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High-Frequency mechanical impact treatment of welded joints

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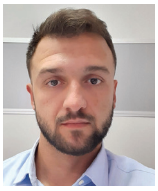

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Subject review

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In welded structures, fatigue damage often occurs in welds, which are the points of geometrical and material discontinuity. Accordingly, post-weld treatment methods have been developed. One of the relatively new methods is the high-frequency mechanical impact treatment. The method is characterised by the change in weld geometry, local increase in hardness, and elimination of residual stresses generated by the welding process. An overview of this method is provided, and areas requiring further consideration are highlighted.

Key words:
welded joints, fatigue, post-weld treatment, HFMI

Pregledni rad

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Obrada zavarenih priključaka metodom mehaničkog udara visokom frekvencijom

Kod zavarenih konstrukcija, oštećenja umorom najčešće nastaju na mjestima zavara, koji predstavljaju geometrijske i materijalne diskontinuitete. Zbog toga su razvijene metode obrade zavara nakon zavarivanja. Jedna od relativno novih metoda obrade je metoda mehaničkog udara visokom frekvencijom. Ta metoda utječe na promjenu geometrije zavara, lokalno povećanje tvrdoće te uklanjanje nepovoljnih zaostalih naprezanja nastalih procesom zavarivanja. U radu se daje pregled navedene metode te se ističu područja koja zahtijevaju dodatna razmatranja.

Ključne riječi:
zavareni priključci, umor, obrada zavara nakon zavarivanja, HFMI

Übersichtsarbeit

Boris Fuštar, Ivan Lukačević, Darko Dujmović

Bearbeitung von Schweißverbindungen mittels der mechanischen Hochfrequenzmethode

Bei verschweißten Konstruktionen entstehen Ermüdungsschäden am häufigsten an den Schweißnähten, die eine geometrische und materielle Diskontinuität darstellen. Deshalb wurde die Bearbeitungsmethode der Schweißnaht nach dem Schweißen entwickelt. Eine der relativ neuen Bearbeitungsmethoden ist die mechanische Hochfrequenzmethode. Diese Methode beeinflusst die Geometrie der Schweißnaht, die lokale Erhöhung der Härte sowie die Beseitigung der ungünstigen Restspannung, die durch den Schweißprozess entsteht. In der Abhandlung wird eine Übersicht der angeführten Methode gegeben und hebt Bereiche hervor, die zusätzliche Betrachtungen erfordern.

Schlüsselwörter:
Schweißverbindung, Ermüdung, Bearbeitung der Schweißnaht nach dem Schweißen, HFMI

1. Introduction

Fatigue is a progressive and localised process of damage accumulation in material due to prolonged, periodically varying loads, i.e. stresses. The magnitude of variable stresses is below the material yield strength. The useful life of a structural element subjected to fatigue consists of a period of crack initiation from the element surface, and a period of crack propagation until failure (Figure 1). More information on the fatigue mechanism can be found in [1].

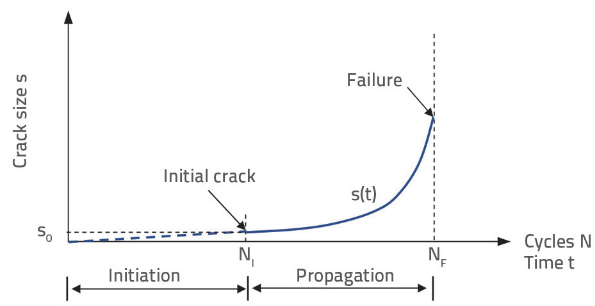


Figure 1. Crack development with the number of load cycles

Fatigue usually occurs at places of high-stress concentration such as welds, which are the points of geometric and material discontinuities within the structure. Welding is a complex metallurgical process that results in irregular geometry, imperfections within the material, and residual stresses in the weld area. Geometric and material discontinuities significantly reduce the fatigue life of welds and, in particular, the period of crack initiation [2-5]. From a material discontinuity of microscopic size, the crack can begin to expand already with the first load cycle. Even though welds are critical locations in fatigue loaded structures, welding is nowadays the most widely used and frequent method of joining cyclically loaded steel structures such as steel bridges. The fatigue problem becomes even more significant in the case of high-strength steel. By using high-strength steel, it is possible to reduce element dimensions and structure weight, resulting in a much more significant impact of the variable load portion that causes fatigue damage. Namely, the fatigue resistance of as-welded joints does not depend on the steel strength of joining materials. Leading parameters are mainly the global and local joint geometry. Therefore, increasing the yield strength of steel does not increase fatigue resistance of the welded joint. For this reason, the fatigue criterion becomes a leading design problem of cyclically loaded steel structures and is therefore crucial for selecting element dimensions such as thicknesses of plates, stiffeners, welding processes, and other geometrical parameters.

In the light of the above mentioned, the fatigue resistance of welded structures is still one of the leading research topics [6]. In order to increase the fatigue resistance of the structure, it is necessary to use joints with a lower stress concentration factor, predict welds in lower-stress areas, select the material and the welding process properly, etc. There are numerous standards and guidelines that facilitate the design of steel structures from the aspect of fatigue [7-11]. Methods aimed at solving fatigue issues in structures also include increasing the frequency of inspections to detect damage, limiting load imposed on structures, and strengthening or replacing structural members. In some cases, holes are drilled in crack notches to reduce stress concentrations and hence to increase fatigue resistance of the joint.

However, in some cases, the fatigue resistance of welded joints cannot be achieved with the aforementioned recommendations and standards. That is why Post Weld Treatment (PWT) methods have recently been developed. These methods eliminate imperfections, improve the geometry of the weld, and eliminate adverse tensile residual stresses generated by the welding process by introducing compressive residual stresses [12]. Further improvements in the fatigue resistance of welds are thus achieved [6], Figure 2. In this way, full utilisation of high strength steel (f_y > 355 MPa) is made possible. Treatment methods can be applied immediately after welding or during service life (rehabilitation of existing structures). For existing structures, this can be very effective since all the stresses from permanent loads have already been imposed before application of PWT methods [13]. Detailed information and recommendations for steel and aluminium structures can be found in the IIW guidelines [14].

Fatigue resistance of welded details depends on the initial size of weld imperfections from which the crack propagates [15]. Post weld treatment methods eliminate geometric and material imperfections and extend the period of crack initiation over the overall fatigue life of the steel detail (Figure 2) [6]. PWT methods are simple and effective methods that in some cases, due to different limitations, become the only way to improve fatigue resistance.

PWT methods can be divided into two groups. In the first group, the weld toe is modified to reduce stress concentrations by

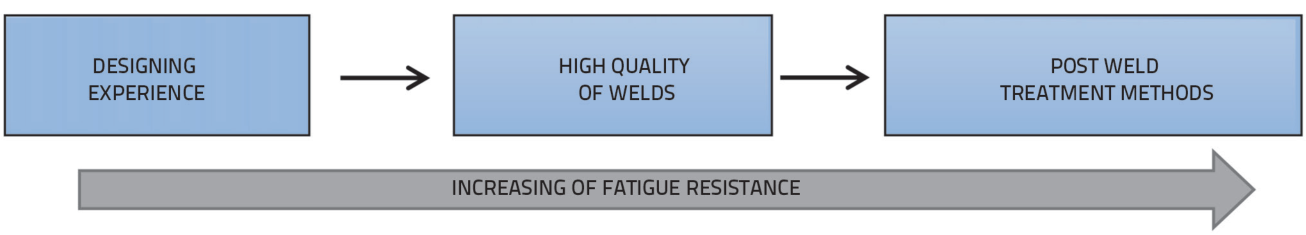


Figure 2. Method for reaching high fatigue resistance

providing smoother transition between the weld face and the elements that are being joined. Such procedure extends the crack initiation period of the details. The best known methods in this group are the TIG dressing and burr grinding. These methods are explained in greater detail in the literature [16-18]. n the second group, residual stresses are modified, thus eliminating adverse tensile residual stresses generated by the welding process. These methods are also used to modify the weld toe and reduce stress concentrations, similarly to the methods belonging to the first group. The most popular methods of this group are the shot peening, hammer peening and the most recently developed and increasingly used method of mechanical treatment at high frequency, the so-called HFMI (High-Frequency Mechanical Impact) method [6, 14]. An overview of the weld toe improvement possibilities offered by the mentioned improvement methods is given in Figure 3 [14].

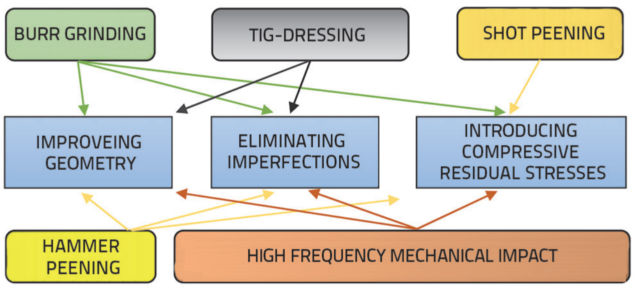


Figure 3. Weld improvement possibilities by improvement method

This paper considers the HFMI (High-Frequency Mechanical Impact) method, which is classified as a method for modifying residual stresses, but also modifies the local geometry of details and locally influences the increase in the hardness and yield stress of material at the weld toe [19].

2. High-frequency mechanical Impact method

The High-Frequency Mechanical Impact (HFMI) method is a relatively new and effective group of post welding treatments that is nowadays becoming increasingly popular and widespread [6, 14]. The application of the HFMI method can be traced back to the former Soviet Union [[20, 21].Despite its many positive effects, the implementation of this method on large structures has been relatively slow. The HFMI method includes various procedures such as the "Ultrasonic Peening Treatment" (UPT) [22, 23], "Ultrasonic Impact Treatment" (UIT) [23-25], "High Frequency Impact Treatment" (HiFIT), "Ultrasonic Peening" (UP), "Pneumatic Impact Treatment" (PIT) [26], and "Ultrasonic Needle Peening" (UNP) [27]. The HFMI method extends the fatigue life of details by up to 18 times compared to untreated details [6]. HFMI improvements show the best results in details exposed to a large number of stress changes, and the application of HFMI treatment in the design of new structures can reduce the self-weight of structures and increase their reliability [28].
Over the last ten years, a large number of commercial HFMI devices have been developed, and their number continues to increase. Ultrasonic and pneumatic devices typically consist of energy sources and tools with indenters of various shapes. The indenters are made of high-strength steel and manufacturers have developed the shape over time to maximise the effect. Figure 4 shows an example of an HFMI device and indenters of various shapes [12].
The principle of HFMI device is that the energy source drives piezoelectric elements, ultrasonic magnetostrictive elements, or compressed air with high frequency. Cylindrical heads alternately accelerate and strike the component of the structure (weld toe) at high frequency (> 90 Hz). The positive effect results from the impact energy at each stroke determined by the velocity (frequency) and moving mass [12]. Figure 5 shows the untreated weld and weld after HFMI treatment.
During treatment, the material is locally plastically deformed, causing changes in microstructure of the material and in local geometry of the weld toe. Compressive residual stresses are also introduced, thereby reducing the residual tensile stress, which further increases the fatigue resistance of the welded detail [29]. Due to plastic deformation (cold forming of the material), the impact of the indenter results in strain hardening of the material, which locally increases the yield strength and fatigue resistance of the weld toe [30]. The interaction of these improvement parameters has not yet been fully investigated and is not adequately quantified. HFMI procedures for welded

Figure 4. Example of HFMI devices and various indenters [12]

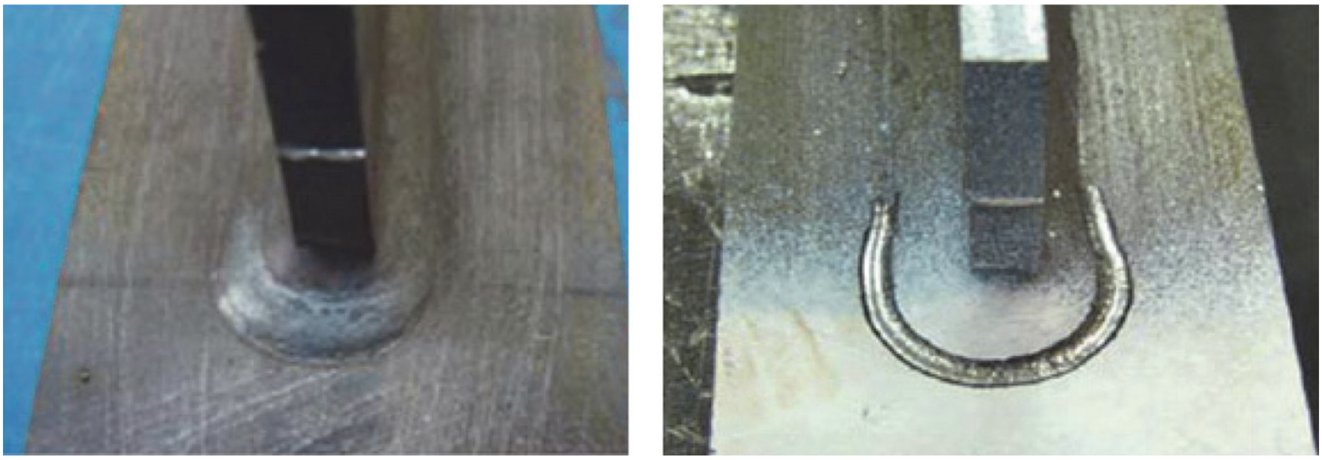


Figure 5. Untreated weld (left) and angle weld after HFMI Treatment (right) [12]

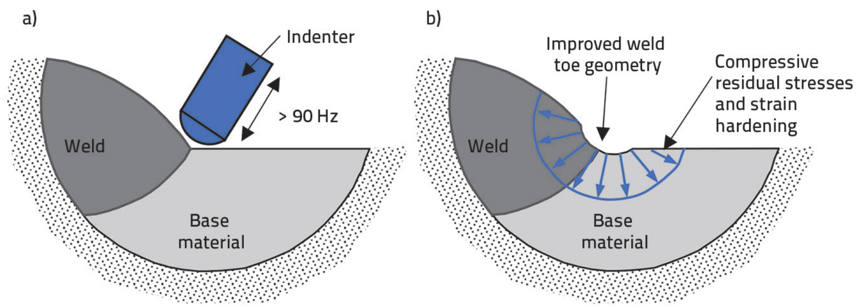


Figure 6. a) HFMI processing b) parameters influencing improvement of fatigue resistance

details significantly extend the crack initiation period (by increasing the required number of cycles to crack initiation), which is neglected in untreated welds [31]. fter the crack grows outside the HFMI treatment zone, the residual crack growth life is similar to that of the untreated details [30]. The positive effect of HFMI treatment on the weld toe is shown in Figure 6.

The HFMI treatment can only be applied if a fatigue crack occurs at the weld toe. In the case of crack initiation at the root of the weld, the HFMI treatment is ineffective. After the weld toe treatment, it is possible to change the critical failure mode of the welded detail to the crack initiation at the weld root or from defects in the base material. In this way, the desired increase in fatigue resistance will not occur [32, 33]. For example, the HFMI treated and as-welded details of cover plates were considered in paper [34]. It was observed that the cracking of treated details sometimes occurs at the root of the treated weld, while in case of as-welded details it occurs at the weld toe. Therefore, when welding treatment is planned, welds that are not susceptible to crack initiation at the root should be applied, as indicated in relevant literature [12]. Improvements in welded details that are susceptible to crack initiation at the root should be further verified by experimental or numerical analyzes [12]. Guidelines for the implementation of HFMI treatment, quality control, and evaluation of fatigue life improvement using nominal stresses, hot spot stresses, and effective notch stress, are given in [12].

Although, in the past, HFMI was only used for the repair of the existing structures, today it has become a part of the industrial process applied for new structures. Due to an increase in commercial applications, the need is currently felt to standardise the HFMI treatment process and the fatigue resistance assessment methods [12, 35]. Better understanding of all the parameters and limitations that affect the fatigue resistance improvement level is the basis for the development of the HFMI guidelines for fatigue life assessment. Parameters that influence improvement of fatigue resistance of the HFMI treated welded details are described.

3. Parameters influencing fatigue resistance improvement by HFMI method

3.1. Weld toe geometry improvement after treatment

Weld constitutes a sudden change in the geometry of the joint that causes high-stress concentrations, as shown in Figure 7. The stress concentration is defined by the stress concentration factor K_t. The highest concentration occurs at the weld toe, which is therefore the most likely place of fatigue failure. The smaller the notch radius, the higher the stress concentration and, ultimately, the shorter the fatigue life. HFMI procedures improve geometry by increasing the radius of the weld toe $r_2 > r_1$.

Increasing the radius of the weld toe ensures a "smoother" transition between the weld face and the welded plate, thus reducing stress concentration and increasing fatigue resistance. In order to obtain a uniform geometry along the weld, three passes of the HFMI device over the weld toe are considered optimal [36]. For numerical calculation of untreated welds, a radius of weld toe of r = 0,25 mm can be assumed [37, 38], while

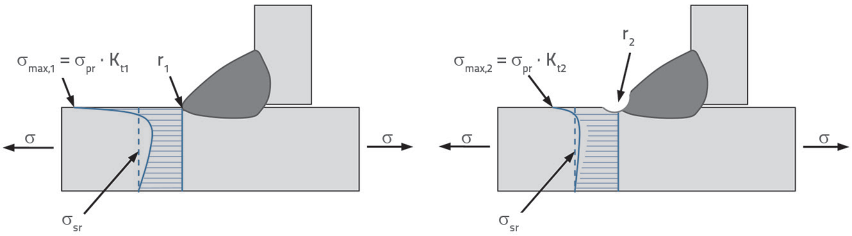


Figure 7. The stress concentration at the weld before and after HFMI treatment ($\sigma_{max,1} > \sigma_{max,2}$), where K_{t1} and K_{t2} are the stress concentration factors, and r_1 and r_2 are the weld toe radii

in case of the HFMI treated weld a radius of r = 3,3 mm (0,2 mm deep and 3,8 mm wide) can be assumed [39]. These numbers are also within the range of dimensions suggested in the HFMI treatment guidelines [31].

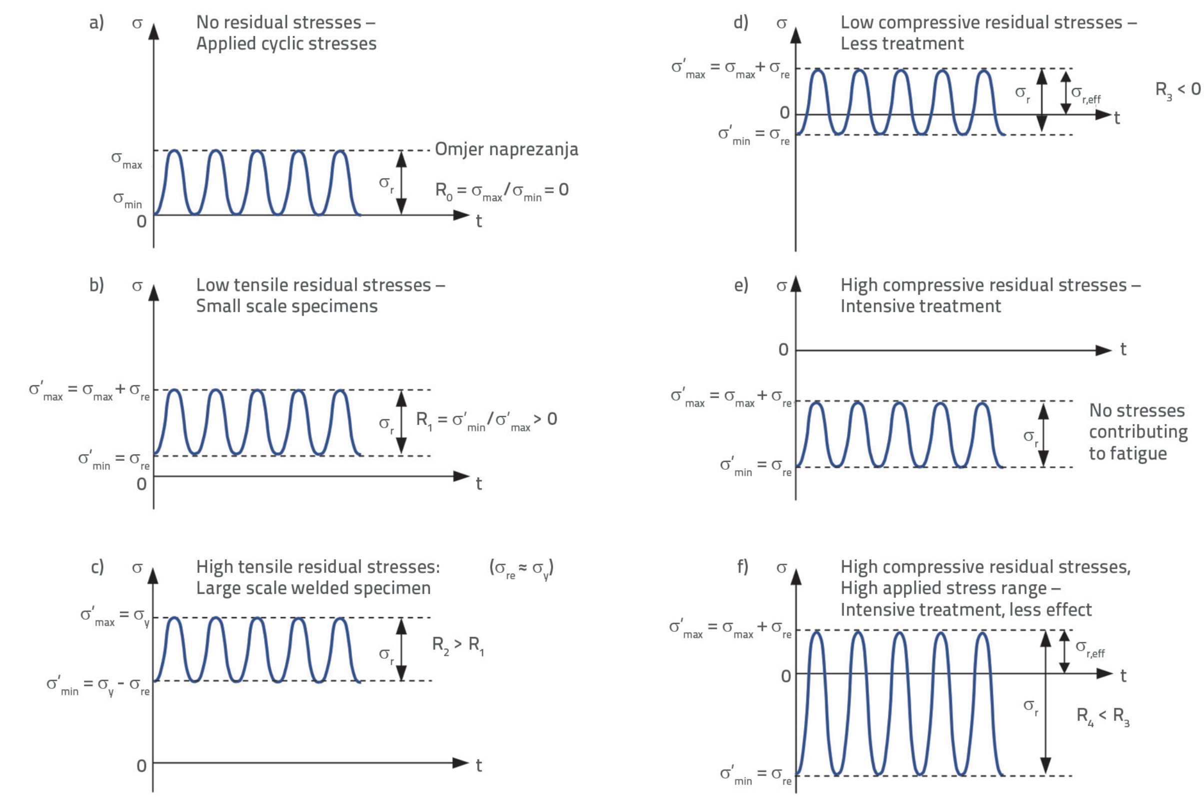
3.2. Residual stresses after HFMI treatment

Residual stresses are self-equilibrating stresses that are introduced within a structural component due to previous individual activities such as welding or cold forming, and they remain within the element even after termination of such activities. In the case of welding, residual tensile stresses occur in the weld toe area, as a result of local shrinkage of material in weld area after cooling. This phenomenon has a negative effect on fatigue crack initiation and contributes to brittle fracture of the material. HFMI treatment introduces compressive residual stresses, which reduce tensile stresses at the weld toe. According to some authors [40], this is the most important parameter of improvement in the case of HFMI treatment. The total stress in the welded joint amounts to:

$$\sigma_{uk} = \sigma_{vanjsko} + \sigma_{zaost,zavar} + \sigma_{zaost,\ HFMI} \quad (1)$$

Figure 8 shows an example of various stress conditions within a welded detail. The stress ratio R is defined as the ratio of minimum to maximum stress and is usually different from the stress ratio from external load.

F igure 8 shows that high tensile stresses contribute to fatigue by increasing the maximum stress. When the residual compressive stress is introduced through HFMI treatment, the tensile stress generated by welding and the tensile stress part of the externally variable load can be eliminated or partially reduced. The ideal effect of HFMI treatment is shown in case (e) given in the figure. The positive effect of HFMI treatment is more pronounced when the stress range is smaller. Tensile



Legend:
σ_{max} - max stress; σ_{min} - min stress; σ_r - stress range; σ_{re} - residual stress; σ_y - yield stress; R - stress ratio

Figure 8. Various stress conditions in welded joints as related to residual stress condition [41]

stresses combined with external loading can increase the value of the mean stress and cause the component to be exposed to a higher load compared to the load that is in reality exerted on that component. Due to better understanding of the level of weld improvement by HFMI method, a number of studies have been conducted in recent years on the effect of the HFMI method on residual stress within welds [42-46].

HFMI treatment can involve up to 400 MPa of positive compressive stresses up to 1,5 mm in depth from the surface of the material [6]. The magnitude of the residual stresses introduced increases with an increase in yield stress [6], which is advantageous for high-strength steels. Residual stresses remain in the treated weld toe area even after application of pre-load (such as constant load), and before fatigue loading [47, 48]. Turski et al. [42] have shown that HFMI treatment introduces compressive residual stresses up to 2 mm in depth of the material, while Liu et al. [43] have established that compressive stresses extend to 4 mm in depth. A German research project called "Henry Granjon Prize Competition 2009" [49] has revealed experimental data according to which compressive residual stresses reach 1,5 – 2,0 mm in depth with maximum values at about 0,4 mm to 0,5 mm below the surface of the material. After treatment, the average weld radius is 1,5 mm to 2,0 mm with a groove depth of 0,1 mm to 0,2 mm. The groove depth is closely related to local residual stresses and is an essential measure in the quality control of HFMI treatment [48, 50].

The tool most commonly used for estimating residual stresses is the finite element method and, in this respect, a number of numerical models have recently been developed [42-45, 51]. More information on the influence of the finite element mesh type, material characteristics, boundary conditions, indenter sizes, modelling methods, and strain hardening rules, on the results obtained in numerical calculations can be found in [44, 52, 53]. Residual stress simulations can be evaluated experimentally by various measurement methods such as the X-ray diffraction and neutron diffraction [41].

Residual stresses introduced by HFMI treatment can be partially or completely relaxed due to individual stress peaks caused by live loads (or preloading) [54-58], which has the effect of reducing fatigue life of the welded detail. Preloading can relax residual stresses in proportion to their magnitude [56]. For example, a static load of approximately 40 % of the steel nominal yield strength reduces the positive compressive residual stress introduced by the Hammer Peening method, which has a similar effect as HFMI treatment [29].

The stability and relaxation of residual stresses in a HFMI treated detail depends on factors such as the stress to preload ratio, initial residual stress value, local stress concentration, and local yield strength [59]. The positive effect of the residual stress modification methods is also reduced by the increase of the mean stress [54], as it also increases the local mean stress at the weld toe, which in turn reduces positive effect of compressive residual stresses.

The relaxation of residual stresses occurs mainly in low-strength steels subjected to high tensile stresses [30, 60]. Generally, there is no residual stress relaxation for high-strength steels, so that residual stress remains stable throughout the life span. As mentioned above, the overall improvement of HFMI treated welds is manifested by the input of compressive residual stresses, changes in geometry, and local increase in hardness. Even when the residual stress relaxation does occur, the improvement of fatigue resistance still exists due to the remaining two parameters. However, in such cases, the level of resistance improvement must be investigated more thoroughly.

3.3. Increase in material hardness at the weld treatment zone

Due to plastic deformation in the treatment zone (cold forming of material), the HFMI treatment results in an increase in surface hardness of material in the treated area [61], which in turn leads to a local increase in yield strength [62]. This also increases fatigue resistance of the welded detail [30]. he increase in material hardness can be as much as 100 % as related to the as-welded state [29, 63]. In general, the depth of material hardening is less than 1 mm. According to [47], the increase in hardness can range from 0.3 to 0.5 mm in depth. The increase in hardness depends on the steel strength, and so a high strength steel has a lower hardness increase potential [47, 49]. Weich et al. [17] applied HFMI treatments for yield strengths of 434 MPa and 719 MPa. When comparing hardness values in the non-treated and treated state, they found an increase in hardness of about 66 % for low strength steel, and an increase of about 28 % for high strength steel. In the case of low strength steels, a slightly higher depth value, of about 0,3-0,4 mm, was registered, while for high strength steels, the depth of hardness increase amounted to 0,3 mm. Although an increase in hardness is a common phenomenon in cold forming of steel, no systematic quantification of this effect has been made for HFMI treated details [30].

4. Fatigue assessment for HFMI treated welded steel joints

4.1. S-N method based on nominal stresses

4.1.1. General

Fatigue assessment of welded details is usually based on the S-N method, as often suggested in standards [7, 8]. Each detail is categorised with the corresponding experimentally obtained S-N curve, which shows fatigue resistance of the detail. Resistance curves show the ratios of amplitudes of variable stresses to the number of changes in these amplitudes until failure of the detail. Typical curves for as-welded details according to EN 1993-1-9 and IIW standards are shown in Figure 9.

Each resistance curve is identified by the characteristic fatigue strength (stress range) at $N = 2 \cdot 10^6$ stress cycles, expressed

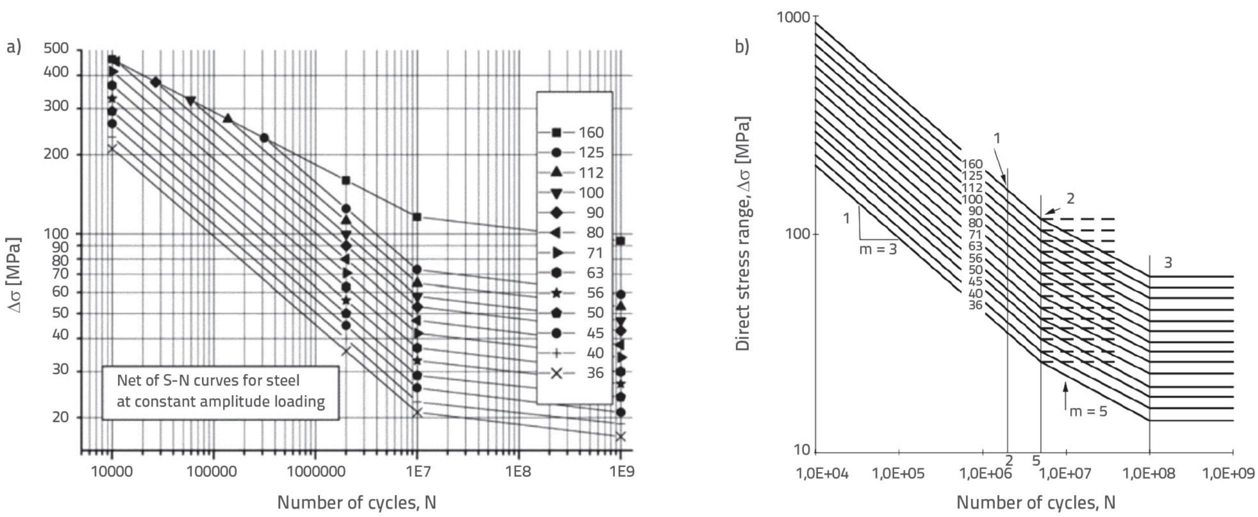


Figure 9. S-N resistance curves for untreated welded steel details according to IIW (left) and EC3 (right) [7, 8]

in MPa. This value marks the detail category. S-N curves proposed by Eurocode [8] for as-welded details have a slope of m = 3 above the stress range known as the constant amplitude fatigue limit (CAFL), where the slope becomes m = 5. This point corresponds to stress range at $5 \cdot 10^6$ stress cycles.

The estimation of fatigue life consists of detail categorisation into a specific category, which represents resistance and determination of stress range at the observed location. The most commonly used approach for fatigue assessment with the S-N method is the nominal stress approach, which is based on an average stress in the considered cross-section. The stress is calculated using a traditional structural mechanics procedure, and is based on the linear-elastic theory. At that, local influences that cause an increase (concentration) in stress are neglected. Local influences are indirectly taken into account using S-N curves. An estimation based on nominal stresses is presented in this section, while other approaches are presented in subsequent sections.

Resistance curves for HFMI treated welds [23, 47, 64, 65] are based on the assumed S-N curve slope of m = 5, and the fatigue detail category is also defined for N = $2 \cdot 10^6$ number of stress cycles [12, 22]. The assessment of the fatigue life of HFMI treated details according to IIW guidelines [12] covers details belonging to fatigue classes from FAT50 to FAT90. This limitation is due to the fact that more classes refer to non-welded details or details with already improved welds [66]. Details belonging to a class lower than FAT50 have not been considered since such details also have a high risk of failure over the weld root, where HFMI will not provide improvement. S-N curves for the HFMI treated details are shown in Figure 10.

The maximum detail category that can potentially be achieved by weld treatment is the category that is by the amount closest to the category obtained when the value of the as-welded category is multiplied by a factor of 1,6 [12]. To simplify the calculation, this corresponds to an improvement of four fatigue categories. For example, if a FAT71 category is HFMI treated, the new value of the category is FAT112. In Figure 10, such S-N curve is designated as 112 (71). If the fatigue class FAT90 detail from Figure 10 is considered, it can be seen that the curve of untreated welds with the slope of m = 3, and the curve of HFMI improved weld, intersect at a point of approximately N = 72.000 cycles. This means that, for welded structures of low strength steel, there will be no significant improvement in fatigue resistance by HFMI treatment for a fatigue life of less than 72.000 cycles.

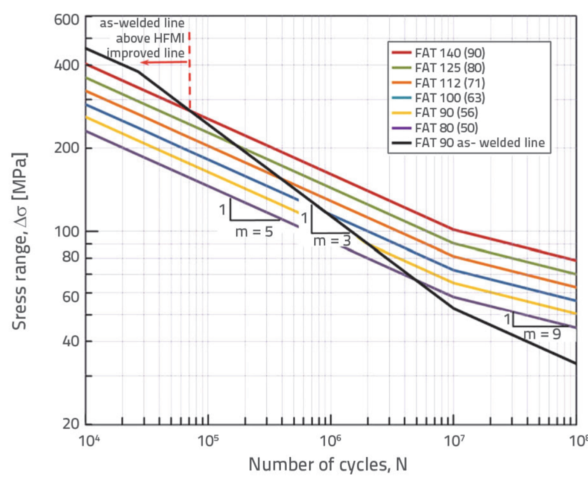


Figure 10. Characteristic nominal S-N curves for HFMI treated welded details for low strength steels (f_y < 355 MPa) for R ≤ 0,15. The value in brackets represents the fatigue class FAT (detail category) for as-welded details according to Hobbacher [7, 12]

4.1.2. Influence of plate thickness

It has been known since the 1950s that fatigue resistance depends on the thickness of the element and that it decreases with an increase in thickness [67]. For thicker panels, a greater volume of material is exposed to high stresses and the fatigue resistance of such details is lower. In addition, an increase in

plate thickness (while maintaining local geometry of the weld toe) also creates higher stress concentrations at the weld toe due to a smaller ratio of notch radius to plate thickness [68, 69]. More about the effect of element thickness on fatigue resistance can be found in [68, 70]. It is also significant to note that residual stresses due to welding are higher in case of thicker elements.
Although the effect of element thickness on fatigue life of welded details is known and covered by a variety of standards, this influence has not been systematically investigated for welds treated by HFMI procedures [67]. Guidelines for assessing fatigue of details improved by HFMI treatment are applied for panel thicknesses ranging from 5 to 50 mm [12]. he thickness of plates and welds affects the local stress concentration at the weld toe and stress gradients through plate thickness. Therefore, estimations through nominal and hot spot stresses, which will be discussed later in this paper, require the application of a reduction factor for all panels exceeding 25 mm in thickness [7].

4.1.3. Influence of steel strength

As mentioned earlier, fatigue resistance of as-welded joints does not depend on the quality of material of connecting elements. However, numerous studies show that the level of improvement of welds by HFMI methods increases with an increase in strength of the material [6, 23]. It was confirmed in [71] that HFMI treatment with the introduction of favourable compressive stresses in the depth of up to 1 mm, and with the introduction of a 2 mm weld toe radius, has the greatest effect in high-strength steels. It was shown in paper [72] that, if the yield stress of f_y = 355 MPa is taken as the reference, an increase in fatigue resistance is approximately 12,5 % for each 200 MPa increase in steel strength. This can be explained by the fact that compressive residual stresses introduced by treatment are proportional to yield stress [30].
In guidelines [67], an increase of one FAT class is proposed for each 200 MPa increase in the yield strength [72], which has proven to be a conservative assumption. Design recommendations include an increase of four FAT classes for steel joints with yield strength of f_y <355 MPa with respect to curves for nominal stresses for the as-welded condition. An increase for additional class is carried out for each increase in the yield strength of 200 MPa. The specific class increase is defined for N = $2 \cdot 10^6$ cycles and assumes an S-N slope of m = 5 for the HFMI treated details and m = 3 for the as-welded condition. An allowable increase in the number of FAT classes as a function of yield strength can be found in [12].
Characteristic S-N curves for HFMI treated joints for steels with f_y > 355 MPa can be found in [67]. An as-welded joint of high strength steel, e.g. FAT 80 (m = 3), would be FAT180 (m = 5) in HFMI treated condition. In treated condition, FAT 90 would have the same class as FAT 180. This limitation is due to current lack of experimental data and is the highest class in which detail can be improved, i.e. FAT180.

4.1.4. Influence of loading and stress ratio

For fatigue assessment of as-welded details, according to IIW guidelines, the maximum values of the nominal stress range and hot spot stress range are limited to 1,5 f_y [7], and 2 f_y [12]. For treated welded joints, the limitation of the stress ratio is R ≤ 0,5 and the maximum stress is $\sigma_{max} \le 0{,}8\, f_y$ [14]. TThese limits must be applied because of possible instability of residual stresses when the limit values are exceeded. Laboratory tests of fatigue loaded treated welded joints with variable amplitudes and nominal preloads of 0,9 f_y, 1,0 f_y, and 1,1 f_y have been presented in literature [32]. These tests confirm that the effect of HFMI treatment is reduced.
HFMI treated details can have up to 8 FAT classes of improvement depending on material strength, geometry of welded details, etc. The influence of stress ratio is expressed as a limitation in the maximum allowable increase in the number of FAT classes [12].

4.1.5. Stress cycles with variable amplitudes

S-N curves are based on test data that are mainly obtained at constant amplitudes, whereas in reality steel details are exposed to variable stress amplitudes. In such situations, stress history is converted to a constant amplitude record based on stress-amplitude counting methods such as the rain flow method or the reservoir method [73]. A series of stress ranges of constant amplitude, with the corresponding number of cycles, are obtained in this way. The total fatigue life is then calculated using the Palmgren-Miner rule [74], although the Miner sum can give incorrect results in the case of HFMI treated details [32]. Basic parameters that influence fatigue behaviour of the HFMI treated structure are the frequency of occurrence of preload, the arrangement of load cycles in the load spectrum, and the maximum and minimum stress levels. An equivalent stress range given by the following expression is used to determine the fatigue life of the details:

$$\Delta\sigma_{eq} = \left(\frac{1}{D} \cdot \frac{\sum \Delta\sigma_i^m N_i + \sigma_k^{(m-m')} \cdot \sum \Delta\sigma_j^{m'} N_j}{\sum N_i + \sum N_j} \right)^{\frac{1}{m}} \quad (2)$$

in Eq. (2) $\Delta\sigma_k$ is the stress range associated with the knee computed at N = $1 \cdot 10^7$, N_i is the number of stress cycles $\Delta\sigma_{i\ i}$ where $\Delta\sigma_i > \Delta\sigma_k$, N_j is the number of stress cycles $\Delta\sigma_j$ where $\Delta\sigma_i < \Delta\sigma_k$, m is the slope of S-N curve above the knee point, m '= 2m-1 is the slope of S-N curve below the knee point and D is the damage sum, e.g., D = 0,5. Yildirim and Marquis [39] show that Eq. (2) can be used to correlate variable stresses of constant and variable amplitudes for HFMI treated welds.
In the case of HFMI treated welds, a significant proportion of fatigue strength improvement is related to favourable compressive stresses. Therefore, any change in residual stress during variable amplitude loading can have a significant effect

on fatigue strength. For HFMI treated details of high-strength steel, changes in failure mode have been reported depending on whether the fatigue load is of constant or variable amplitude [75]. In the case of variable amplitudes, the stress range spectrum consists of individual cycles with large stress ranges, which results in a failure in the HFMI produced groove, whereas a constant amplitude load results in failure at other locations. In paper [76] the results of laboratory tests with constant amplitudes (R = 0,5 to 0,7) and limited variable amplitudes are compared with IIW guidelines[14]. It was confirmed that the slopes of the S-N curves vary from 4,4 to 9,6. It was concluded that a lower slope is more appropriate for designing treated weld toes for medium and high cyclic fatigue (10^4 to 10^7 cycles).

4.2. S-N approach based on hot spot stresses

Hot spot stresses are geometric stresses obtained by extrapolating stresses from reference points at a certain distance from the weld toe, as shown in Figure 11 [3]. The extrapolation is performed to exclude from calculation the nonlinear stress component that is taken into account indirectly through S-N curves, and extrapolation is performed from locations where the stress distribution is still linear. For plate elements, this location starts approximately at a distance of 0,4t from the weld toe, where t is the plate thickness. Recommendations for the determination of reference points and extrapolation can be found in [77].

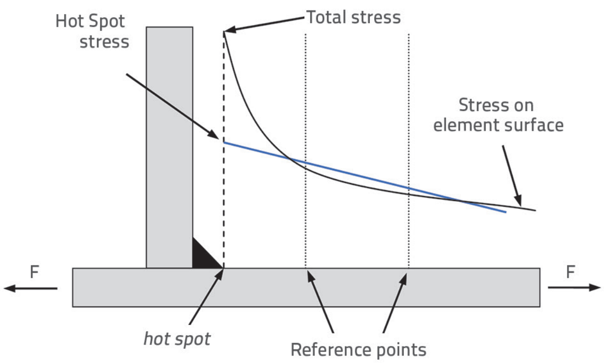


Figure 11. Definition of hot spot stress according to [78]

The procedure proposed in [77] is recommended for fatigue assessment based on geometric hot spot stress. As in the case of nominal stresses, the characteristic curves of the HFMI improved details are defined for $N = 2 \cdot 10^6$ and are based on an assumed slope of m = 5 in the range $10^4 \leq N < 10^7$ and m' = 9 for $10^7 \leq N$. In the context of the fatigue assessment approach based on nominal stresses for HFMI treated details, it was mentioned earlier that the maximum allowable S-N curve corresponds to the FAT180 class. The problem with ‚hot spot calculations can be found in welded details with relatively low-stress concentrations, where a very high detail category can be achieved but, in the guidelines, it is limited to FAT180.

The stress concentration in the hot spot method is defined as the ratio of the geometric s_s to the nominal stress s_{nom} by the following equation:

$$K_s = \frac{\sigma_s}{\sigma_{nom}} \quad (3)$$

As was the case with nominal stresses, the fatigue strength reduction factor due to thickness should be used, and guidelines for variable amplitudes must be used in conjunction with the hot spot approach. Examples of fatigue life calculations for improved welded joints based on the hot spot approach can be found in [79, 80].

4.3. S-N method based on effective notch stress approach

This approach is currently increasingly used in the industry, and guidelines for fatigue assessments by this approach can also be found in standards [81, 82]. The basic concept of this approach is numerical modelling of the weld root or toe with notches of a certain reference radius, Figure 12. The effective notch stress is the total stress at the weld root obtained from the calculation assuming linearly elastic behaviour of the material [3].

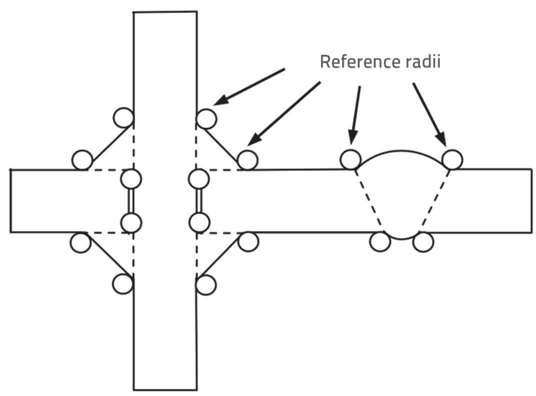


Figure 12. Calculation of notch stress with reference radii [3]

There are two commonly used fictive radii of 1 mm and 0,05 mm for fatigue assessment based on the notch stress approach [81, 83]. Each notch in the root or weld toe is modelled without discontinuity assuming linearly elastic behaviour of the material. A reference radius of 1 mm is used for panels thicker than 5 mm, and so this method can be applied for civil engineering structures. The notch stress fatigue assessment follows the same procedure as the nominal stress approach, with the consideration of the local effective notch stress instead of global stress. The estimation procedure is based on a comparison of the effective fatigue stress range with the corresponding S-N curve representing resistance. Such curves are proposed in the IIW recommendations [83] for plated structures loaded with longitudinal forces and bending moments. In 2008, IIW approved guidelines for fatigue assessment of post-weld treated details using “notch” stresses [84]. The calculation proposal is based on stress analysis using a fictive notch radius ρ_f = 1 mm and the procedure described by Fricke [83]. The slope of S-N curves of the HFMI treated details is the same as that of the hot spot approach. As was the case with the nominal stress method, characteristic curves are defined for N = $2 \cdot 10^6$. For HFMI treated welds, the corresponding S-N curves for various steel grades are given in [12], There is also a limitation, i.e. the improved detail category can not exceed FAT 180.

Fricke [83] defines the effective notch stress concentration as the ratio of the effective notch stress σ_w to geometric stress σ_S according to the following equation:

$$K_W = \frac{\sigma_W}{\sigma_S} \tag{4}$$

Fricke [12] also proposes that the minimum K_W could be 1.6 for details with a low-stress concentration, even if a smaller factor is obtained by calculation. Additional requirements for HFMI treated details are not necessary as K_W is defined with respect to the geometric stress σ_S, where certain constraints and requirements already apply. Fatigue strength recommendations given in [12] are based on the assumption that $\Delta\sigma$ is calculated in terms of the maximum principal notch stress. As with nominal stress range, a reduction in FAT class is required regarding the stress ratio, and also according to variable-amplitude guidelines. As this method is extremely local in nature, no reduction is required for element thickness [12].

Nominal and hot spot stresses do not take into account local HFMI influences, and include global geometry influences only [30]. An analysis considering local weld-toe improvements using the Notch stress method was performed in [85] but, to simplify calculation, it was concluded that the HFMI groove could be neglected.

4.4. Crack initiation-propagation model

4.4.1. General

An unconventional fatigue assessment method based on a combination of crack initiation and propagation models will be presented in this section. The method can be applied for assessing fatigue of welds improved by the HFMI method [86]. The crack initiation is modelled by the notch strain approach, where the number of stress ranges of a certain amplitude is determined until a crack of a given size occurs. The crack propagation is modelled by fracture mechanics, which gives the required number of stress cycles for crack propagation to a critical value when failure occurs. Although this approach has not been adopted in standards, it enables efficient evaluation of fatigue life of treated and as-welded steel joints [3, 86]. The fatigue process consists of a crack initiation period and crack propagation period, and so it is appropriate to consider these two stages separately. The S-N method does not distinguish these two phases but instead observes the total fatigue life.

Since HFMI treatment only relates to the crack initiation period, it is possible to estimate the extension of the crack initiation period using the notch strain approach. In this way, the change in geometry, compressive residual stresses, and increase of hardness, can be taken into account.

4.4.2. Crack initiation model – Notch strain model

The Notch strain approach was proposed by Seeger et al. [87]. Resistance estimation consists of determining the stresses and deformations at the weld toe under elastoplastic conditions and comparing it with the S-N deformation curve of the miniature material specimen (Ø = 6-8 mm) until its complete failure (Figure 13). An introduction to the Notch strain approach can be found in [88].

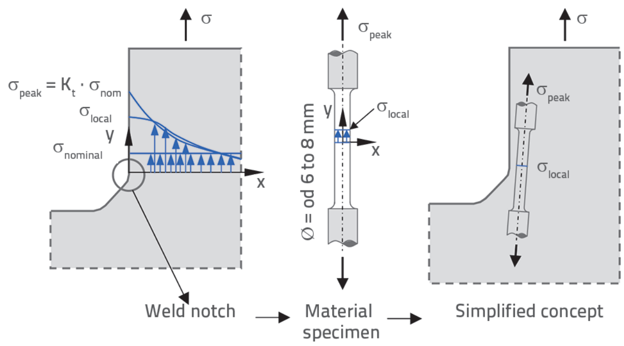


Figure 13. Similarity concept for notch strain method

Stresses and deformations at the weld toe within the welded detail are calculated from the stress-strain curve and using the Neuber equation from [89]. The residual stresses introduced by HFMI treatment are also taken into account. Stresses and deformations at the weld toe can also be obtained by using a stress concentration factor in the notch K_t. The "Notch" factor for fatigue is derived from the stress concentration factor according to Peterson [90, 91]. The value of the notch factor for fatigue decreases compared to the value of stress concentration factors, especially for sharp notches. For a more conservative calculation, the stress concentration factor, through which it is possible to take into account the change in geometry after HFMI treatment of the weld toe, is taken into account. Stresses and deformations in the weld notch in the elastoplastic state according to Neuber are given as:

$$\sigma_k \varepsilon_k = \sigma_n \varepsilon_n K_t^2 = \frac{(\sigma_n K_t)^2}{E} \tag{5}$$

$$K_{t\sigma} K_{t\varepsilon} = K_t^2 \tag{6}$$

where K_t is the elastic stress concentration factor, $K_{t\sigma}$ is the elastoplastic stress concentration factor, $K_{t\varepsilon}$ is the elastoplastic stress concentration factor, σ_k is the maximum stress in the notch, ε_k is the maximum deformation in the notch, σ_n is the nominal stress, and ε_n is the nominal deformation ($\varepsilon_n = \sigma_n/E$).

The calculation of stress and deformation in the notch is based on a stabilized cyclic stress-strain curve. Local stresses and deformations follow a cyclic stress-strain curve approximated by the Ramberg-Osgood equation [92]:

$$\varepsilon_a = \varepsilon_{a,el} + \varepsilon_{a,pl} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \quad (7)$$

where ε_a is the total strain amplitude, $\varepsilon_{a,el}$ is the elastic strain amplitude, $\varepsilon_{a,pl}$ is the plastic strain amplitude, σ_a is the stress amplitude, E is the modulus of elasticity, K' is the cyclic strain hardening coefficient, and n' is the cyclic strain hardening exponent.

The cyclic stress-strain curve forms a hysteresis loop in the stress-strain diagram. Individual sections of the curve are approximated by doubling instantaneous amplitudes of the primary cyclic stress-strain curves. Hysteresis loop branches, which rise or fall down from endpoints, include the Bauschinger effect [93] and are described by the double strain curve [94] as:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \quad (8)$$

Failure or crack initiation is described by the S-N deformation curve, which includes the elastic and plastic parts. The curve according to Manson and Coffin, together with the correction effect of the mean stress according to Morrow [95-97] is:

$$\varepsilon_a = \varepsilon_{a,el} + \varepsilon_{a,pl} = \frac{\sigma_f' - \sigma_m}{E}(2N)^b + \varepsilon_f'(2N)^c \quad (9)$$

where σ_f' is the coefficient of fatigue strength, ε_f' is the coefficient of fatigue ductility, b is the fatigue strength exponent, c is the fatigue ductility exponent, σ_m is the stress, and 2N is the number of cycles until cracking. The crack initiation period ends when the crack size becomes a_i = 0,5 – 0,8 mm [98].

For the fatigue life estimation, i.e. for variable amplitude stress ranges¸ the Rainflow method [73] is used to determine the nominal stress amplitudes $\Delta\sigma_{nom,1}$, $\Delta\sigma_{nom,2}$, $\Delta\sigma_{nom,i}$, etc. from the stress spectrum. Subsequently, local stress amplitudes $\Delta\sigma_{local,1}$, $\Delta\sigma_{ocal,2}$, $\Delta\sigma_{local,\ 3}$, etc. are determined from these systems of equations. The fatigue life until crack initiation is estimated by the Miner's rule so that contribution of each individual stress amplitude to the total damage is observed, as shown in Figure 14. The crack occurs when the sum of all contributions to the damage reaches 1.0, Eq. (10). The Coffin-Manson equation is used for calculating for each stress range the total maximum number of cycles until failure (N_i).

$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \ldots = 1 \quad (10)$$

The application of the local strain approach requires definition of material parameters, which are determined through appropriate tests. Several methods are used for determining material parameters [99], including the "uniform material law" and "hardness method". These methods can be used to determine parameters for the notch strain approach and thus to accurately estimate fatigue life of the welded detail, as confirmed by experimental results [99]. The "uniform material law" was proposed by Bäumel and Seeger [100]. Only the modulus of elasticity and tensile strength of steel are required for the estimation of parameters.

The above-mentioned "hardness method" also deserves mentioning in this paper since it is essential for the assessment of HFMI treatment by taking into account the hardness of material. It was proposed by Roessle and Fatemi [101]. Some parameters are estimated from Brinell hardness, which must be between 150 HB and 700 HB. Brinell hardness and modulus of elasticity of steel are required for parametric estimation by this method.

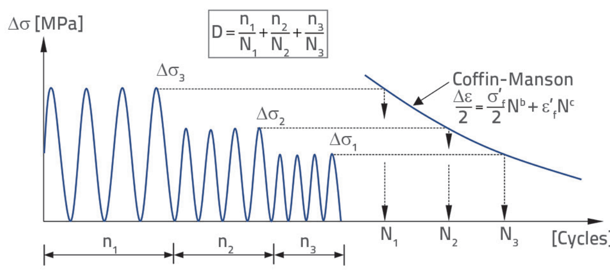


Figure 14. Sum of damage for crack initiation period

4.4.3. Crack propagation model – fracture mechanics

The crack propagation period is modelled using principles of fracture mechanics. This approach is based on a number of assumptions with some degree of uncertainty and can be used to estimate the crack propagation period if used with model calibration [3]. Calibration means that the model first adjusts to a specific S-N curve and then extrapolates to the required detail. In order to estimate the fatigue life of the details as accurately as possible, the initial and final crack size, the parameters of the crack propagation, and the corresponding S-N curve, should accurately be determined.

The degree of crack growth is proportional to the stress range, which is expressed via the stress intensity factor. It describes the state of stress near the tip of a crack caused by external load, and is expressed as:

$$\Delta K = Y \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a} \quad (11)$$

where Y is the correction factor dependent on crack geometry, a is the crack size, and Δσ is the stress range. Fatigue crack propagation occurs if the stress intensity factor exceeds the critical stress intensity factor. More information about this topic can be found in [3].

ZTo estimate the crack propagation period for fatigue-exposed welded details with constant amplitudes, the use is made of the Paris-Erdogan equation, which approximates the cyclic crack growth rate under plane deformation conditions at the crack tip. In this case, it is assumed that the crack propagates perpendicular to the direction of loading. The Paris equation is:

$$\frac{da}{dN} = C \cdot \Delta K^m \tag{12}$$

where a is the crack size, N is the number of load cycles, C and m are the experimentally determined material constants, and ΔK is the stress intensity factor. Material parameters m and C depend on the material microstructure, the mean stress, environmental conditions, temperature, degree of corrosion, etc. The values of these constants, as well as a list of literature where they can be found, are presented in [3]. Figure 15 shows a typical crack propagation curve according to Paris law.
The propagation process consists of slow propagation, a stable and unstable crack propagation, which is followed by failure. The Paris equation is related to the linear stable crack propagation. Fatigue life is assessed by integrating the Paris equation:

$$N_{i,j} = \int_{a_i}^{a_j} dN = \int_{a_i}^{a_j} \frac{1}{D \cdot \Delta K^n} \cdot da \tag{13}$$

where N is the number of stress cycles from a_i to a_j. During crack propagation assessment based on this method, the estimation of the initial crack size a_i is of major significance for determining the crack propagation period. Initial crack size values are usually in the range from a_i = 0,01 to 0,05 [102] or even 0.15, as recommended by IIW [7]. These crack sizes are approximations of microstructural properties of the material. The grain size typical for steel is approximately 0,01 mm, and so it does not make sense to assume a crack size below this value. An initial crack size equal to the crack size at the end of the crack initiation period is selected in the case of a crack initiation-propagation model. According to the Notch strain analysis, the fatigue life up to crack length of 1 mm and a depth of about 0,5 mm is observed. For the calculation of crack propagation, BS7910 [103] recommends an initial crack size a_i between 0,1 and 0,25 mm.

4. Conclusions

Based on the review of available literature on the HFMI treatment of welded joints exposed to fatigue, the following can be concluded:

- The HFMI treatment of welded joints is a simple and cost-effective method for improving the fatigue resistance of fatigue loaded welded joints and, in some cases, it can even be the only solution when a sufficient fatigue resistance can not be achieved with conventional design rules.
- Improvement of fatigue resistance involves increasing the weld toe radius (reducing stress concentration), introducing compressive residual stresses that reduce or eliminate unfavourable tensile residual stresses generated by welding, and material hardening due to cold forming where the material yield strength increases locally (in proportion to an increase in steel grade).
- Unlike as-welded joints, steel grade contributes to the fatigue resistance of the improved fatigue loaded welded joints, which is especially important in high-strength steel applications.
- The reliability of improved welded details, as related to constant and variable stress amplitudes occurring in real structures, should be further investigated.
- The combined effect of residual stresses and the level of relaxation due to different types of loading, weld toe geometry, and material hardening due to cold forming, should be further investigated in order to assess more accurately the level of improvement of fatigue resistance of welded details.
- A better understanding of all above mentioned issues will continue to promote the HFMI method implementation in civil engineering and other industries, and will allow progress in standardisation process, as well as the development of new guidelines for fatigue assessment of post-weld treated details.
- It should be noted that, due to insufficient laboratory test results for various details, there is still a certain level of uncertainty in fatigue assessment. Therefore, in addition to additional laboratory testing, probabilistic models need to be developed to asses the level of uncertainty for everyday engineering applications.
- Particular attention should be paid to individual loads that can significantly relax compressive residual stresses and thus influence the level of resistance improvement. This should be taken into account in fatigue assessment, especially when considering variable stress amplitudes obtained from stress spectrum.
- Previous studies have shown the benefit of the HFMI method in increasing the fatigue strength of welds at constant amplitudes and low-stress ratios. However, there is limited knowledge about the effect of high-stress ratios and variable amplitudes, and various mechanisms such as the residual stress relaxation, geometry improvement, and strain hardening, on the fatigue resistance improvement level.
- Understanding the combined and joint effect of residual stresses, local weld toe geometry, and strain hardening, is of crucial significance for determining the effect of high-stress ratios and peak stresses on the level of improvement of welded structures by the HFMI method.

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