Tomáš Brtník, Ivan Mika, Jakub Dolejš

HFMI Method-Based Increase in Fatigue Service Life of Welds in High-Strength Steels

Abstract: Until recently, the fatigue service life of welded joints exposed to medium and high-cycle fatigue has been a factor restraining the wider use of high-strength steels. Recent research on increasing the fatigue service life of welded joints (weld) has revealed that the aforesaid strength can be significantly increased using the high frequency mechanical impact (HFMI) method. Independently performed tests demonstrated that an increase in fatigue service life was proportional to the strength of the base material subjected to the aforesaid method. The HMFI method involves the application of compressive stress at the critical point of the interface between the weld and the base material. The method is an advanced variant of methods developed in the Soviet Union in the 1970s, used to increase the fatigue service life of welded joints in submarine structures. The method can be applied both in relation to butt and fillet welds. The article summarizes the current state of the art concerning the practical usability of the HFMI method in relation to conventional steels (characterised by lower mechanical properties) and high-strength steels. An important factor affecting increasingly high popularity of the HMFI method is that fact that the method has been included in IIW's recommendations concerning fatigue-related structural calculations.

Keywords: fatigue service life of welded joints, HFMI method

DOI: *10.17729/ebis.2018.5/8*

Introduction

Fatigue-triggered damage is one of the most common reasons for failures of load-bearing steel structures. This is because of significantly lower fatigue strength of steels in comparison with static strength, particularly in terms of sharp notches, e.g. welds [1]. In cases of high-strength steels, it is advisable to use the strength of the base material and unload the load-bearing structure. In terms of changeable loads, the foregoing translates into fatigue service life becoming a factor decisive for structural operation. Fatigue service life is divided into the phase of the initiation and the phase of the propagation of cracks. The number of cycles preceding the initiation of a crack depends on the sharpness of a notch. In cases of the base material, where cracks are initiated on

---

Tomáš Brtník, Eng.; Ivan Mika, Eng. – SSAB Swedish Steel s.r.o., Ostrava Poruba, Czech Republic;
Jakub Dolejš, PhD (DSc) Eng., Associate Professor – Czech University of Technology in Prague, Faculty of Building Engineering

the surface of sheets/plates or on the edge of the notch, the phase of crack initiation is dominant. The stress triggering the initiation of a crack in the base material containing small notches is proportional to the static strength of the material. In addition to the aforesaid strength, the quality of surface and edges of sheets/plates significantly affects fatigue strength. The tests confirmed that based on parameters R_z and R_a (describing surface roughness) it is possible to determine the effect of the notch size on fatigue service life [2]. In cases of the typical quality of surface of hot-rolled plates and strips, higher material strength is accompanied by longer fatigue service life up to a yield point restricted within the range of 800 MPa to 1200 MPa. Usually, TMCP steels are characterised by superior quality surface, thus higher fatigue strength in relation to the same yield point values as those characteristic of thick plates.

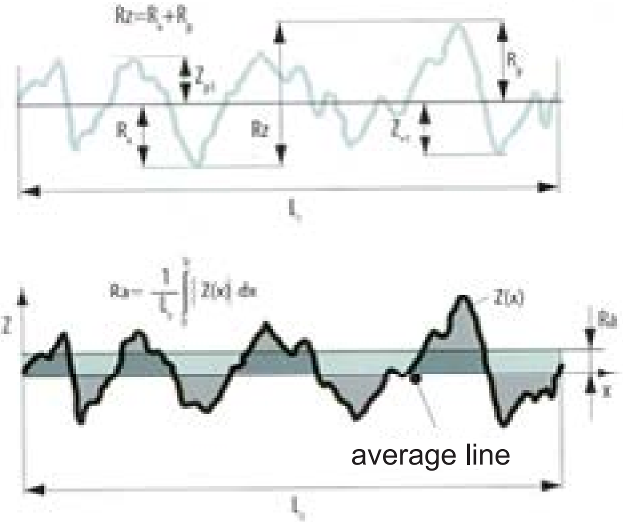

Fig. 1. Significance of values Rz (μm) and Ra (μm) used to describe the roughness of the material surface [2]

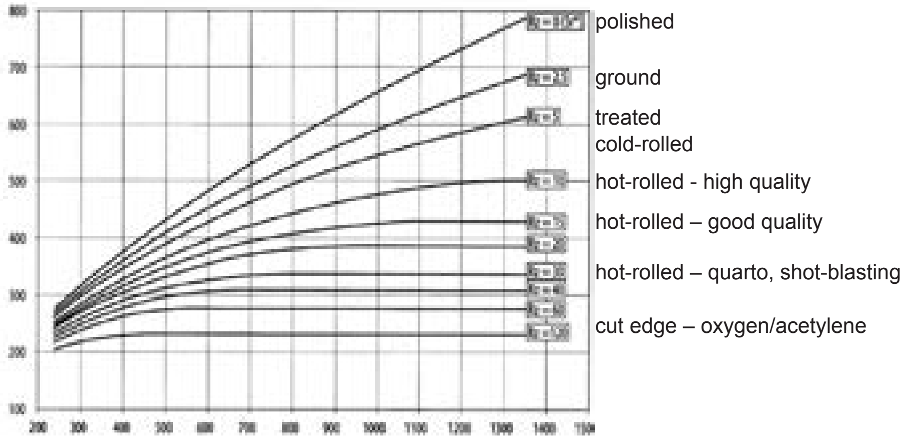

Fig. 2. Effect of surface roughness Rz (μm) on the initial fatigue strength value in relation to N = 106, R = 0 and 50% failure probability 50% [2]

Quality of welds versus fatigue service life

In cases of sharp notches, such as welds, fatigue service life is dominated by the phase of crack propagation. Welded joins often have sharp notches on the edge or the root of the weld, favouring the very fast initiation of cracks. The rate of the propagation of fatigue cracks is roughly dependent on the strength of a material. The fatigue service life welded joints made of conventional structural steels without additional modifications depends primarily on the quality and geometry of welds. The assessment of weld quality is an important factor enabling the determination of the fatigue service life of a welded joint. Using recommendations formulated by the International Institute of Welding [3] and the method of nominal stresses it is possible to clearly identify the difference between the fatigue service life of the best and worst test specimen. The aforesaid difference may be significant and, sometimes, be counted in orders of magnitude. For instance, the quality of arc welded joints is based on the ISO 5817 standard. The standard specifies three quality levels, i.e. B, C and D. Applying this classification it is possible to obtain fatigue service life by one or two classes higher in relation to the best and the worst specimen within the same class. An issue related to such an assessment is the fact that the above-presented system of quality assessment was developed having the welding process in view. As a result, it may not focus on the quality of welded joints in terms of geometric features and their effect in high-cycle fatigue. Some welding imperfections referred to in standard ISO

5817 have little or no effect on fatigue service life, whereas other features of weld geometry are not taken into consideration at all. N. Karlsson and P.H. Lenander [4] applied the theory of crack mechanics to verify the usability of assessment in accordance with quality levels specified in ISO and internal standard STD 5605 (Volvo) in relation to fatigue service life. It was ascertained that the quality levels did not sufficiently correspond to requirements applied when assessing welded joints for fatigue. For instance, an increase in requirements from quality level D to quality level C does not automatically translate into the extension of fatigue service life. It was also demonstrated that the application of assessment consistent with the above-named standards could be accompanied by differences in calculated fatigue service life in relation to one weld class. Depending on the type of a welding imperfection, such differences correspond to one or two orders of magnitude. A. Hobbacher and M. Kassner [5] compared the classes specified in ISO 5817 and those in IIW recommendations concerning the assessment of the quality of fillet and butt welds. In cases of fillet welds, quality level D is sufficient for most welding imperfections, yet in some cases level C or even B may be required. Results were similar in cases of butt welds, yet in many cases the minimum quality level required was level B. In cases of two assessment criteria quality level B proved insufficient to obtain the required fatigue service life in accordance with IIW recommendations. Because of the lack of cohesive correlation between the weld quality level and the weld fatigue service life, the Volvo company developed a new internal system for assessing the quality of welded joints exposed to fatigue [7,8]. An important principle adopted when developing the above-named quality system was the obtainment of comparable fatigue service life of welded joints in the same class. The second principle aimed to increase fatigue service life by 25% in relation to each higher class, which corresponded to an approximately two-fold increase in fatigue service life. The third principle of the new system assumed the application of assessment criteria relevant to the fatigue service life of welded joints.

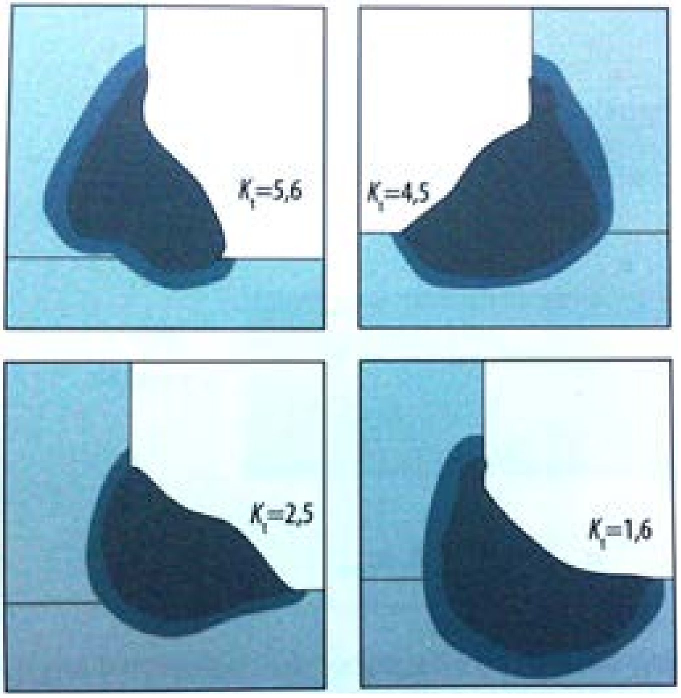

Fig. 3. Effect of angular weld geometry in the stress concentration coefficient [2]

Possibilities of extending the fatigue service life of welds made of conventional and high-strength steels

When using “regular” welding materials, the transition area (interface) between the weld and the base material develop residual tensile stresses in relation to the base material. Such stresses my even reach the yield point of the softer material used in the joint (weld metal/ base material). These stresses help initiate fatigue cracks and significantly reduce the fatigue service life of a given welded joint. Residual stresses can be reduced as early as during the process of welding, for instance, by using special LTT materials (LTT = low transformation temperature). These special materials have been enjoying growing popularity because of their applicability at the welding process stage as well as due to the fact that they eliminate the necessity of the addition treatment of welded joints. However, apart from the above-presented progressive method, there are many other post-weld treatment procedures extending fatigue service life. Post-weld treatment methods involving the application of similar principles enabling an increase in fatigue service life as those of the HFMI method have been known since the 1970s. Such methods are based on the improvement of geometry in critical areas of weld aimed to initiate the propagation of fatigue cracks and, at the same time, to adjust residual stresses in this area. The aforementioned methods include peening, shot blasting, rolling, restriking and, partly, the TIG method-based melting of weld edges. The primary advantage of the HFMI method in relation to the above-named processes is higher effectiveness in cases of high-cycle fatigue, high repeatability, better quality control and less demanding operation in terms of training and HSE-related requirements in everyday work. In addition, advanced models of HFMI equipment are significantly more compact than those made originally.

HFMI method

HFMI is an acronym covering a number of modifications related to the technology and including ultrasonic impact treatment (UIT), ultrasonic peening (UP) also known as ultrasonic peening treatment (UPT), high frequency impact treatment (HIFIT), pneumatic impact treatment (PIT) and ultrasonic needle peening (UNP). All of these processes involve the use of tools in the form of rollers or sets of rollers made of high-strength steels and having various diameters and shapes. Such tools are used as high-frequency (>90 Hz) vibrating indenters. The energy of the indenters induces the high plasticisation of a workpiece at the point of impact thus changing the material microstructure, local geometry as well as stresses in the treatment-affected area and its direct vicinity. The above-named technology was developed at the Arctic Centre of Tests and Technology in Severodvinsk (Russia) in conjunction with the E.O. Paton Electric Welding Institute from Kiev. Because of the growing popularity and increasingly large number of producers of these machines, the technology has seen its significant development over the past decade. Individual producers test the effect of various configurations, tool shapes and treatment intensity on properties of welded joints.

Fig. 4. HFMI machines and available tools

Taking into consideration significantly lower weight and quieter noise emitted by the device, the emphasis should be given to a more friendly operational procedure, e.g. in comparison with peening or restriking systems. Presently, advanced HFMI machines are not limited by HSE-related limitations in terms of noise and vibration. In addition, such devices can be operated by one person for the entire time of work. Because of the fact that advanced HFMI machines are characterised by higher frequency, the distance between individual indents performed by indenters is shorter and the path on the welding edge is smoother after treatment, affecting the quality and effectiveness of the treatment. A depth, at which the state of residual stresses undergoes transformation is restricted within the range of 1.5 mm to 2 mm. The schematic distribution of stresses in relation to the treatment affecting the base material and the edge of the weld is presented in Figure 5.

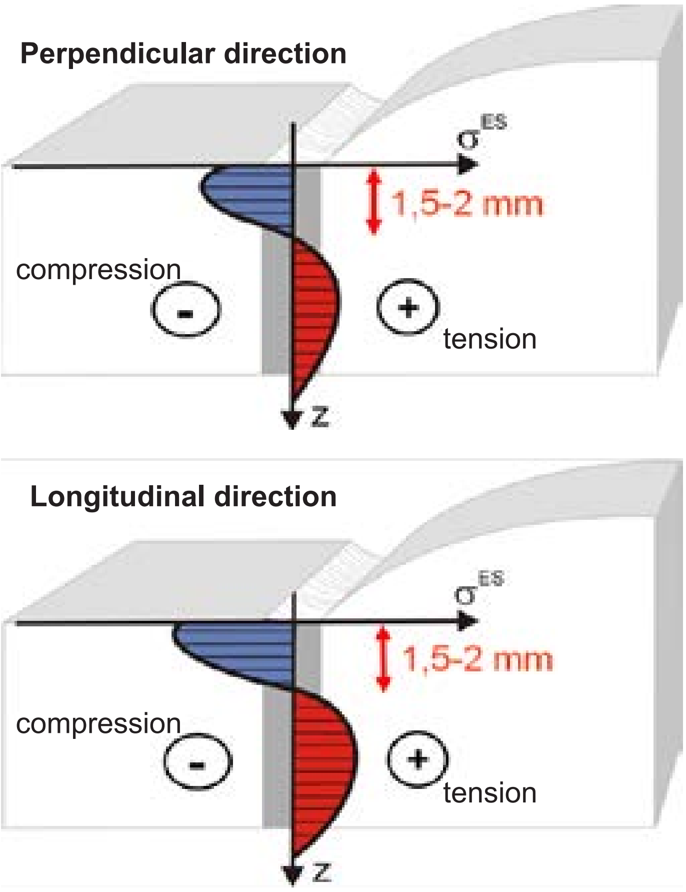

Fig. 5. Residual stresses generated by the HFMI treatment in the base material and in the edge of the weld [9]

It should be noted that all of the above-named HFMI-based methods can be used only for the modification of the edge of the weld. In certain cases of improperly made welded joints the critical area can be located in the root of the weld. In such cases it is not possible to increase the fatigue service life of the weld using the above-named methods. Available data concerning tests of welds subjected to the HFMI method-based modification were assessed by several authors. The most comprehensive information can be found in the doctor's dissertation by H. C. Yildirim [10]. The work presents results of individual tests and information found in other scientific publications. The test involved a total of 400 welded joints. Information concerning a number of tests in relation to types of welded joints is presented in Table 1.

Another complex research was performed within project RFCS FATWELDHSS [11], involving tests of welded joints subjected to constant and variable amplitude loads. The tests revealed that, in accordance with the IIW's convention, the method of nominal stresses enables the improvement of fatigue service life from class FAT 50 to FAT 90. The above-named restriction results from the fact that higher FAT classes also cover unwelded elements and elements, the fatigue service life of which does not result from damage to the edge of the weld or welds previously modified to increase their fatigue service life (e.g. welds subjected to milling). Welded elements representing classes lower than FAT 50 were not subjected to experimental tests. Such elements are characterised by higher risk of developing fatigue cracks on the root side and not (favourably) affected by the HFMI method. The results revealed that the HFMI method significantly extended the high-cycle fatigue service life in all of the tested cases (Figs. 6 and 7). In terms of steels having a yield point below 355 MPa, the HFMI effect improved the fatigue service life by four FAT classes. In cases of steels, the yield point of which exceeds 355 MPa, the effect of the HFMI method is demonstrated by one FAT class higher in relation to an

Table 1. Number of tests in relation to types of welded joints [10]

Weld/node	Type of load	Number of specimens	R	Thickness [mm]	Yield point [MPa]
Elongated	Extension	149	0.1…0.5	5…30	267…969
Cross-wire	Extension	68	-1…0.5	9.5…20	350…812
Butt	Extension	147	0.1…0.5	5…16	422…786
T-joint	Bending	53	0.1	5…20	420…960

increase of 200 MPa. In addition, data obtained on the basis of the tests revealed that the use of the HFMI method allows S-N curve inclination m = 5 instead of m = 3 for the post-weld state, which is manifested by a significant difference in fatigue service life in relation to cycles above $2\cdot10^6$ (as can be concluded from the S-N curves in Figure 8). Therefore, if an element originally classified as FAT 80 is subjected to the HFMI method, it will obtain a class restricted within the range of FAT 125 to FAT 180, depending on the fatigue strength of the base material.

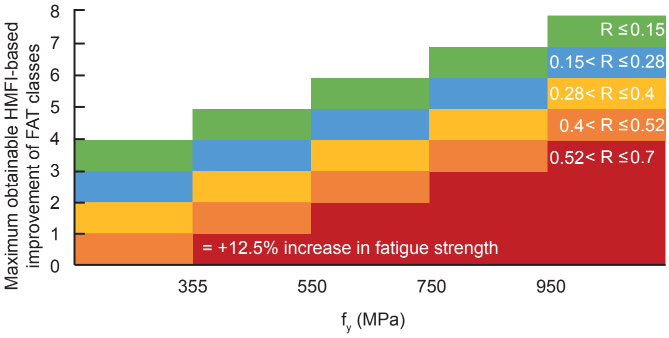

Fig. 6. Project concerning the improvement of FAT classes in relation to welded joints subjected to the HFMI method and various values of R

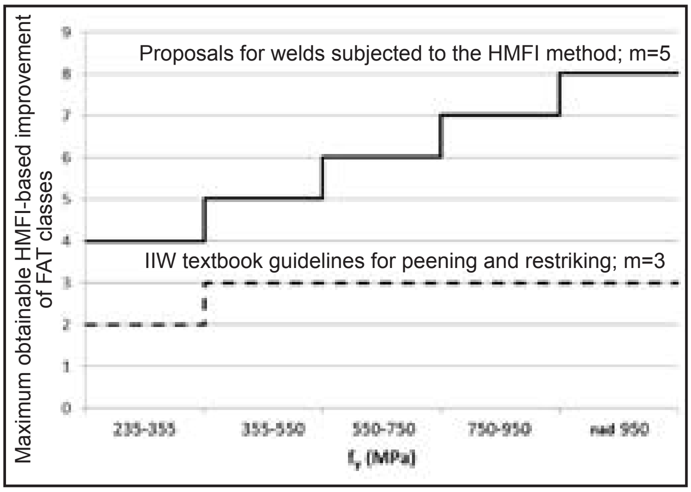

Fig. 7. Project concerning the improvement of FAT classes in relation to welded joints subjected to HFMI and R ≤ 0.15

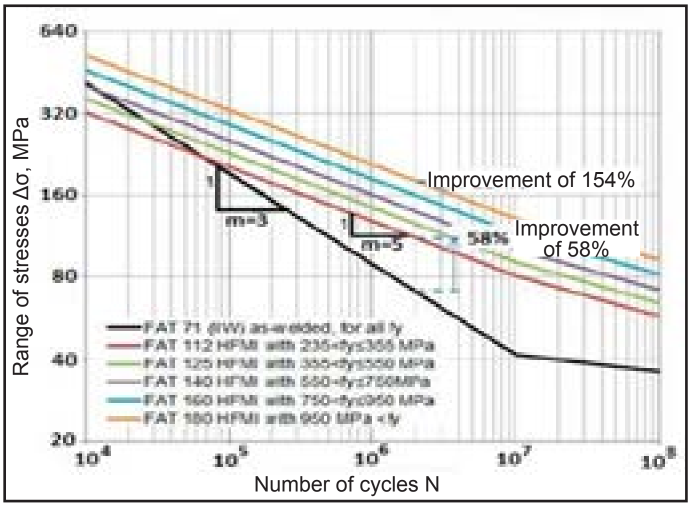

Fig. 8. S-N curves for welds of class FAT 71 in the base variant and after being subjected to the HFMI method in relation to various values of material strength R ≤ 0/15

The possibility of increasing the fatigue service life depends on residual stresses present at the critical point of the welds. In turn, residual stresses depend on relaxation and, consequently, the mean stress effect. The above conclusions concerning the improvement of fatigue strength-related calculation classes are based on tests where *R* = -1 to 0.1. In cases of loads characterised by higher values of mean stress expressed by higher value *R* it is recommended to reduce the improvement effect by the number of FAT classes in accordance with Tables 2 and 3.

Table 2. Reduction of FAT classes in relation to the mean stress

R	Minimum reduction of FAT classes
R ≤ 0.15	No reduction
0.15 < R < 0.28	Reduction by one FAT class
0.28 < R < 0.40	Reduction by two FAT classes
0.40 < R < 0.52	Reduction by three FAT classes
0.52 < R < 0.70	Reduction by four FAT classes
0.70 < R	No data, test-based verification required

As presently available test results are concerned with welded joints made of steels s235 through s960, thicknesses of which are restricted within the range of 5 mm to 50 mm, all of the recommendations can only be applied to the above-presented strength and thickness values. In addition, there are no sufficient results in relation to certain configurations of loads, particularly those characterised by higher mean stress and variable amplitude. If the maximum stress exceeds 80% of the yield point, the maximum load should be avoided because of the possible loss of the initial stress.

Table 3. IIW's FAT classes in relation to post-weld conditions and various additional modifications (recommendations for HFMI)

Re [MPa]	Longitudinal welds	Cross-wire welds	Butt welds
post-weld state, $m = 3$			
all Re	71	80	90
improved by peening or restriking, $m = 3$			
$Re \leq 355$	90	100	112
$355 < Re$	100	112	125
improved using HFMI, $m=5$			
$235 < Re \leq 355$	112	125	140
$355 < Re \leq 550$	125	140	160
$550 < Re \leq 750$	140	160	180
$750 < Re \leq 950$	160	180	-
$950 < Re$	180	-	-

Summary

The HFMI method is highly advanced and friendly when it comes to extending the fatigue service life of steel structures. Although the method can be used in relation to regular steel grades, it proves particularly advantageous in terms of high-strength steels, e.g. Strenx, Hardox etc. An important advantage of the method is the possibility of using it both in new and already existing structures, yet before the initiation of fatigue cracks. Test results concerned with welds enhanced using the HFMI method can justify a conclusion that when calculating the fatigue service life of welds it is possible to adopt the more gentle inclination of the S-N curves, i.e. $m = 5$ instead of $m = 3$ (as is usually the case with welds not subjected to modification or modified by means of peening or restriking). Because of the more gentle inclination of the S-N curve, the use of the modification and the "transfer" of the elements to a higher class, i.e. FAT, translates into significantly higher fatigue strength, particularly in relation to a high number of cycles, i.e. above $2 \cdot 10^6$. A more gentle (less steep) inclination of the S-N curve is related to, among other things, the higher reliability of results obtained when using the HFMI. According to some authors, in certain cases a more gentle inclination of the S-N curve could also be used in older methods, i.e. peening and restriking, yet the justification of these assumptions is prevented by the significantly greater scatter of measurement results, which is directly connected with the reliability of individual methods. Other unquestionable advantages of the HFMI method include the simple verifiability of the quality of implemented modifications, the possibility of providing fast training to personnel and the predictability of results. The above-presented facts justify suppositions that the HFMI method is going to become very popular when increasing the fatigue service life of welded structures. The potential of the method is also demonstrated by the list of existing implementations from load-bearing structures of wind power plants to bridges used in the automotive, ship-building and railway industries. Previously, the use of the method has been restricted to more sophisticated applications, the economic conditions of which enabled the performance of tests verifying the usability of the methods. Owing to the initiative undertaken by the International Institute of Welding and international community of researchers, in the second half of the year 2016 the principles governing the design of welds resistant to fatigue by means of the HFMI method were introduced to an IIW's handbook, significantly facilitating the use of the method by designers and estimators.

References:

[1] Marquis G.B., Barsoun Z.: IIW Recommendations for HFMI Treatment. IIW Collection. ISBN 978-981-10-2504-4, 2016.

[2] SSAB Design Handbook – kap. 5 – Fatigue Design, Ed. 1, 2012.

[3] Hobbacher A.F.: IIW Recommendations for Fatigue Design of Welded Joints and Components. IIW Collection ISBN 978-3-319-23757-2, 2008.

[4] Karlsson N., Lenander P.H.: Analysis of Fatigue Life in Two Weld Class Systems. Diploma Work , Linköping University,

Sweden, 2005.
[5] Hobbacher A., Kassner M.: On Relation Between Fatigue Properties of Welded Joints, Quality Criteria and Groups in ISO 5817. Welding in the World, 2011, vol. 56, no. 11-12, pp. 53–169, https://doi.org/10.1007/BF03321405.
[6] Marquis G.B.: Durability of advanced fabricated structures. Materialwissenschaft und Werkstofftechnik, 2011, vol. 42, no. 12, pp. 1050-1058, https://doi.org/10.1002/mawe.201100910.
[7] Internal standard of the Volvo company for assessments of weld quality in terms of fatigue service life. Volvo Group Standard 181-0004, 2008.
[8] Jonsson B., Samuelsson J., Marquis G.: Development of Weld Quality Criteria Based on. Fatigue Performance. Welding in the World, 2011, vol. 55, no. 11-12, pp. 79-88, https://doi.org/10.1007/BF03321545.
[9] Weich I.: Edge layer condition and fatigue strength of welds improved by mechanical post-weld treatment. Welding in the World, 2011, vol. 55, nos. 1-2, 3-12, https://doi.org/10.1007/BF03263510.
[10]Yildirim H.C.: Design aspects of high strength steel welded structures improved by HFMI treatment. Doctor’s dissertation, Aalto University (Finland), 2013.
[11] Research project Improving the fatigue life of high strength steel welded structures by post weld treatments and specific filler materials - FATWELDHSS. Research Fund for Coal and Steel (RFCS), 2015.