crack propagation tests. (14)(16)(17)

T6. There is no significant difference between the fatigue crack propagation behaviour of welded joints made with two different filler materials - matching and undermatching for S1100M steel and two undermatching materials for S1300Q steel - for the investigated base materials. This conclusion was confirmed by the results of fatigue crack propagation rate tests carried out on S1100M steel in 21 and 23 orientations and on S1300Q steel in 21 orientation. (16)(17)

T7. The choice of the filler material used for the welded joints of both investigated steel grades (matching or undermatching, in case of undermatching also the strength difference) is influenced by the stresses of the welded structure. This conclusion was confirmed by the influence of the filler materials on the test results (basic mechanical properties, resistance to high cycle fatigue and fatigue crack propagation). (2)(6)(15)(16)(17)(18)(20)

4. INDUSTRIAL UTILIZATION AND FURTHER DEVELOPMENT

The application of the investigated high strength steels is not common either abroad or in our country, so the knowledge of the mechanical properties and fatigue characteristics as well as the effect of welding is limited. Also, the specifications in the relevant standards only cover lower strength steels, so there are no specifications that take into account the different properties of these high strength steels. Since the different high strength steels are produced by different manufacturing technologies and have different alloying elements, different reactions to heat input and different fatigue resistance, it is not possible to make general recommendations for their welding and application. Therefore, one of the aims of the present dissertation is to provide useful information for the industry (in case of thick plates) on the thermomechanically rolled and quenched and tempered structural steels of the highest strength category which are currently available.

The results of the physical simulation and the parameters and specifications used for welding can provide useful knowledge for welding engineers. Since the risk of softening - especially in the heat affected zone - is a major issue for high strength steels, proper limitation of the heat input is a key priority. Furthermore, in the case of thick plates, it must also be taken into account that in the heat affected zone of joints produced from several passes, there may be areas which are even more affected by softening.

For high strength steels, the choice of filler material is also challenging, because matching filler materials are only available up to a yield strength of 1100 MPa. In addition, these filler materials are also considered as new and therefore information on these can be useful for the engineers. In my dissertation, I present results of different material tests on joints made with two different filler materials belonging to different strength categories. According to these, the hardness and impact energy values were similar for both filler materials, thus the use of undermatching filler materials may be advantageous from this point of view. However, in case of tensile stresses, it is advantageous to choose a filler material with a higher strength category.

Related to the results of the physical simulations and the actual welded joints, it is also relevant to mention that the results of the instrumented impact tests showed a rather brittle behaviour, especially in the heat affected zone. Consequently, in case of dynamic loading, it is worth to pay great attention to welded structures made of high strength steels in negative temperature applications for safety reasons.

Both welding engineers and design engineers can use the results of the fatigue tests on the investigated steels and their welded joints. My dissertation also includes limit curves for high cycle fatigue and fatigue crack propagation. Based on the high cycle fatigue tests, it is clear that the fatigue characteristics of the welded joints for both investigated steels are worse than those of the base materials, and this should be taken into account during design. The results obtained suggest that for both strength grades it is advisable to use the higher strength category filler material. Furthermore, since the results show a large standard deviation of the fatigue cycle numbers in the vicinity of the fatigue limit, it may be useful to describe the fatigue behaviour of the investigated high strength steels by two decreasing lines instead of the classical S-N curve (decreasing and horizontal line). This also results the disappearance of a defined fatigue limit, which can and does have design aspects.

Limit curves for the crack propagation conditions were also determined for both investigated materials and their welded joints. From an industrial point of view, this may be advantageous because these limit curves can be used to evaluate the integrity of welded structures, to estimate their service life and remaining life, and to perform comparative calculations.

In addition to welding and design engineers, the results of this dissertation can also be beneficial for steel developers, since those can highlight the unfavourable structural changes that occur during welding of high strength steels, which affect the mechanical properties. Therefore, during development, this information can provide a good basis for the appropriate choice of different alloying elements or manufacturing processes.

As a possible continuation of the research work, further mechanical tests (e.g. tensile or bending tests) and, in the case of cyclic loading, low cycle fatigue tests may be carried out. Furthermore, it may also be useful to systematically investigate the effects of different post heat treatments.

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

Publications in English

(1) J. Kovács, J. Lukács: Effect of the welding thermal cycles based on simulated heat affected zone of S1300 ultrahigh strength steel, Key Engineering Materials, 890, pp. 33-43, 2021, https://doi.org/10.4028/www.scientific.net/KEM.890.33

(2) J. Kovács, J. Lukács: Influence of filler metals on microstructure and mechanical properties of gas metal arc welded high strength steel, Lecture notes in mechanical engineering, Vehicle and automotive engineering 4, pp. 995-1005. 2022. https://doi.org/10.1007/978-3-031-15211-5_83

(3) J. Kovács; J. Lukács: Comparison of fatigue strength curves of different high strength steel categories, 76th IIW Annual Assembly and International Conference on Welding and Joining, Singapore, (2023) Paper: 130

(4) J. Kovács; M. Gáspár; J. Lukács: Comparative study about the results of HAZ physical simulations on different high strength steel grades, 76th IIW Annual Assembly and International Conference on Welding and Joining, Singapore, (2023) Paper: 26_IX-L-1273-2023

(5) J. Kovács, J. Lukács: Effect of the welding thermal cycles based on simulated heat affected zone of S1300 ultrahigh strength steel, 11th International Conference on Innovative Technologies for Joining Advanced Materials, TIMA20, Timisoara (online), (26-27.11.2020.)

(6) J. Kovács: Influence of filler metals on microstructure and mechanical properties of gas metal arc welded high strength steel, International conference on vehicle and automotive engineering, VAE 2022., Miskolc, (8-9 Sept. 2022.)

(7) J. Kovács: Comparative study about the results of HAZ physical simulations on different high strength steel grades, Commission IX, Sub-Commission meeting, Behavior of materials subjected to welding, IX-2789-2023, Munich, (6-8. March 2023.)

(8) J. Kovács: Comparison of fatigue strength curves of different high strength steel categories, 76th IIW Annual Assembly and International Conference on Welding and Joining, OR-16-0130, Singapore, (16-2.1 July 2023.)

(9) J. Kovács, M. Gáspár, J. Lukács, H. Tervo, A. Kaijalainen: Comparative study about the results of HAZ physical simulations on different high-strength steel grades, Welding in the World, 1714, 2024.

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