

A REVIEW OF THE RESEARCH ON HIGH FREQUENCY MECHANICAL IMPACT TREATMENT – PAST RESULTS, PRESENT STATUS AND FUTURE TRENDS



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1. ABSTRACT

High Frequency Mechanical Impact (HFMI) is a group of post-weld mechanical treatment methods applied for the prolongation of welded joints' fatigue life. Such methods have been deployed since the 70's in practice on new and existing mechanical components, but their consideration in the structural design was only recently regulated. Extensive experimental research in the last two decades regarding the effectiveness of the method has been the base for the establishment of new relevant design codes. Statistical analysis of numerous fatigue series led to the proposal of improvement factors for the fatigue strengths of HFMI-treated weldments during fatigue design. Integration of the method in Eurocode design codes is imminent, while no application of the method in the Greek industry is known to the authors of the present study. Therefore, the highlights of past research on HFMI are presented in the first part of the present paper. In the second part, current and future trends regarding ongoing research for the application of the method, such as studies regarding the numerical simulation of HFMI or more complicated experimental investigations, are discussed.

2. INTRODUCTION

The term High Frequency Mechanical Impact (HFMI) [1] refers to a group of post-weld hammer treatment methods such as the Ultrasonic Impact Treatment (UIT) [2], [3], the High Frequency Impact Treatment (HiFIT) [4], [5], the Pneumatic Impact Treatment (PITEC) [6], [7], [8] etc., the application of which leads to a significant enhancement of the weldments' fatigue life. The main principle of HFMI is common for all the relevant methods and includes the impact treatment, in other words hammering, of the welded

joints by a craftsman handling a device that accelerates one or more pins made of hard steel towards the weld toe (see Fig. 1). The weld toe is therewith plastically deformed, the geometrical weld notch effect is reduced and compressive RS (residual stresses), which counterbalance the detrimental tensile WRS (welding residual stresses), are introduced in the treated area. The difference between the various sub-methods lies in the design of each respective HFMI device and the applied accelerating mechanism. Each device has its own settings, which influence the impact energy and the frequency. These two along with the driving speed, the speed with which the craftsman drives the device along the weld toe, are the main treatment parameters that define the treatment intensity and can be measured in the laboratory for each device and treatment.

To the authors' knowledge, first documented application of hammer peening dates back to 1975 and the work of Statnikov et al. [3]. Although hammer peening was initially intended to be applied on the weldments of ship and submarine structures, after the evolution of HFMI it is applied on various mechanical components and civil engineering structures, which are prone to fatigue loads. Until recently the method was applied in the European construction industry under special approvals. Nonetheless, intensive experimental investigations for the quantification of fatigue strength enhancement in the last two decades led to the standardization of the method by the International Institute of Welding [1] in 2016 and more recently, in 2019, by the German Committee for Steel Construction (DAST) [9], while the integration of the method in upcoming revisions of EN 1993-1-9 is imminent.

In the present paper, a thorough review on the experimental investigations of the past decades is presented, while recent advances and future goals, regarding both numerical and experimental work are discussed.

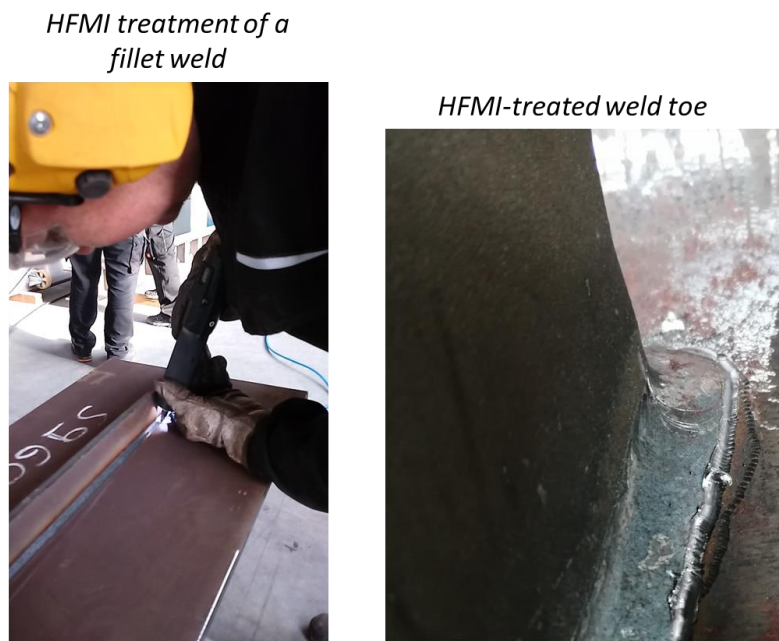


Fig. 1 The HFMI treatment of a fillet weld and a deformed, HFMI-treated weld toe [47]

3. PHENOMENOLOGICAL APPROACH - EXPERIMENTAL INVESTIGATIONS

The effectiveness of HFMI for the extension of fatigue life of welded joints has been thoroughly validated by numerous experimental investigations in the past. For the sake of space, a portion of these investigations are presented in the current review, the most representative according to the authors' view.

Numerous fatigue tests were carried out mostly on small-scale HFMI-treated fatigue test specimens and their estimated fatigue strength was compared with that of the as-welded ones (see for instance [8], [10] - [14] etc.). In many cases, a fatigue strength enhancement of more than 100 % and a prolongation of fatigue life in the upper high cycle fatigue regime of more than 10 times was documented. The fatigue life of HFMI-treated butt welds has been proven to be higher than that of parent material in several occasions [10], [12] etc. The effectiveness of the method was also investigated for different geometries, plate thicknesses and parent material, as these parameters can significantly influence the distribution of the RS introduced during welding and through the HFMI treatment: transversal and longitudinal stiffeners and hollow sections of various thicknesses were tested in [12], [13], [16], [17], [18], [19] and analogous significant fatigue life enhancement was met along. In most cases a significant increase of fatigue strength was documented, while the inverse slope m of the calculated SN curve of the HFMI-treated specimens was larger than 5 ([10], [12], [16], [20] etc.). This meant that the increase of fatigue life was even more predominant in the right region of the high cycle fatigue regime, close to the endurance limit (2×10^6 to 5×10^6 load cycles). Tests on specimens made of S355, S690, S910, S1100 and S1300 ([10], [11], [12], [18], [21], [22] etc.) have shown a positive effect of the increased yield strength on the HFMI effectiveness. This confirmed initial expectations that the higher magnitude of introduced compressive RS by the HFMI treatment of high strength steels would act positively in comparison to that of mild structural steels.

All the above have revealed quite early the effectiveness, straightforwardness and reproducibility of the method and even its applicability on existing structures [23]. A thorough review of the experimental work up to 2013 was presented in [24], where clear tendencies based on evaluation of several fatigue tests regarding the fatigue strength enhancement for the major welded details were shown. At that point it was becoming clear that fatigue strength improvement factors could be established for each welded detail based on its as-welded fatigue strength, considering as well the influence of the material's yield strength. Such improvement factors based on the classification of as-welded joints by IIW recommendations [25] and Eurocode 3 [26] were proposed in [27], [28], [29] and [30] and set the background for drafting the recommendations for the application of HFMI. Prior to the establishment of design codes though, the stability of the introduced compressive RS, with respect to peak loads near the material's yield limit, had to be ensured. As the compressive stresses introduced by HFMI are contributing to the fatigue strength enhancement, service loads near or above the yield limit of the structure could cause a relaxation and/or redistribution of the introduced RS profiles and in extension lead to an increase in fatigue strength smaller than expected. Different ranges of loads that can be applied without risking the stability of the introduced RS have been documented in [31], [32], [33] and quite recently in [34]. In the last one, the stability of the RS even for tensile loading close to 90 % of the real yield limit was confirmed, as minor relaxation was observed for S355 and S960 specimens. For compressive loading at such levels tough, significant RS relaxation was observed for the S960 specimens. Based on such investigations from the above-mentioned sources, the DAST-Guideline recommends that the applied stress ranges and the compressive and tensile loads should not exceed 150 %, 80 % and 100 % of the yield limit respectively.

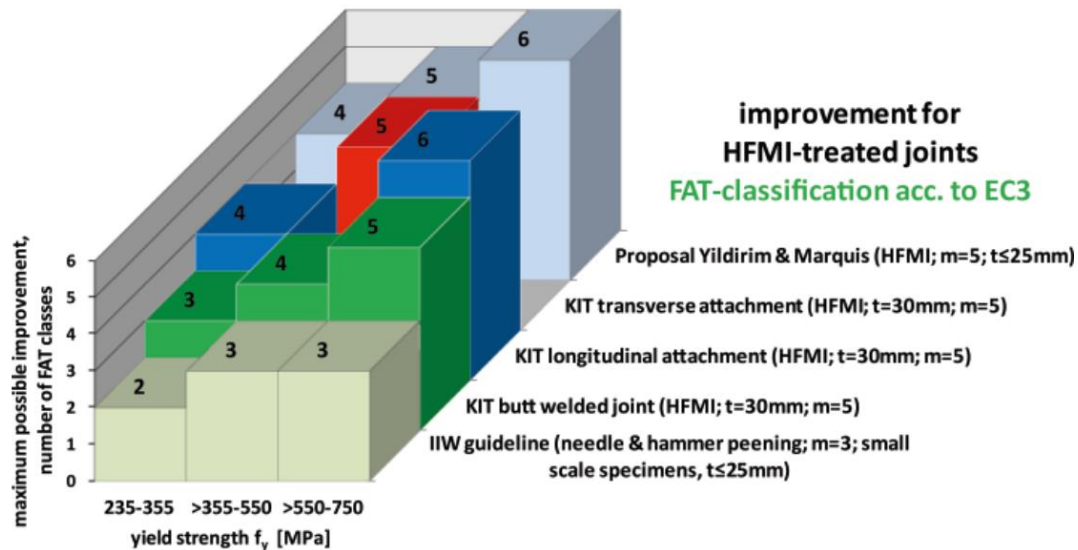


Fig. 2 Improvement in number of FAT classes for HFMI-treated joints based on the FAT classification of Eurocode 3 proposed by Ummenhofer and Weidner [29]

4. INTERGRATION IN DESIGN CODES

Based on the extended experimental investigations of the previous decades, Marquis and Barsoum drafted in 2015 the International Institute of Welding (IIW) recommendations for the application of HFMI [1]. Therewith, the fatigue strength of a HFMI-treated welded joint is predicted based on the weldment's fatigue strength at the as-welded state (see [25]), the applied load and the weldment's material, while size and thickness effects are as well considered. Design recommendations for the cases of the nominal stress approach, the structural hot-spot stress approach and the effective notch stress approach are provided. As for the case of as-welded structural details, the fatigue strength of the HFMI-treated weldments is given in FAT classes (each FAT class is characterized by the fatigue strength at 2×10^6 load cycles). Moreover, guidelines for the appropriate application and the quality control of HFMI was included in the drafted recommendations. A slope $m = 5$ is recommended for the FAT curves of all HFMI-treated weldments.

In the same spirit, the DAST Guideline 026 for the application of HFMI [9] was drafted by the German Committee for Steel Construction (DAST) in 2019, in order to regulate the application of the method in the German construction branch. Once again, guidance for the proper application of the method is provided and a slope of $m = 5$ for the FAT curves of the HMI-treated weldments is recommended. Nonetheless, discrepancies between the two guidelines are met as well. The DAST Guideline 026 acknowledges only the HiFIT, PITEC and UIT devices as part of the HFMI method, as according to the same guideline, sufficient experimental data had been provided only for those. This was in contrast with the IIW Recommendations, where more hammer devices are acknowledged as part of the HFMI method. Another significant difference between the DAST Guideline 026 and the IIW recommendations lies in the range of application, as the former is valid only for three common welded details, the butt weld, the transverse and the longitudinal stiffeners, and for structural steel grades with yield strength from 235 MPa up to 700 MPa, while the latter one refers to all weldments whose as-welded state is regulated in [25] and even for high strength steels with yield strength higher than 950 MPa (with no upper limit defined). Different definitions of the maximum allowed applied load, are given as well by the two guidelines, while only the nominal stress approach is considered in the DAST guideline.

5. CURRENT STATUS AND FUTURE TRENDS

Numerical Investigations

In the last years, interest in numerical modelling of HFMI increased significantly. Although the experimental investigations have been crucial for validating HFMI's efficiency and establishing the above-mentioned design recommendations, they were mostly empirical. Apart from RS measurements on the HFMI-treated weld toe, the rest of the experimental procedures provided no insight in the physical processes that take place during the HFMI treatment and/or the fatigue loading of the HFMI-treated specimens. On the contrary, validated numerical models could offer such an insight, for instance regarding the material behavior during the HFMI treatment or the effectiveness for local variations of the notch geometries. Moreover, numerical modelling could be a valuable alternative to the costly fatigue tests, as the previous experimental verification of the method's efficiency had required yearlong tests. If the existing guidelines should be extended to new materials or geometries, experimental investigations could be partially substituted by numerical ones. Numerical simulation of HFMI coupled with weld simulation could predict the final RS field and therewith, enable a prediction of the HFMI-treated component's fatigue life. Hence, an improvement of the HFMI devices or selection of more suitable treatment parameters and a less conservative consideration of the fatigue strength enhancement during design could as well be enabled through numerical modelling of the treatment.

Some numerical investigations of HFMI had been carried out in the previous years, parallel to the above-mentioned experimental investigations (see [10], [35], [36], [37], [38], [39], [40], [41], [42], etc.), which could provide some first conclusions regarding modelling of HFMI and the possibilities it enables. Nonetheless, they partially or completely neglected significant aspects of the simulation. During HFMI, multiple impacts take place and several cycles of material deformation under significant speed occur. Appropriate material modelling has to be undertaken, considering material laws suitable for cyclic plasticity and high strain rates. Additionally, accurate modelling of the HFMI pin's kinetic energy and the coverage between consecutive impacts have to be considered by a simulation model, for its results to be considered valid. Of course, prior to all these, an accurate simulation of the WRS is required [45], so that it can be applied as input for the subsequent HFMI simulation.

All, these aspects were considered in more recent numerical investigations of HFMI, [46], [47], [48], [49], [50]. Especially in [47], [48], [49], where the treatment of both parent material and weldments was investigated, material modelling, modeling the impact energy of the HFMI pin and the significance of considering the RS field at the weld toe prior to the HFMI treatment introduced by welding and other manufacturing processes were thoroughly discussed. Moreover, the results of these numerical investigations were validated by comparison with RS measurements on real components. Practical aspects of HFMI modelling are presented in [48], while first-step investigations to predict the fatigue life of the HFMI-treated weld toes based on the HFMI simulation results have been presented in [45]. Only minor shortcomings were met during these investigations, mostly due to computational capacity restrictions. For instance, the HFMI treatment was modelled for some mm of the real weldment's length (Fig. 3), even when supercomputing capabilities were deployed (see [48]). Based upon though, safe conclusions could be drawn for the real weldment due to the local nature of the treatment.

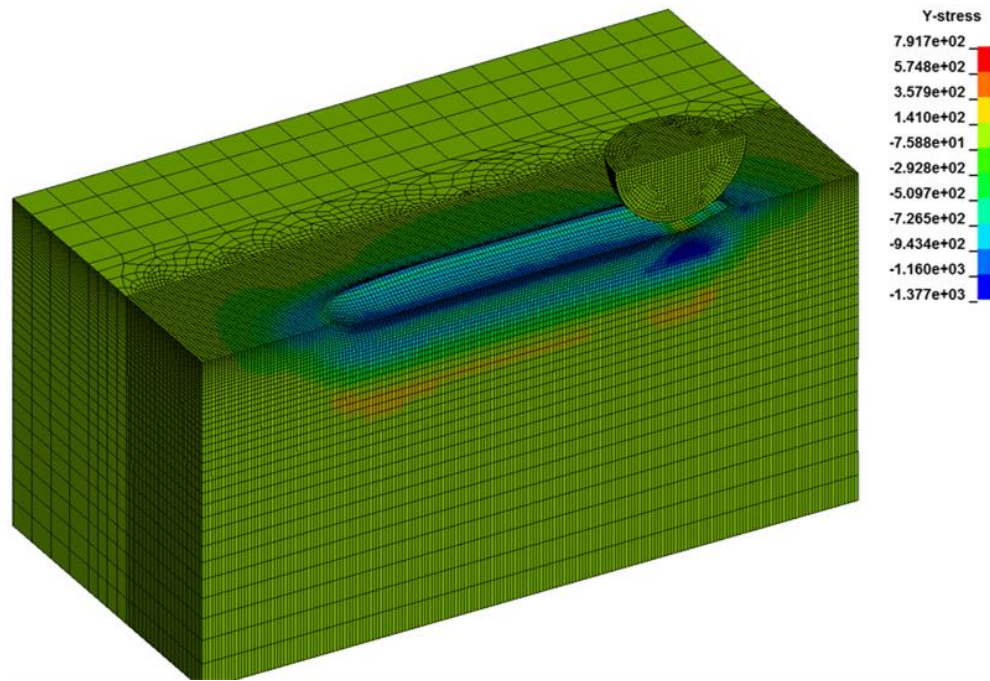


Fig. 3 FE Simulation of the HFMI treatment of a specimen of parent material [48] – longitudinal stresses (y-stresses, i.e. parallel to the direction of travel) in MPa – only the tip of the HFMI pin is simulated, symmetry conditions considered

It is expected that in the upcoming years, the results of the recently validated models will enable an optimization of the HFMI application, for maximizing the potential fatigue life gains through appropriate selection of HFMI treatment parameters. They may as well contribute to the successful introduction of HFMI in production chains containing multiple manufacturing steps, as in the case of offshore wind turbines. Such possibilities are already investigated in an ongoing research project [50]. Improvement of computational methods and increase in computational power in the future may enable the simulation of the HFMI treatment on larger components.

Experimental Investigations

Experimental investigations have been ongoing as well in the last years, nevertheless under different and more complicated testing conditions in comparison to the past investigations. Increased interest has been expressed by the offshore industry for a possible application of HFMI in the production chain of offshore wind energy turbines [50], [51], for which fatigue design is predominant [52]. Questions have arisen though, regarding the influence of corrosion on the effectiveness of HFMI. More specifically, it was not clear whether the corrosion of a HFMI-treated weld toe, which leads to removal of the material's upper surface layers, would possibly cause a redistribution of the RS fields, limiting in this way the fatigue strength enhancement.

Of course, in practice the weldments of offshore wind turbines should be coated and protected from corrosion, while frequent inspection intervals are already recommended [52], [53]. As coatings can fail unexpectedly though, the corrosion fatigue behavior of uncoated common HFMI-treated weldments has been investigated in recent studies in the laboratory (see Fig. 4A), for corrosion exposure corresponding to the inspection intervals of the offshore wind turbines in [51], [54], [55] and [56]. Promising results, showing in most cases negligible limitation of the fatigue strength enhancement was documented for laboratory corrosion equivalent to short-term marine corrosion.

For the integration of HFMI in the production chain of offshore wind turbines though, more aspects have to be clarified in the upcoming years. For instance, the influence of surface preparation treatments necessary for the proper adhesion of coatings, on the stability of the introduced compressive RS field, or the influence of the HFMI trace on the coatings' adhesivity and mechanical performance have to be tested. Such investigations are currently carried out in the framework of [50].

Other aspects to be investigated in the upcoming years, would be the influence of HFMI on the fatigue strength of real size components, where more complex weldments and multiple locations of possible fatigue crack initiation are met [57] (see Fig. 4B and 3C), or as part of a repair procedure for existing structures, on which fatigue cracks have already occurred [58]. For the former case, as the majority of the past investigations has been carried out on small-scale fatigue test specimens scaling effects could be possible. Few recent investigations (see [57]) show positive results, as real size HFMI-treated specimens exhibit comparable fatigue life to the small-scale ones, while potential for even higher fatigue strength enhancement is shown in their case, if other manufacturing issues that restrict the fatigue life can be solved.

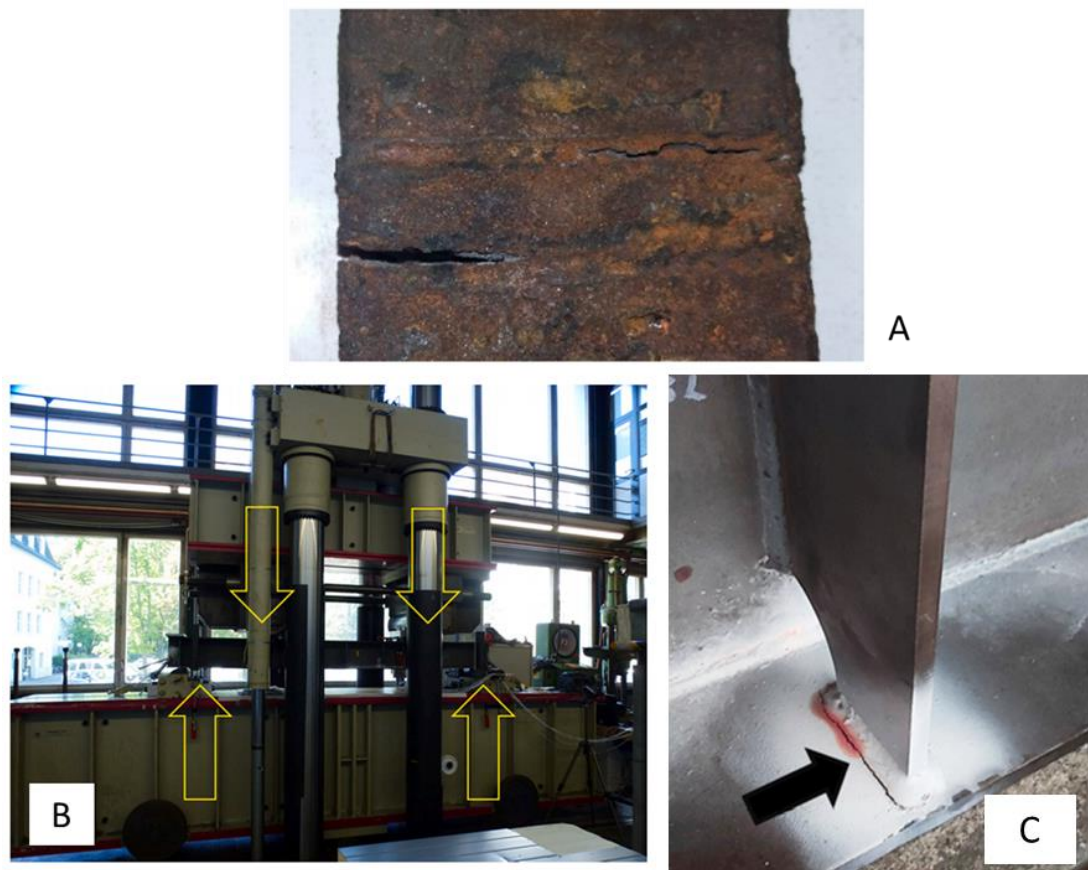


Fig. 4 A: Butt weld with fatigue cracks, corroded in laboratory and subsequently dry tested [51] – B: 4-point bend test of real size welded HEA 260 beam with welded transverse stiffeners at the KIT Steel and Lightweight Structures, the arrows show the locations of support and load bearings [47]– C: Fatigue crack on the HFMI-treated weld toe of a transverse stiffener welded on a HEA 260 beam made of S690QL tested under 4-point bending [47]

Quantifying treatment intensity

As it was mentioned above, each HFMI device has its own settings that directly influence the treatment's intensity. Experiments have been carried out in the laboratory, which correlated the device settings for HiFIT and PITEC with measured intensity, i.e. treatment frequency and impact speed [47]. However, this correlation itself could not enable a direct comparison of the treatment intensity between hammering with different devices. This obstacle was overcome, with the introduction of the quantity of applied kinetic energy $E_{95\%}$ in [59], [60], which is a function of the impact velocity perpendicular to the treated surface, the impact frequency, the number of indenters carried by the applied device, the treatment length and the number of treatment passes.

Automatization of the method

HFMI device manufacturers make efforts in the recent years towards the automatization of the method, analogous to robotic welding. With the procedure expected to be completed in the next few years, HFMI treatment parameters can be re-optimized, exploiting new possibilities offered by the automated treatment.

6. SUMMARY

The research regarding the post-weld treatment method High Frequency Mechanical Impact is reviewed in the current study. Past experimental research, which led to the standardization of the method, along with an overview of the existing guidelines is presented. Moreover, current trends of the recent years' research are highlighted, while future steps to be taken in the upcoming years are discussed. To summarize:

- The high efficiency of HFMI has been proven in the past through extensive experimental work by several researchers. The effectiveness of the method on various weldment geometries, steel grades, wall thicknesses has been validated.
- These extensive experimental investigations led to the recommendation of empirical improvement factors for the consideration of the fatigue strength enhancement during the design of HFMI-treated weld details based on their as-welded fatigue strength, as it was predicted by existing respective design guidelines. These improvement factors were subsequently adopted in design recommendations regarding the application of HFMI, along with guidelines for the proper application and quality control of the procedure.
- In the recent years, validated numerical models for the simulation of HFMI, considering all physical phenomena with the required accuracy, have been published. Main goal of these models is the accurate estimation of the RS fields introduced by HFMI, so that the numerical estimation of the fatigue life of HFMI-treated specimens will be enabled in the upcoming years.
- Experimental work in the recent years focused mainly on the integration of HFMI in the production chain of offshore wind turbines, which is expected to be further investigated in the upcoming years.

Finally, automatization of the method is currently under development by manufacturers of HFMI devices, which aim for a wider integration of HFMI in further production chains.

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ΑΝΑΣΚΟΠΗΣΗ ΤΗΣ ΕΡΕΥΝΑΣ ΣΧΕΤΙΚΑ ΜΕ ΤΗΝ ΜΕΘΟΔΟ ΜΗΧΑΝΙΚΗΣ ΣΦΥΡΗΛΑΤΗΣΗΣ ΥΨΗΛΗΣ ΣΥΧΝΟΤΗΤΑΣ – ΠΡΟΤΕΡΑ ΑΠΟΤΕΛΕΣΜΑΤΑ, ΠΑΡΟΥΣΑ ΚΑΤΑΣΤΑΣΗ ΚΑΙ ΜΕΛΛΟΝΤΙΚΕΣ ΤΑΣΕΙΣ

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Περίληψη

Ο όρος Μηχανική Σφυρηλάτηση Υψηλής Συχνότητας (ΜΣΥΣ) αναφέρεται σε ένα σύνολο τεχνικών βελτίωσης των συγκολλήσεων, η εφαρμογή των οποίων έχει ως αποτέλεσμα την σημαντική επέκταση του χρόνου ζωής των συγκολλητών συνδέσμων. Πρώιμες μορφές της μεθόδου εφαρμόζονται ήδη από την δεκαετία του '70 σε νέα και υπάρχοντα στοιχεία μηχανών, αλλά η εισαγωγή τους σε κανονισμούς σχεδιασμού των κατασκευών πραγματοποιήθηκε μόλις πρόσφατα για πρώτη φορά. Εκτενής πειραματική έρευνα στις δύο προηγούμενες δεκαετίες, η οποία απέδειξε την αποτελεσματικότητα της μεθόδου, αποτέλεσε την βάση για την συγγραφή των άνωθεν κανονισμών. Η στατιστική αποτίμηση πολυάριθμων αποτελεσμάτων δοκιμών κόπωσης είχε σαν αποτέλεσμα τον υπολογισμό συντελεστών βελτίωσης ώστε να ληφθεί υπόψιν η αντοχή σε κόπωση των βελτιωμένων με ΜΣΥΣ συγκολλήσεων κατά τη φάση σχεδιασμού. Καθώς πρόσφατα ξεκίνησε η συζήτηση για την ενσωμάτωση της μεθόδου στις ερχόμενες αναθεωρήσεις του Ευρωκώδικα και καμία εφαρμογή της μεθόδου στον ελληνικό κατασκευαστικό κλάδο δεν είναι γνωστή στους συγγραφείς της παρούσας εργασίας, τα σημαντικότερα στοιχεία της παρελθούσας έρευνας σχετικά με την ΜΣΥΣ παρουσιάζονται στο πρώτο μέρος της παρούσας εργασίας. Επιπλέον, παρούσες και μελλοντικές τάσεις της έρευνας σχετικά με την μέθοδο τίθενται υπό συζήτηση στο δεύτερο σκέλος, όπως για παράδειγμα η προσομοίωση της ΜΣΥΣ με αριθμητικές μεθόδους, ή πιο περίπλοκες πειραματικές δοκιμές.