UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

PHYSICAL SIMULATION BASED DEVELOPMENT OF WELDING TECHNOLOGY FOR QUENCHED AND TEMPERED STRUCTURAL HIGH STRENGTH STEELS

Booklet of PhD Theses

PREPARED BY:
MARCELL GYULA GÁSPÁR
MECHANICAL ENGINEER (MSC), ECONOMISTS (MSC),
WELDING ENGINEER, EWE/IWE

ISTVÁN SÁLYI DOCTORAL SCHOOL
TOPIC FIELD OF ENGINEERING MATERIAL SCIENCE, PRODUCTION SYSTEMS AND PROCESSES
TOPIC GROUP OF MATERIALS ENGINEERING AND MECHANICAL TECHNOLOGY

HEAD OF DOCTORAL SCHOOL
DR. MIKLÓS TISZA
DOCTOR OF TECHNICAL SCIENCE, FULL PROFESSOR

HEAD OF TOPIC GROUP
DR. MIKLÓS TISZA
DOCTOR OF TECHNICAL SCIENCE, FULL PROFESSOR

SCIENTIFIC SUPERVISOR
DR. ANDRÁS BALOGH
PHD, ASSOCIATE PROFESSOR

Miskolc
2016

JUDGING COMMITTEE

chair: **Prof. Dr. Miklós Tisza**
DSc, full professor (ME)

secretary: **Dr. Mária Maros**
PhD, associate professor (ME)

members: **Prof. Dr. Károly Jármai**
DSc, full professor (ME)

Dr. Géza Gremsperger
CSc, college professor (DUE)

Dr. Péter Szabó
PhD, chief technology officer (Quality Pack ZRt.)

OFFICIAL REVIEWERS

Dr. Gyöngyvér B. Lenkey
CSc, director of the division (Bay Zoltán Nonprofit Ltd for Applied Research)

Dr. Béla Palotás
CSc, college professor (DUE)

1. INTRODUCTION

1.1 PRELUDE

On the basis of accessibility, complex properties and economic reasons iron alloys have still preserved their leading role. The Earth's crust includes significant amount of iron which can be simply produced in a more energy saving method compared to other metals, and furthermore iron alloys are also recyclables. Mechanical, physical and chemical resistance can be varied in a wide range, therefore by considering the user properties an appropriate steel can be produced for the demanded purpose. The application of metals is also determined by the production price. Statistical data verify that related the application of metals a ten-fold increase in price brings a hundredfold reduction in usage [1].

Structural steels applied in welded structures have been significantly developed in the past decades. The development of strength properties, especially yield strength was the primary motivation [2]. Due to the thinner plates and the smaller cross sections achieved by the application of high strengths steels the consumption of vehicle reduces, therefore smaller amount of fuel is needed resulting lower CO_2 emission values and favourable operation costs. Less base and filler materials are needed [3], which reduce the CO_2 footprint of a welded product. [1]. In the vehicle industry the application of high strength steels can be advantageous in mobile cranes due to the higher lifting height and in agricultural vehicles because of the reduced soil load (destruction) [4]. Furthermore, besides the vehicle industry high strength steels can provide effective solutions for the designers where slender structures are demanded (e.g. bridges) [5].

In high strength steel structures welding is a frequently used joint method. The core of the weldability problem is originated from the irreversible change of the microstructure due to the welding heat cycle, which can be limitedly recovered after the welding. As a result of the unfavourable microstructural changes crack initiation and propagation can occur in the weld and in the heat-affected zone, and the reduction of strength and toughness properties can be also noticed. Therefore, during the welding technology planning for advanced high strength steels welding engineers should endeavour to minimize the unfavourable microstructural changes.

Nowadays, there is still a limited available knowledge about the fatigue behaviour of high strength steels and their welded joints. In case of static tensile loading conditions the advantage of higher yield strength can be fully utilized, however at stability problems and cycle loading conditions the possible advantages are not obvious. In recent years numerous research projects [6] dealt with the fatigue resistance of high strength steels and the results can motivate further research.

1.2 THE PURPOSE OF DISSERTATION

During the research work I focused on the highest strength category, so-called quenched and tempered group of structural steels. Within the group I determined to investigate the weldability of S960QL according to MSZ EN 10025-6. During the development of welding technology I emphasised two research areas: role of the selection of filler materials and the safe determination of welding lobe.

- At the beginning of the research work I aimed to study the field of filler metal selection on the basis of welding experiments and the related material tests.
- By considering that fatigue properties are one of the most significant failure methods the area of filler metal selection, especially the role of mismatch ratio was analysed by welding experiments and fatigue tests.

Physical simulation, contrary to conventional methods, has opened a precise and reproducible possibility for the determination of welding lobe based on the (toughness) properties of heat-affected zone.

- The goal of the research work is to investigate the fusion welding lobe of the examined steel category on the basis of the microstructural changes in the heat-affected zone and the acceptable toughness reduction in this area.
- An important part of my dissertation was to elaborate guidelines for the welding technology, by which the local reduction of toughness properties in the heat-affected zone can be limited or compensated.
- Since in the physical simulator the achievable cooling rate significantly depends on the specimen geometry, therefore I aimed to develop a new specimen geometry which is capable to realize shorter cooling times relevant at welding technologies with low heat input.

2. METHODOLOGY

In the *theoretical research* I especially dealt with the strength increasing methods applied in quenched and tempered high strength steels [7][8]. By considering that these steels are quenched in the first cycle of the heat treating, therefore the non-equilibrium martensitic transformation was presented in details, especially the properties of lath martensitic microstructure occurring in steels with low carbon content. In quenched and tempered high strength steels the main strength increasing method can be originated rather from the fine, lath-like martensitic microstructure and from the dislocation density than the solved carbon content [7]. Lattice stress can decrease due to the effects of high temperature tempering and the microstructure transforms towards a more equilibrium condition [8]. Carbide former alloyers (Mo, Cr) applied in quenched and tempered steels improve the tempering resistance of the steel, hence these steels have still outstanding strength properties after the heat treating.

The increased brittle behaviour of quenched and tempered grades compared to mild steels the yield/tensile strength ratio also indicates. Besides that, brittle precipitates – carbides, martensite islands and occasionally inclusions can contribute to cleavage cracks [1]. The brittle phases can be originated from the steel production, and local brittle zones can also form due to the welding heat input [9]. The welding heat cycle irreversibly changes the non-equilibrium microstructure resulting the reduction of strength and toughness in the heat-affected zone [3]. As a consequence of impropriate welding technology and the high carbon equivalent of base and filler metals cold cracking may occur in the weld and the heat-affected zone [10]. Therefore the welding of quenched and tempered high strength steels demands new approach compared to low and medium strength steels.

Because of the weldability difficulties of the investigated steel category I studied the aspects of welding technology planning in details. Therefore I elaborated the available different methods for the determination of preheating temperature [11], and the conception for the design of welding technology based on the $t_{8.5/5}$ cooling time [12]. I especially focused on the extensive overview of the topic of filler material selection. The primal difficulty during the development of filler metals that the rolling and heat treating conditions of the base material cannot be reproduced during welding. The only possibility for the demanded strength to alloy the filler metals more than the base material. Hence, the chemical composition of filler materials significantly differs from the steel plates. The expression *matching* means the correspondence, sameness of the properties, especially strength characteristics (primarily yield strength, tensile strength) of base material and the weld. There can be situations [13][14], when the application of *undermatching* (namely lower strength but higher elongation) weld is advantageous in terms of the cracking sensitivity and the non-static loading conditions. Furthermore, the increased ductility of the lower strength weld metal and the reduction in residual stresses can reduce lamellar tearing tendencies as well [15]. Softening in the HAZ, together with the strength of the weld metal, are important factors affecting cross-weld strength and fracture behaviour, and they need to be taken into account in structural integrity calculations [1].

The *experimental research* can be divided into two groups. In the first part I investigated the effect of mismatch on the fatigue resistance of the welded joints made of Weldox 960 E (S960QL). In the other part I analysed the effect of welding parameters on the properties of heat-affected zone by physical simulation.

During the welding experiments, performed by active gas metal arc welding, a Union X96 *matching* and an OK Tubrod 14.03 *undermatching* wire electrodes were applied. Welding parameters were registered by a welding monitoring system. The static load bearing capacity of the welded joints prepared by the application of $t_{8.5/5}$ = 5-10 s cooling time interval and the necessary preheating temperature were analysed by an optical strain analysis system [16]. In case of the *undermatching* welded joint the strain concentrated to the weld and the measured maximal strain was higher compared to the *matching* joint.

Constant strain amplitude tests [17] were applied for the determination of the low cycle fatigue resistance ($N \leq 10^4$) of the welded joints by applying $R = -1$ and a triangle shape loading function. The 10% reduction of maximal force at the tensile side was set as a damage criteria. The elastic strain amplitude of the *undermatching* joint was under the measured values of the *matching* joint and the base material. However, the plastic strain amplitudes were higher than the *matching* joint and the base material at the smaller cycles ($N_t \leq 1000$). After the fatigue tests the location of crack initiations were also analysed.

During the high cycle fatigue tests ($N > 10^4$) on the *matching* and the *undermatching* joints the staircase method was applied due to the time-consuming tests and the large specimen number [18]. Constant load amplitude, with $R = 0.1$ stress ratio, $f = 30$ Hz loading frequency and sinusoidal loading wave form were applied during the experiments. The high cycle fatigue resistance of the *undermatching* joint was slightly higher than the *matching* one, so the filler material selection based on the *undermatching* conception was not detrimental for the behaviour of the welded joints under high cycle fatigue.

Fatigue crack growth tests were performed for the determination of crack propagation resistance of the different part of the *matching* welded joint [17]. For the sake of the statistical approach the notch locations were varied in two orientations from the weld centreline. During the experiments $R = 0.1$ stress ratio and sinusoidal loading wave form were applied. Crack propagation was followed by an optical method. The first part of the determined kinetic diagrams, belonging to the slow crack growth rate, indicated the differences of the cracks initiating in the several parts of the welded joint. In case of the specimens, notched in the weld and in the critical areas of the heat-affected zones, the cracks started to propagate with a relatively high growing rate, and then after a few millimetre size the differences equalized.

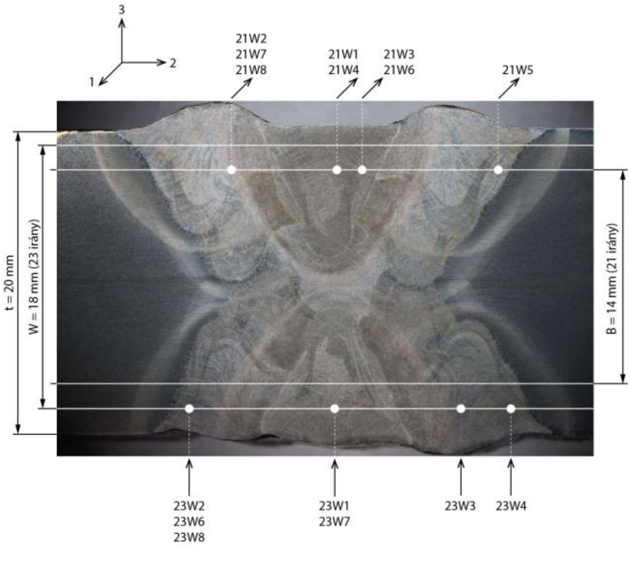

Figure 1. Location of the notches at FCG tests

During the physical simulation of materials technologies the thermal and mechanical processes of the real production can be precisely produced in laboratory circumstances. According to a possible definition, physical simulation is the realization of the industrial processes in a real time, and nearly a real geometrical (volumetric) scale [17][19]. In quenched and tempered high strength steels due to the welding heat cycle an inhomogeneous heat-affected zone forms in terms of the microstructure and the mechanical properties. The areas of the heat-affected zone can be limitedly examined in real welded joints due to their narrow extent. By the physical simulation the desired HAZ areas can be precisely produced from the base metal in a sufficient volume for the further material tests [20]. The thermal processes in the heat-affected zone can be described by the welding heat cycle models. For the determination of the necessary mathematical formula the differential equation of the thermal conduction needed to be solved. The *Rykalin-3D* model [21] was applied during the physical simulation, which describes the temperature field of relatively slowly moving, point-like heat source on a thick plate. In this model the heat transfer can be negligible at the surface, therefore the equation is independent from the material thickness, thus smaller amount of variables complicate the evaluation and the application of the results [22]. During the design of the experimental work, in cooperation with the University of Oulu (Finland), the thermophysical properties of Weldox 960 E was determined, and their average values were used for the simulation of the critical HAZ areas. In order to investigate the whole technological scale of the relevant fusion welding technologies seven cooling times ($t_{8.5/5}$ = 2.5 s; 5 s; 10 s; 15 s; 22-5 s; 30 s és 100 s) were selected for analysing the effect of welding parameters.

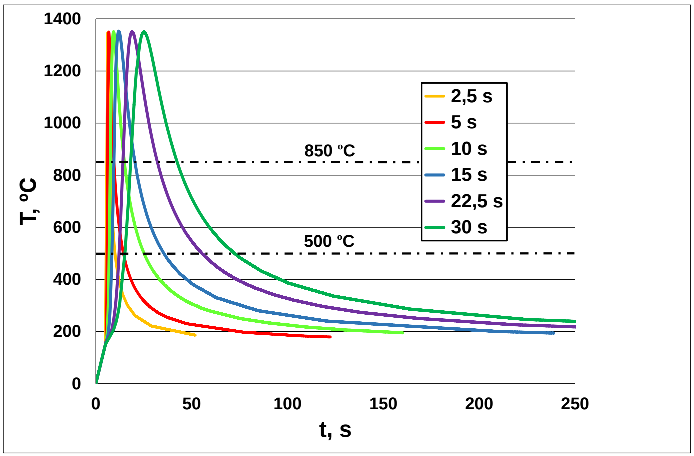

Figure 2. Heat cycles of CGHAZ

In case of the general set-up and specimen geometry (10x10x70 mm) the achievable shortest cooling time is 5 s (≈ 60 ºC/s), whilst during welding technologies with lower heat input (root welding, high speed robotic welding, laser beam welding etc.) the cooling time can be much shorter. Therefore a special physical simulation specimen geometry was designed which is capable for the realization of 2.5 s with external cooling. The peak temperatures for the simulation of coarse-grained (CGHAZ), intercritical (ICHAZ) and intercritically reheated coarse-grained zones (ICCGHAZ) were selected on the basis of TTA diagram, literature data [23][24] and preliminary experiments. The applied heat cycles are presented in Figure 2.

The successfully simulated HAZ areas were examined by optical and electron microscopic tests, macro- and micro hardness measurements and instrumented Charpy V-notch impact tests. Compared to the traditional impact test this method is able to determine further information about the fracture and the behaviour of the material. Based on the registered force-time or the calculated force-deflection diagrams the characteristic points of the fracture process can be marked (the start of plastic forming, maximum force, start and end of the instable crack propagation). Hereby the absorbed energy can be divided into two groups: energy for crack initiation and propagation. The reduction of the ratio of crack initiation indicates the improvement of the toughness because more energy absorbed for the stable crack propagation [25].

After evaluating the results of impact tests I noticed that in the whole parameter interval of fusion (especially arc) welding all heat-affected zones have a significantly lower toughness than the base metal. In the investigated steel grade of quenched and tempered high strength steels ICHAZ has similarly low toughness as CGHAZ, independently of the applied cooling time. In multi-pass welded joints the locally occurring ICCGHAZ seemed the most critical HAZ area.

By the physical simulator I could also investigate the effect of local postweld heat treatment (PWHT). The impact energy of CGHAZ was doubled due to the set 650 °C tempering temperature, whilst in ICHAZ the improvement was triple. In ICCGHAZ the results were also favourable.

3. NEW SCIENTIFIC RESULTS - THESES

T1. By the aimed modification of the geometry of the physical simulation specimen I developed an externally cooled specimen for the reliable examination of heat-affected zones of joints welded by cooling time shorter than $t_{8.5/5}$ = 5 s (20)(23).

T2. By physical simulation and real welding experiments I proved that a narrow, 5-10 s interval of critical $t_{8.5/5}$ cooling time is needed because of the significant toughness reduction taking place in the heat-affected zone. The lower limit of the interval aims to avoid higher hardening than the permitted value, whilst the upper limit ensures that the change of the thermally instable non-equilibrium microstructure should not exceed an acceptable value in the heat-affected zone (4)(13)(21)(25)(27).

T3. Based on the performed physical simulation experiments and materials tests it can be concluded, that in terms of the toughness of heat-affected zone of quenched and tempered high strength structural steels in single-pass welding the microstructure of coarse-grained, intercritical zones, and in multi-pass welding intercritically reheated coarse-grained zones are equally determining. In multi-pass welded joints the intercritically reheated coarse-grained stripe is the most brittle part of the heat-affected zone, which unfavourable effect is should be reduced by the conscious design of joint geometry and welding technology (4)(21)(25)(27).

T4. By instrumented Charpy V-notch impact tests I determined that the critical, local toughness reduction in the heat-affected zone of quenched and tempered high strength structural steels cannot be avoided, and its extension cannot be significantly influenced by the $t_{8.5/5}$ cooling time. The effect of cooling time primarily appeared in the variation of the width of HAZ areas (4)(21).

T5. By experimental method I ensured that the toughness of the coarse-grained, the intercritical and the intercritically reheated coarse-grained zones of quenched and tempered high strength steels can be significantly improved by a postweld heat treatment providing a well-controlled local heat input (3).

4. INDUSTRIAL UTILIZATION AND POSSIBILITIES FOR THE FURTHER DEVELOPMENT

Nowadays the knowledge of welding engineers is still limited about the weldability of high strength steels. Practical guidelines are often available, although sufficient information is not accessible about the consequence of welding heat input on the properties of heat-affected zone and the behaviour of welded structures under dynamic and cyclic loading conditions. Therefore present dissertation also aimed to summarize results about the effect of welding parameters by providing useful information for industrial experts.

Experimental results about the effect of *undermatching* filler metals provide usable information for the consumable producers and welded structure designer engineers. The results of the performed low cycle fatigue tests, high cycle fatigue tests and fatigue crack growth tests can be used for the design of welded structures including quenched and tempered high strength steels. For the full utilisation of the possibilities provided by quenched and tempered structural steels new design approaches are needed besides the technological development [26].

Related to the physical simulation tests it is important to highlight that those specimens which fulfilled the 27 J requirement at -40 ºC still showed brittle behaviour. The ratio of the absorbed energy during the crack initiation was around 80-90% similarly to the specimens with lower impact energy. Therefore the 27 J requirement should be critically considered, whether it is capable to ensure safe operation and the resistance to dynamic loading in negative temperature. The results of the instrumented Charpy V-notch impact tests highlighted that the welding engineers should strictly limit the heat input and the quality assurance of the whole welding process should be put forward.

The presented results in the dissertation may provide useful information for materials engineers working in steel industry. The detailed information about the unfavourable effect of the welding heat cycle on the microstructure and the mechanical properties of the investigated quenched and tempered high strength steel can be a base for the development of new high strength steels being less sensitive to the welding heat input. The performed simulation tests, especially the presented methodology can be applied for the weldability analysis of other steel grades (e. g. S960M). The thermomechanical high strength steels seem to be demanding according to the *Graville diagram* [27] because of their lower cold cracking sensitivity. The designed and successfully tested new physical simulation specimen geometry can be applied for other type of steels, and for the analysis of low heat input welding processes.

As a continuation of the research the effect of postweld heat treatment can be tested by welding experiments in practice, and the influence on residual stresses and fatigue behaviour can be also investigated.

5. LIST OF THE PUBLICATIONS RELATED TO THE TOPIC OF THE DISSERTATION

IN ENGLISH

(1) Lukács, J., Dobosy, Á., Gáspár, M.: *Fatigue crack propagation limit curves for high strength steels and their welded joints, and their applicability of these curves for ECA calculations*, IIW 2016 International Conference, The Total Life Cycle of Welded Components, Melbourne, Australia, 14-15th July 2016. (under publication)

(2) Dobosy, Á., Gáspár, M., Nagy, Gy.: *The mismatch effect on LCF resistance of Q+T high strength steels and their welded joints*, 8th International Conference on Low Cycle Fatigue, DVM, Dresden, Germany, 27-29. June 2017. (under publication)

(3) Gáspár, M., Balogh, A.: *Effect of postweld heat treatment on HAZ toughness of Q+T high strength steels*, XXXth microCAD International Scientific Conference, University of Miskolc, Miskolc, Hungary, 21-22. April 2016. D2_5 8p.

(4) Gáspár, M., Balogh, A., Sas, I.: *Physical simulation aided process optimisation aimed sufficient HAZ toughness for quenched and tempered AHSS*, IIW 2015 International Conference on High Strength Steels - Challenges and Applications, Helsinki, Finland, 2-3. July 2015, Paper IIW 2015 1504 7p.

(5) Gáspár, M., Dobosy, Á., Lukács, J., Sas, I.: *Behaviour of undermatched AHS steel welded joints under static and cyclic loading conditions*, IIW 2015 International Conference on High Strength Steels - Challenges and Applications, Helsinki, Finland, 2-3. July 2015, Paper IIW 2015 1801 8p.

(6) Lukács, J., Kuzsella, L., Koncsik, Zs., Gáspár, M., Meilinger, Á.: *Role of the Physical Simulation for the Estimation of the Weldability of High Strength Steels and Aluminium Alloys*, Materials Science Forum, Vol. 812., 2015. pp. 149-154, DOI: 10.4028.

(7) Gáspár, M.: *Application of instrumented Charpy V-notch impact test for the investigation of simulated HAZ*, Young welding Professionals International Conference (YPIC), Budapest, Hungary, 7-8 October 2015.

(8) Gáspár, M., Balogh, A.: *The effect of* $t_{8.5/5}$ *cooling time ont he critical HAZ areas of high strength steel welded joints*, International Engineering Symposium at Bánki (IESB), 20th November 2014.

(9) Gáspár, M..: *The analysis of HAZ of high strength steel welded joint by physical simulation*, Young welding Professionals International Conference (YPIC), Budapest, Hungary, 17-20. September 2014.

(10) Gáspár, M., Balogh, A.: *Behaviour of mismatch welded joints when undermatching filler metal is used*, Journal of Production Processes and Systems, Vol. 7 No. 1, 2014. pp. 63-76.

(11) Gáspár, M., Lukács, J.: *Fatigue crack growth resistance of S960QL high strength steel and its GMAW welded joints*, Journal of Production Processes and Systems, University of Miskolc, Vol. 7 No. 1, 2014. pp. 41-52.

(12) Lukács, J., Gáspár, M.: *Fatigue Crack Propagation Limit Curves for High Strength Steels and their Application for Engineering Critical Assessment Calculations*, Advanced Materials Research, Vol. 891-892., 11th International Fatigue Congress, Melbourne, Australia, 2-7 March 2014. DOI 10.4028.

(13) Gáspár, M., Balogh, A.: *GMAW experiments for advanced (Q+T) high strength steels*, Journal of Production Processes and Systems, University of Miskolc, Vol. 6 No. 1, 2013. pp. 9-24.

(14) Gáspár, M., Balogh, A.: *Structural inhomogeneities in the heat affected zones of (Q+T) high strength steel joints*, XXVIIth microCAD International Scientific Conference, University of Miskolc, Miskolc, Hungary, 21-22. March 2013., Paper M3. (ISBN 978-963-358-018-9)

(15) Gáspár, M., Balogh, A.: *Efficient Increase of the Productivity of GMA Welding of AHSS Using Flux Cored Wire*, Design, Fabrication and Economy of Metal Structures, Springer, Miskolc, 24-26. April 2013, pp. 463-468.

(16) Gáspár, M., Balogh, A.: *Experimental investigation on the effect of controlled linear energy applied to the welding of high strength steels*, XXVIth microCAD International Scientific Conference, University of Miskolc, Miskolc, Hungary, 29-30. March 2012., Paper M3. (ISBN 978-963-661-773-8)

(17) Gáspár, M., Balogh, A.: *Effect of weld build-up on high strength steel joints*, 8th International Conference of PhD Students, Miskolc, Hungary, 6-10. August 2012, Paper D7.

(18) Balogh, A., Török, I., Gáspár, M., Juhász, D.: *Present State and Future of Advanced High Strength Steels*, Production Processes and Systems, Vol. 5 No. 1., 2012. pp. 79-90.

(19) Gáspár, M., Illés, B.: *High Strength Steels in Mobile Cranes, 4th International Doctoral Students Workshop on Logistics*, Otto von Guericke University, Magdeburg, Germany, 28 June 2011, pp. 103-108.

IN HUNGARIAN

(20) M Gáspár, M., Balogh, A.: *Gleeble próbatest fejlesztése a szimulált hőhatásövezet szívósságának vizsgálatához*, GÉP, 67. évf. 1-2. sz., 2016. pp. 19-22.

(21) Gáspár, M., Balogh, A.: *Fizikai szimulátorral előállított S960QL hőhatásövezeti sávok szívósságának elemzése műszerezett ütővizsgálatok segítségével*, Hegesztéstechnika, XXVI. évf. 4. sz., 2015. pp. 51-64.

(22) Balogh, A., Dobosy, Á., Frigyik, G., Gáspár, M., Kuzsella, L., Lukács, J., Meilinger, Á., Nagy, Gy., Pósalaky, D., Prém, L., Török, I.: *Hegeszthetőség és a hegesztett kötések tulajdonságai: Kutatások járműipari acél és alumíniumötvözet anyagokon,* Miskolci Egyetem, 2015. 324 p. (ISBN 978-963-358-081-3)

(23) Gáspár, M.: *Próbatest fejlesztése kis fajlagos hőbevitellel készült hegesztett kötések hőhatásövezetének fizikai szimulációjához,* Tavaszi Szél Konferencia Absztraktkötet, Doktoranduszok Országos Szövetsége, Eger, 2015.04.10-12. p. 326. (ISBN 978-963-397-702-6)

(24) Balogh, A., Gáspár, M.: *A matching kérdéskör: hozaganyagválasztás a konvencionális és korszerű nagyszilárdságú acélok hegesztéséhez*, Hegesztéstechnika, XXV. évf. 3. sz., 2014. pp. 75-80.

(25) Gáspár, M., Balogh, A., *Kritikus sávok a nagyszilárdságú acélok hegesztett kötéseinek hőhatásövezetében*, 27. Hegesztési Konferencia, Óbudai Egyetem, Budapest, Magyarország, 2014. pp. 195-212. (ISBN 978-963-088-585-0)

(26) Gáspár, M., Kuzsella, L., Koncsik, Zs., Lukács, J.: *Hegeszthetőségi problémák megoldása fizikai szimulációval*, 7. Anyagvizsgálat a Gyakorlatban Szakmai Szeminárium, Kecskemét, 2014.06.19-20.

(27) Gáspár, M., Balogh, A.: *A hegesztési paraméterek hőhatásövezetre gyakorolt hatásának fizikai szimulációval történő vizsgálata S960QL esetén*, Hegesztéstechnika, XXV. évf. 1. sz., 2014. pp. 21-28.

(28) Gáspár, M.: *Nemesített nagyszilárdságú acélok hőhatásövezeti zónáinak előállítása szimulált hegesztési hőciklusok segítségével*, Multidiszciplináris Tudományok, 3. évf. 1. sz., Miskolci Egyetem, 2013. pp. 27-38.

(29) Gáspár, M.: *Nagyszilárdságú acélból készült hegesztett kötések hőhatásövezetének vizsgálata fizikai szimulációval*, Tavaszi Szél Konferencia, Doktoranduszok Országos Szövetsége, Sopron, 2013. pp. 179-184.

(30) Balogh, A., Gáspár, M., Prém, L.: *A hegesztett szerkezetek konvencionális és korszerű nagyszilárdságú acéljainak rendszerezése és hegesztési nehézségei*, GÉP, 64. évf. 8. sz., 2013. pp. 7-12.

(31) Gáspár, M.: *A nemesített állapotú nagyszilárdságú acélok hagyományostól eltérő hegesztési megoldásai középvastag lemezeknél*, Hegesztő Szakmérnöki Diplomaterv (témavezető: Dr. Balogh András), 2013.

(32) Balogh, A., Gáspár, M.: *Nagyszilárdságú acélok hegesztésének standardtól eltérő koncepciója*, Hegesztéstechnika, XXIII. évf. 3. sz., 2012. pp. 23-28.

(33) Gáspár, M., Balogh, A.: *Hegesztéstechnológiai paraméterablak nagyszilárdságú acélok hegesztésénél*, GÉP, 63. évf. 11. sz., 2012. pp. 11-16.

(34) Gáspár, M., Balogh, A.: *A vonalenergia optimális tartománya nemesített nagyszilárdságú acélok hegesztésekor*, 26. Hegesztési Konferencia és Hegesztéstechnikai Kiállítás, Óbudai Egyetem, Budapest, 2012.05.10-12., pp. 173-180. (ISBN 978-615-501-828-2)

(35) Gáspár, M., Balogh, A.: *Feszegethető technológiai határok nagyszilárdságú acélok ívhegesztésekor*, Hegesztési Felelősök XIV. Országos Tanácskozása, 2012.09.20-21.

(36) Gáspár, M.: *A hűlési idő szerepe nagyszilárdságú acél hegesztése során*, Diáktudomány: A Miskolci Egyetem Tudományos Diákköri Munkáiból, 1. évf., 2011. pp. 46-50.

(37) Gáspár, M.: *Nagyszilárdságú, nemesített nagyszilárdságú acélok hegesztése*, MSc Diplomamunka, 2011.

6. LITERATURE CITED IN THE THESES BOOKLET

[1] Porter, D.: *Weldable high-strength steels: challenges and engineering applications, Portevin lecture, IIW 2015 International Conference on High Strength Steels – Challanges and Applications, Helsinki, Finland, 2-3. July 2015, Paper IIW 2015 0102 13p.*

[2] Tisza, M.: *Járműipari anyagfejlesztések,* GÉP*, LXIII. évf. 4. szám, 2012. pp. 3-10.*

[3] Komócsin, M.: *Nagyszilárdságú acélok és hegeszthetőségük, Hegesztéstechnika, XIII. évf. 1 sz., 2002. pp. 5-9.*

[4] Ohlsson, A.: *Applications in high strength steels – Possibilities on new segments*, IIW 2015 International Conference on High Strength Steels – Challanges and Applications, Helsinki, Finland, 2-3. July 2015, Paper IIW 2015 Plenary Lecture.

[5] S Bursi, O. S., Kumar, A. et al.: *Design and integrity assessment of high strength tubular structures for extreme loading conditions*, Research programme of the Research Fund for Coal and Steel, RFSR-CT-2008-00035, 2011.

[6] O Pijpers, R. J. M., Kolstein, M. H., Romeijn, A., Bijlaard, F. S. K.: *Fatigue experiments on very high strength steel base material and transverse butt welds*, Advanced Steel Construction, 5. No. 1, 2007. pp. 14-32.

[7] Porter, D. A., Easterling, K. E.: *Phase Transformations in Metals and Alloys*, Second edition, Chapman and Hall, 2-6 Boundary Row, London SE1 8HN, UK 1996. (ISBN 0-412-45030-5).

[8] Tisza, M.: *Az anyagtudomány alapjai*, Miskolci Egyetemi Kiadó, Miskolc, 2008. pp. 1-285. (ISBN 978 963 661 844 5).

[9] Nevasmaa P: *Evaluation of HAZ Toughness Properties in Modern Low Carbon Low Impurity 420, 550 and 700 MPa Yield Strength Thermomechanically Processed Steels with Emphasis on Local Brittle Zones*, Lisensiaatintyö, University of Oulu, 1996. pp. 176.

[10] Nevasmaa, P.: *Predictive model for the prevention of weld metal hydrogen cracking in high-strength multipass welds*, PhD Dissertation, University of Oulu, Finland, 2003.

[11] Palotás, B.: *A finom szemcsés acélok hegeszthetősége*, Acélszerkezetek, MAGÉSZ, XII. évf. 2. sz., 2015. pp. 59-67.

[12] Balogh, A., Kirk, S., Görbe, Z.: *Role of cooling time when steels to be welded requires controlled heat input*, GÉP, L. évf. 5. sz. 1999.

[13] Rodrigues, D.M., Menezes, L.F., Loureiro, A., Fernandes, J.V.: *Numerical study of plastic behaviour in tension of welds in high strength steels,* International Journal of Plasticity, Vol. 20. 2004. pp. 1-18.

[14] Satoh, K.; Toyoda, M.: *Joint Strength of Heavy Plates with Lower Strength Weld Metal,* Welding Journal, No. 9. 1975. pp. 311s-319s.

[15] Structural Welding Code - Steel (AWS D1.1/D1.1.M:2006).

[16] Kovács, P. Z.: *Alakítási határdiagramok elméleti és kísérleti elemzése*, PhD értekezés, 2012. p. 114.

[17] Lukács, J., Nagy, Gy., Harmati, I., Fótos, R., Koncsik, Zs.: *Szemelvények a mérnöki szerkezetek integritása témaköréből,* Miskolci Egyetem, Miskolc 2012. (ISBN 978-963-358-000-4).

[18] Nakazawa, H., Kodama, S.: *Statistical S-N testing method with 14 specimens: JSME standard method for determination of S-N curves,* Statistical research on fatigue and fracture, Current Japanese materials research - Vol. 2. Elsevier Applied Science and The Society of Materials Science, Japan, 1987. pp. 59-69.

[19] Verő B.: *A fizikai és matematikai szimuláció helye és szerepe a műszaki anyagtudományban*, Bányászati és Kohászati Lapok, 145. évf. 1. szám, 2012. pp. 2-6.

[20] Adonyi, Y.: *Heat-affected zone characterization by physical simulations*, Welding Journal, October 2006. pp. 42-47.

[21] Rykalin, N. N.: *Teplovie processzi pri szvarke*, Vüpuszk 2, Izdatelsztvo Akademii Nauk SzSzSzR, Moszkva, 1953. pp. 56.

[22] Balogh, A.: *A hegesztés hőfolyamatai*, Oktatási segédlet, Hegesztő Szakmérnöki Jegyzet, 2010, p. 18.

[23] Laitinen, R.: *Improvement of weld HAZ toughness at low heat input by controlling the distribution of M-A constituents,* PhD Dissertation, University of Oulu, 2006. pp. 164.

[24] Heikkilä, S. et al: *Hardness Profiles of Quenched Steel Heat Affected Zones*, Materials Science Forum Vol. 762, Trans Tech Publications, Switzerland, 2013. pp. 722-727.

[25] Lenkeyné Bíró, Gy.: *Ütővizsgálat információtartalma - Hagyományos, műszerezett,* GÉP, 49. évf. 7-8. sz. 1997. pp. 55-64.

[26] Farkas, J., Jármai, K.: *High strength steel application for welded stiffened plate structure of a fixed storage tank roof,* IIW 2015 International Conference Programme High Strength Steels - Challenges and Applications, Helsinki, Finland, 2015.07.02-2015.07.03, Paper IIW 2015 1001 7 p.

[27] Metals Handbook, Volume 6.: *Welding, Brazing and Soldering,* ASM International, USA, 1995.