

## **A Literature review for the state of the art Fatigue life extension of welded structures by peening and TIG dressing**

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## ABSTRACT

Fatigue is one of the most detrimental phenomena that endangers the life expectancy of welded steel structures. Weld is susceptible to fatigue more than other parts because of the high stress concentration, the existing weld defects and the residual stress induced by welding. If the structure is in service, the structure might be already cracked. Different techniques were developed to extend the fatigue life of the structure and retrofit any existing crack, Peening and TIG remelting are just examples. A literature study is conducted to establish better understanding on the effect of these two treatment methods their efficiency in crack retrofitting.

The crack retrofitting experiments consist of two stages, pre-fatigue loading and loading after treatment. The first stage requires crack detection, different methods were investigated and the most efficient among them is the use of local strain drop measured by strain gauges.

Peening treatment is found to be a function of the crack depth. Retrofitting the crack when it's still shallow results in longer fatigue life. The treatment is found to be mainly relying on two effects: the crack orientation and the introduced residual stress. Peening causes a change in crack orientation which elongate the fatigue life. The higher and deeper compressive residual stress causes retardation of crack growth and deceleration of crack propagation.

TIG remelting is another effective method which can retrofit crack deeper than peening. Its efficiency is a function of the crack depth and the fusion depth. Usually, the fusion depth is greater than 2mm which is greater than the peening indentation depth which hardly can reach 0.6 mm. In short, TIG is more appropriate to retrofit cracks deeper than 1mm while Peening results in longer life if the largest crack is shallower than 1mm.

Keywords: Peening, HFMI, TIG remelting, TIG dressing, Life extension, Post weld treatment, Crack retrofitting, Crack detection, Linear elastic fracture mechanics, Strain gauge, fatigue crack, LEFM, Microhardness, Concentration factor, Gain factor.

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# 1 Fatigue life extension of welds: A critical view on the state of the art

This chapter deals with fatigue life extension and rehabilitation of welded steel structures after pre-fatigue loading using two methods: Peening and TIG remelting. A critical literature review on the existing scientific papers is conducted. It was found that crack detection is an important measure to assess the efficiency of the treatment. Many crack detection methods are discussed, strain drop measurement is found to be relatively simple and accurate method of crack depth detection and estimation. The efficiency of peening or TIG remelting in extending fatigue life is a function of the crack and treatment depth. However, Peening is safe only for cracks shallower than 2mm, While TIG remelting can be applied for slightly deeper cracks. Finally, fracture mechanics is widely used tool for crack propagation prediction. However, its limitations for welded structure analysis should be taken into account.

## 1.1 Introduction

Since the life expectancy of large steel infrastructure (e.g Bridges) is long, there is a need to have them in a good condition during their service life. The technological development makes it possible to extend the fatigue life of welded steel structures used in different fields. The structural engineers use life extension methods for extending the fatigue life of steel bridges, the mechanical engineers are using them for improving welds used in automotive industry. In addition to that, these methods are also used in aerospace industry to utilize the high strength steel for the sake of weight saving. Moreover, the marine engineer are using them as improvement methods for ship manufacturing and assessment.

Various methods have been developed to extend the fatigue life of welded details. The effect of these methods is attributed to removal of the discontinuities at the weld toe. These discontinuities can be in the form of defects (e.g Undercuts) or cracks. Even with the absence of these discontinuities, weld toes are critical region when it comes to fatigue because of two reasons: the first one is the residual stress resulting from the differential cooling of different regions around the weld. In most cases this causes tensile residual stress at the weld toe because of slower cooling rate and compressive residual stress away from the weld. The second reason is the stress concentration resulting from the weld beads shape.

The IIW commission has proposed different post weld treatment methods for steel structures [1]. These methods are burr grinding, TIG remelting, hammer peening and needle peening. The first method (Burr grinding) is aiming to reduce the stress concentration through mechanical material removal. This will also remove the defect existing at the weld toe. The second method (TIG remelting) has a double effect of reducing the stress concentration and increasing the hardness of the weld toe zone. This is done by remelting the material at the weld toe which will create smooth transition between the face of the weld and the base plate. The last two methods (needle and hammer peening) are just different names for a family of treatment methods called high frequency mechanical impact (HFMI). These method have a tripple effect of reducing the stress concentration, increasing the hardness of the weld toe and most importantly inducing permanent deformation which gives raise to compressive residual stresses.

Many research papers are published about the use of grinding [2], TIG remelting [3–5] and peening [6–9] for improvement of fatigue strength of newly built structure. However, there is also a need for studying the effectiveness of these treatment

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techniques on existing welded structures that have been already subjected to fatigue damage or -possibly- containing fatigue cracks. This concept of fatigue life extension is crucial since most of the bridges in Europe were built in the last century. That means part of their service life is consumed because of the loading applied before treatment. A light will be thrown on the existing literature of the use of Peening and TIG remelting as crack retrofitting methods in welded steel structures.

## Life extension stages

Life extension of existing structures is considered as a special case of the fatigue life improvement (which can also be implemented after manufacturing). There are two stages in this special case:

### 1.2 Pre-fatigue loading

The loading history is defined as the stresses which are experienced by the structure before the treatment. It plays a vital role in effecting the efficiency of any weld treatment method. This parameter can be studied in two different ways:

#### Loading history as number of cycles

In this methodology, the effect of loading before treatment is represented by the number of cycles and the stress level. The main benefit of using this kind of representation is the simplicity and easiness in both laboratory specimens study and real structures. However, the applied loading on the structure is not known during its service life but it can be forecast taking into account the increase or decrease of the applied loading with time.

Some researchers [10–12] have studied the effect of pre-fatigue loading on the effectiveness of ultrasonic impact treatment (UIT) for different details and steel strengths. Günter et al.[10] have found that peening the weld toe after pre-fatigue loading of 75-90% of the estimated as-welded fatigue life results in extending the life of steel by a factor of 2.5. Kudryavtsev et al.[11] concluded that peening an existing structures has the same effect of peening on new structures , while Zhang et al.[12] drew the conclusion that the efficiency of peening decrease as a function of pre-fatigue loading period.

Günter, Kuhlmann & Dürr[10] have conducted their work on S450 non load carrying fillet weld subjected to pulsating loading ( $R=0.1$ ). As-welded welded specimens were examined first and the fatigue life is obtained. The fatigue strength (FAT) is found to be 85MPa (which is close to the detail category for transverse attachment in the Euro-code standards). Then a similar specimen is pre-fatigued with the same loading condition up to 75-90 % of the life obtained for as-welded specimens. After treatment, a visual inspection with a 10x magnifying glass was used to inspect any cracks. The crack depth was found to be less than 1-1.5mm. The loading is resumed with the same conditions. The life extension is then calculated by subtracting the pre-fatigue loading cycles from the total number of cycles of the UIT treated specimens. It was found that the extended life is greater than the as-welded life by a factor of 2.5 under a condition that all the crack detected are 'shallow cracks'.



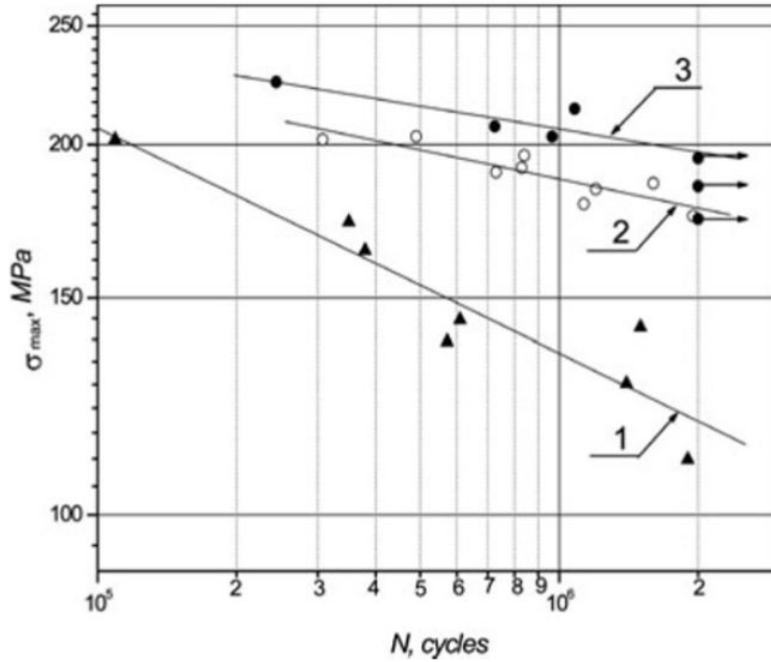


Figure 1: The S-N curves for As-welded (1), as-welded peened (2) and pre-fatigued peened (3).[11, 13]

Kudryavtsev et al.[11] have conducted similar analysis on similar specimen but with thicker base plate and stiffener. The applied loading was alternating ( $R=0$ ) with a stress range  $\Delta\sigma = 155\text{MPa}$ . The yield strength of the steel used is  $260\text{MPa}$ . Three series of specimens are tested, The first is in as-welded condition and it shows a fatigue strength of  $119\text{MPa}$ , the second is for peened specimens after manufacturing and it shows a fatigue strength of  $177\text{MPa}$ . The third series is for specimen peened after 50% of pre-fatigue loading, this one shows surprisingly a strength of  $197\text{MPa}$  which is even higher than the second series. The S-N curves for the three series is shown in figure 1. The authors proposed that the reason for having better improvement in partially damaged series could be either the healing of fatigue damage completely by peening or better welding residual stress redistribution due to pre-fatigue loading despite of the fact that no residual stress measurement by X-ray diffraction or FEM modeling were conducted. However, similar explanation was provided by Mordiyuk and Prokopenko [13].

Contrary to the above mentioned studies, Zhang et al.[12] study was on high strength steel (HSS) with a yield strength of  $790\text{MPa}$ , the joint type is transverse butt welded and the specimens were subjected to pulsating load of  $R=0.1$  and stress range  $\Delta\sigma= 250\text{MPa}$ . The high loading level is used to ease the experiments by reducing the number of cycles to cause failure. The expected as-welded fatigue life is  $1.4 \times 10^5$ . Based on this expectation, groups of specimens are loaded with different number of cycles as a percentage of the expected value (0,25,50,75,100%). It was found that the fatigue life for as-welded was higher than expected value by a factor of 1.75. Which makes the real pre-loading percentages: (0,15,29,43,57%). After peening the pre-loaded groups, it was found that average increase factor in fatigue life is in between 2.6 to 15 for depending on the pre-fatigue loading percentage. The residual stress is confirmed to be compressive after peening down to 1mm deep. However, it's not specified for which group of pre-loading the measurement corresponds. The fractography shows the difference between the pre-fatigued peened and newly peened specimens. In the former case, parallel plastic deformations are found because of peening in the presence of cracks near the surface. In the later case 'tire tracks' are found, these tracks are found because of the extrusion of two opposite

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surfaces of extended fatigue crack. Beach marking is produced by changing the stress level for few thousand cycles to mark the fracture surface.

In the last mentioned four studies [10–12], a very high scatter is found in the results. When some specimens failed other specimens from the same group ran out, that is due to the fact that scatter is expected in high cycle fatigue because of the localization of this phenomena. Which means that the defects existing in one specimen's toe is not necessarily existing in other one. That makes any conclusion regarding pre-fatiguing to a specified number of cycles not inclusive. The scatter is noted to be stronger in HSS. This is because this type of steel is more sensitive to defects, so pre-fatiguing will cause different damage pattern in different specimens especially in high cycle fatigue where the scatter is doubled. In other study [14], The effect of shot peening is studied on Aluminum alloy in low cycle fatigue. Herein, a better relation with lower scatter is found between the percentage of fatigue damage (% of pre-fatigue loading with respect to virgin specimens) and the average fatigue recovery; that is because the loading is globally plastic and independent of the micro-structure.

The reason provided by Kudryavtsev et al.[11] for having higher fatigue strength for pre-fatigued peened conditions than peened without pre-fatigue is not supported with evidence. The damage can't be heal after treatment because it is a permanent mechanical degradation of material proprieties (e.g elastic modulus). This property won't increase after peening, but the damage propagation might be slower because of the compressive residual stresses. Even if healing is taking place, it can't be better than the manufactured specimen which has the original propriety. Another possible explanation is the scatter of the results especially that the loading level is low ( $R=0$ ). Günter et al.[10] results are more expected since detection have shown no crack longer than 1.5mm which is deep enough to cause a distinct difference between the S-N curve of the pre-fatigued peened and as-welded peened specimens..

### **Loading history as crack geometry**

As mentioned in previous section, the use of number of cycle as a representation of loading history in HCF can be misleading and impossible in practice. Instead, the use of predefined damage (e.g cracks with specified length or depth) is more realistic and possible in practice. Moreover, most of researchers are following this methodology. Some of them uses the crack length as deciding parameter [15, 16]. However, the majority find that crack depth would be more relevant [17–28] because treatment methods effect ceases in depth direction. For example, the peening induced compressive residual stress is a function of the indentation depth which was specified not to be less than 0.2mm deep [29].

Since the crack is used as history parameter, some researchers skip the pre-loading stage to create a crack and inspect it. Instead, an artificial crack with defined geometry (Crack depth, crack length , aspect ratio ) is created as close as possible to the weld toe. These cracks are usually created using electric discharge machining [22]. Fueki & Takahashi [22] used a semicircular cracks of different radii in austenitic stainless steel butt weld to study the effect of crack depth on the effectiveness of needle peening. The cracks were created 0.2mm from the weld toe. Fueki, Takahashi & Houjou[23] did the same but for low carbon steel. Akyel et al.[30] have created a large semi-elliptical crack with a depth of 12.5mm and length of 75mm in high strength steel base metal, this crack is to be ground and filled with welds as

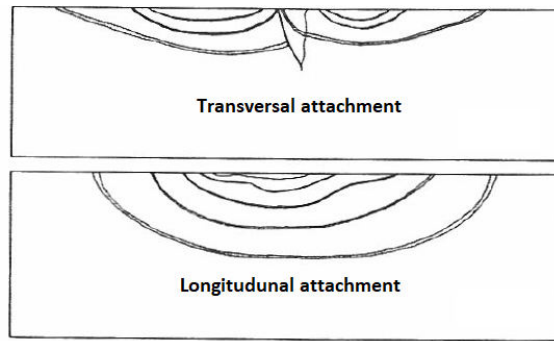


Figure 2: The difference between the development of crack in longitudinal and transversal attachment [27]

treatment method.

The use of this methodology (artificial crack creation) has the advantage of studying a crack effect with perfect geometry (Semi-circular or semi-elliptic) on life extension. This is very useful if a crack propagation is to be studied analytically using fracture mechanics, since shape functions used in fracture mechanics are only available for idealized crack geometries. This methodology is easier to implement because no crack detection is applied. On the other hand, the fatigue loading (which is missing in this methodology) can create different crack shapes than pre-idealized one depending on specimen geometry, residual stresses distribution, quality of weld and other factors. For example; the longitudinal and transverse attachments have different crack shapes with higher aspect ratio for the former and lower for the latter [27] as shown in figure 2. Besides, the crack aspect ratio is usually changing while the crack is propagating [15].

The most complicated but physically sound methodology in pre-loading stage is crack detection after loading. The detected cracks which can be harmlessly repaired are rarely large and can be detected with bare eyes like in [31]. In this paper, the crack is allowed to grow to half of the width of butt welded specimen (160mm) before it was repaired. This crack length can be easily inspected with eyes. But most commonly, the target crack length is much smaller for life extension purposes.

The use of double criterion to stop the pre-fatigue loading and start with treatment also exists in the literature. Maddox used either 10% of as-welded fatigue life or detection of 5mm surface crack, whichever comes first [15]. Fisher et al have studied both pre-loading until 75% of as-welded life and pre-loading until a crack can be visualized. It is found that the first criterion results in short cracks with a length less than 2.5mm, while the second one results in larger crack (Longer than 3mm and deeper than 1.5mm) [26].

A dye penetrant inspection is another simple non destructive crack detection method. High viscosity red dye is applied after cleaning the surface of the weld toe. Then, it's allowed to stay on the surface for a while before it's rinsed. Finally, the surface is dried and a developer is applied to show the crack surface with a red color. This method is cheap and can detect small cracks but it provides no information about the crack depth or its aspect ratio. This method was used to detect a crack for both longitudinal and transversal attachment welds [27]. The method found to be capable of detecting cracks down to 2mm long. Soap solution can also be used if the penetrant is not available [15]. Sometimes, the weld toe already contains some



Figure 3: The difficulty to distinguish fatigue cracks from scratches after dye penetrant is applied

of scratches and edges so it would be difficult to detect fatigue crack and distinguish them from surface scratches as shown in figure 3.

More advanced methods for crack detection are based on signal sending from sender device, the travel time of the signal can be related the crack geometry. For example, Ultrasonic Testing (UT) or Alternating Current Potential Drop (ACPD) are two of these methods. On contrary to eye inspection and dye pentrant, these electronic methods are capable of measuring the crack depth which is more relevant than length in fatigue life extension purposes. However, there are some limitations due to the noise coming from other edges than the crack edge (e.g the outer edges), that makes only deep crack detectable. Fisher et al.[26] specified that a crack in cover plate attachment shallower than 2.5mm can't be reliably detected with UT. Miki et al.[27] used UT to detect a crack depth of 3mm or more in transversal attachment, but since their work was released in the seventies of the last century. A lot of development in technology is created and the method can detect shallower cracks. ACPD are used to detect both deep and shallow cracks down to 0.5mm deep [15, 16, 24].

Newly formed cracks cause a change in the local strains close to the weld toe, that makes measurement of strains/stresses using strain gauge a possible way to detect toe's cracks. That has the advantage of simplicity and accuracy at the same time. Leitner et al.[20] have studied the pre-fatigue effect on longitudinal attachment and one strain gauge is instrumented on each side of the attachment. The exact position of the strain gauges isn't specified in the mentioned paper, but the relative dimensioning in figure 4 shows that the gauge tip is placed more than 1mm from the weld toe. It was found than 20% drop in the maximum stress measured by any strain gauge corresponds to a crack of 1mm deep (as shown in the same figure). This drop was reached after 70000 cycles of nominal stress range equal to 300MPa and stress ratio equal to 0.1. The base metal is made of S355, that means the level of applied loading is very high ( $\Delta\sigma = 0.85fy$ ); this explains the low number of cycles required to cause that crack size. Another specimen with the same geometry and same manufacturing conditions was metallographically inspected to verify the strain drop method, that kind of inspection is destructive and that's why another specimen is needed. The rest of the specimen won't be inspected destructively, and strain gauges readings placed exactly at the same positions are considered to be enough to quantify the crack depth. The method of verification isn't specified in the paper but the authors were contacted by email to get the verification method.

Branco et al.[17, 18] and Ramalho, Ferreira & Branco [28] have used multiple strain gauges to quantify the crack depth in non load carrying T-joint fillet weld subjected to high stress level ( $R=0.1$  ,  $\Delta\sigma = 350MPa = 0.85fy$ ) . The exact position of the strain gauges are not specified but they were placed close enough to measure local strain. Seven strain gauges are used: Three on each side and one placed far away to

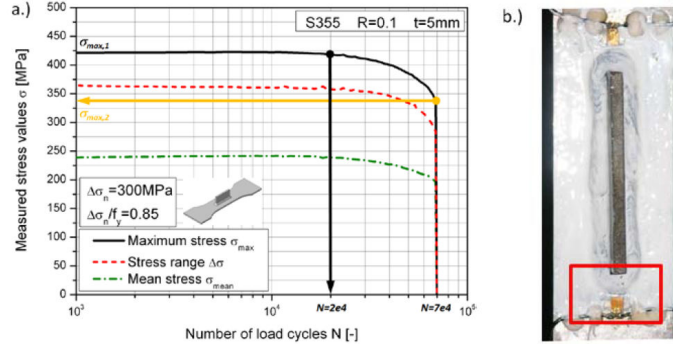


Figure 4: L: The local stress development in the strain gauge R: The position of the strain gauge[20]

measure the nominal stresses. The drop of 20% and 25% in any strain gauge reading are found to correspond to 1.27mm and 1.67mm deep crack respectively as shown in figure 5. The method of verification is not specified in all of the mentioned papers [17–19, 28]. The drop in strain can occur anywhere. In [17, 18] the drop was found in strain gauge 2 and 5 which are placed in the middle, while in [28] the drop was found in strain gauge 3 which is placed at the end. Moreover, the crack initiation was defined as a first 'remarkable' drop or increase in any strain gauge as shown in the same figure.

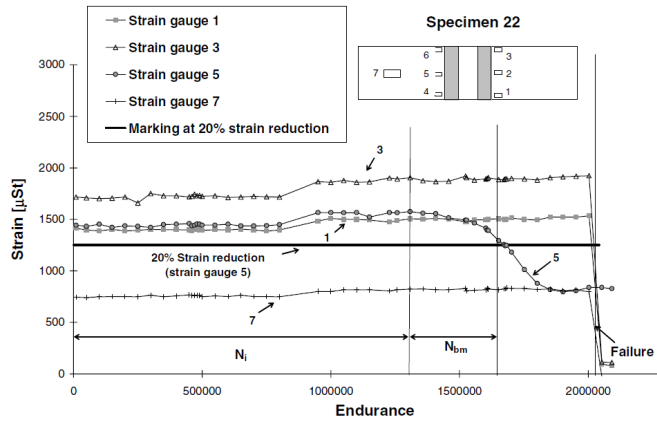


Figure 5: The use of strain gauge drop for crack size quantifying [17]

If the strain gauges are not placed directly at the toe line but not far away from the toe, the strain gauge reading will not vary considerably. They will show variation in later stages of loading. Aykel, Kolstein & Bijlaard.[30, 31] have placed the gauges at 10mm from butt weld toes as shown in figure 6; the reason of this strain gauge measurement is to define the number of cycles required to cause crack initiation.

The use of this methodology (strain measurement drop as mentioned in the precedent paragraph) must be always combined with another supportive crack detection method to calibrate it's results. There is no clearness if this is done in the previously described work which used this methodology [17–20, 28, 30, 31]. The exact position of the strain gauges were not always specified despite the fact that strain and stress values are changing remarkably close to the weld toe [1]; it's vague not to specify where exactly the gauges are placed. Another problem related to this methodology is the ability of formation of multiple cracks as given in [27]. This is typical for



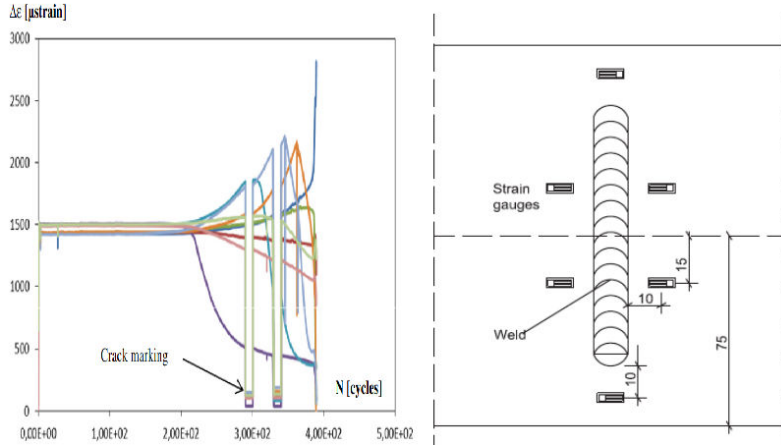


Figure 6: The strain gauges aren't sensitive when placed away from the weld [30]

long welded lines (Butt welds [30] or transversel non load carrying fillet weld [27]); the crack formed earlier might affect the reading of the neighboring gauge so the reading can be misleading; this is not always a problem since shallow crack won't have a tangible effect on the neighbouring strain gauge reading until it becomes deep.

In comparison with cracks created artificially, pre-fatigue loading ( followed by crack detection) is more representative since the crack shape is not perfect and will be similar to the crack generated under real fatigue loading. The difference is shown in figure 7. Besides, the damage created in other regions of the weld will be obtained only in the case of pre-fatigue loading is applied. But despite of the importance of the pre-fatigue stage, the results will be a function of the accuracy of the crack detection methods which are summarized in table 1. In general it can be said that pre-fatiguing until certain crack dimension is better than pre-fatiguing to a certain number of cycles but it requires specific and reliable detection method.



Figure 7: Comparison between real fatigue crack ( black zone) and artificially created crack shapes

Table 1: Summary on the comparison of crack detection method for fatigue life extension

Method	VI(1)	DP(2)	UT(3)	ACPD(4)	SG(5)
Simplicity	Very simple	Very simple	simple	Complicated	Complicated
Accuracy	large surface crack	Length >2mm	depth >2.5mm	depth >0.5mm	No limit in theory
Expenses	Cheap	Cheap	Expensive	Expensive	Moderate
Uses in literature	[30, 31]	[15, 27]	[25-27]	[15, 16, 24]	[17-20, 28, 30, 31]

(1):Visual inspection.

(2):Dye penetrant.

(3):Ultrasonic testing.

(4):Alternating current potential drop.

(5):Strain gauge variation.

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### 1.3 Fatigue life extension

Various methods have been developed for repairing fatigue cracks. These methods can be classified according to the depth of the crack must be retrofitted. This emphasizes the importance of detecting crack depths at which are described in the previous section. When the crack is in early stages (Shallow crack) it can be retrofitted by the methods described in the IIW recommendations [1]: grinding, TIG-remelting and peening. If the crack is deeper than 5mm, other methods are more efficient such as re-welding, hole drilling to arrest the crack and splice plate methods. The focus in this study is on shallow crack retrofitting.

#### 1.3.1 Peening

High frequency mechanical impact (HFMI) can have different names depending on the machine used for the treatment. Needle peening (NP), hammer peening(HP), ultrasonic peening(UIT) and Hifit are usually used to induce compressive residual stresses at the weld toe region. Peening is widely used method for enhancement of fatigue strength of new structures. The effectiveness of the treatment in this case will be a function of:

1. The Peening parameters: It was found that increasing the nominal pin radius increases the level of compressive residual stresses introduced at the weld toe. This is because of the larger impact force generated by bigger pin. However, the smaller pin has higher chance to reach the weld toe. Likewise, The speed of the treatment is an important factor since the higher acceleration creates higher impact forces and results in higher residual stresses [32]. The inclination of the indenter will also influence the resulting groove shape, but there are recommendation in relation to the inclination of axis of indenter with respect to plate surface and direction of travel[29].
2. The base metal strength: One of the benefits of the peening process is the utilization of the material strength for fatigue resistance. This utilization is due to higher compressive residual stress and hardness for higher strength steels. More details can be found in [32, 33].
3. The treated geometry: If the original radius of the as-welded detail is very small, peening results in higher improvement due to enlargement of radius and reduction of stress concentration. This effect is added to the hardness and residual stress enhancement. However, if the toe radius is already large, the improvement in geometry isn't guaranteed.
4. The loading level: Because the main benefit obtained from peening is attributed to the high compressive residual stress introduced at the toe. The local stress ratio changes from positive to negative owing to residual stress. However, under high stress ratio the local stress ratio increases and the efficiency of peening get lost. In addition to stress ratio, the overload and underload might cause a relaxation of the compression and loss of treatment effectiveness [33].

In case of life extension of cracked structures, another parameter will be added which is the depth of the crack before treatment. However, there is a dispute between the specialists about the maximum depth of the crack can be retrofitted by peening, Martin, Barsoum & Schäfers suggested in [20] that peening shouldn't be used when the crack is deeper than 0.5mm in mild steel joints, but Branco et al. increased the limit to 2.5mm for almost the same steel strength [17–19]. Houjou, Fukeri and Takahashi concluded that the maximum crack depth that can be successfully retrofitted

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by peening is 1 and 1.2mm for stainless and mild steel respectively[21–23]. A summary of the differences between their analysis is shown in table 2. It’s noteworthy that the studies that uses the loading history to represent pre-fatigue loading aren’t included in the table.

The main objective of displaying this table is to figure out what is the maximum crack size (depth) that can be retrofitted using peening. The availability of hardness and residual stress distributions before and after treatment would give an indication about the treatment depth. However, that doesn’t directly imply that the depth where compressive residual stresses reached is the allowable crack size before treatment. For example, the depth of compression before and after treatment in [23] is greater than 2mm, but the allowable crack size is 1.2mm, so it’s not one to one relation.

It can be also seen that the original fatigue class (FAT) doesn’t play a major rule and can’t be correlated to the allowable crack depth(a). The gain factor is the ratio between the life with and without treatment of the same detail. it’s immaterial if the original life before treatment was long or short. For instance, if the original life was  $10^6$  cycle and after peening the total life becomes  $1.3 \times 10^6$ , that indicates a gain factor  $G_n = 1.3$ . If it compared with other detail having original life of  $5 \times 10^5$  and after treatment the total life becomes  $10^6$ , that means  $G_n = 2$ , and the second treatment is more efficient than the first despite of the longer fatigue life of the first.

The difference in aspect ratio (crack depth to length ratio) before peening found by different authors is imputed to the difference in geometry of the loaded specimen, the difference in the crack depth and the difference in residual stress distribution. Details with long welds line (T-Joints, Transverse attachment, cover plate) tend to form surface cracks with lower aspect ratio (see table 2) especially if the compressive residual stress is higher in depth direction which traps the crack in upper layers. However, when the crack becomes deeper the aspect ratio tends to increase. After peening, the aspect ratio shows an increase regardless of the detail shape[12].

As mentioned before the high loading level (Stress ratio  $R$ , Maximum stress  $\sigma_{max}$ ) is more harmful for peening, this is found to be also applicable for cracked structures retrofitted by peening. The gain factor in fatigue life decreases from 1.6 to 1 when the nominal stress range increased from 200 to 300MPa [20]. On the other hand Branco et al.[17] have studied the effect of higher nominal stress and the gain factor was found to be still high.

There are two possible explanations for this observation:

1. The radius before and after treatment in [17] are around 3, this implies that the local stresses are low because of the smoothness of the weld toe. However, in the case mentioned in [20], the radius found is very Small (0.05), that causes a high stress concentration at the weld toe, and might cause a relaxation of the local residual stresses there.
2. The welding residual stresses at the weld toe is compressive and the layer of compression is very thin (0.06mm) in the specimen given in [20] which may lead to faster relaxation during pre-fatigue stage. This can’t be compared directly with [17] since the welding residual stress is not known there, but at least in the latter paper, a high compression is measured at the surface after peening



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on contrary to the former mentioned paper.

Zhang et al.[12] has conducted a FEM to simulate the peening effect on the existing cracks with different depths, see figure 8. In this analysis, it was found that efficiency or deficiency of peening is a function of two factors:

1. The residual stress: It is found that treatment in early stages results in crack healing, but when crack is deeper than 0.1mm, it will not disappear. However, compressive stress dominates around the crack. When the crack becomes deeper than 1.2mm, a tensile residual stress starts to appear at the crack tip. This tension is bounded with global compression, the effect of tension is becoming larger for larger cracks[12, 34].
2. The crack inclination: If the crack is peened in its early stages (Not deeper than 0.8mm), it will change its orientation from vertical to horizontal. That might cause a change in crack growth mode from I into II, which is slower [34]. On the other hand, if the crack is deep, peening will be insufficient to change the orientation, and the crack will keep growing in mode I. The crack is assumed to grow in vertical position (with respect to the applied loading level), that is possible crack growth direction, but it could also grow with an angle less than  $10^\circ$ . Another factor which is not studied is the inclination of the indenter, this might also have an influence on the orientation of the crack after peening.

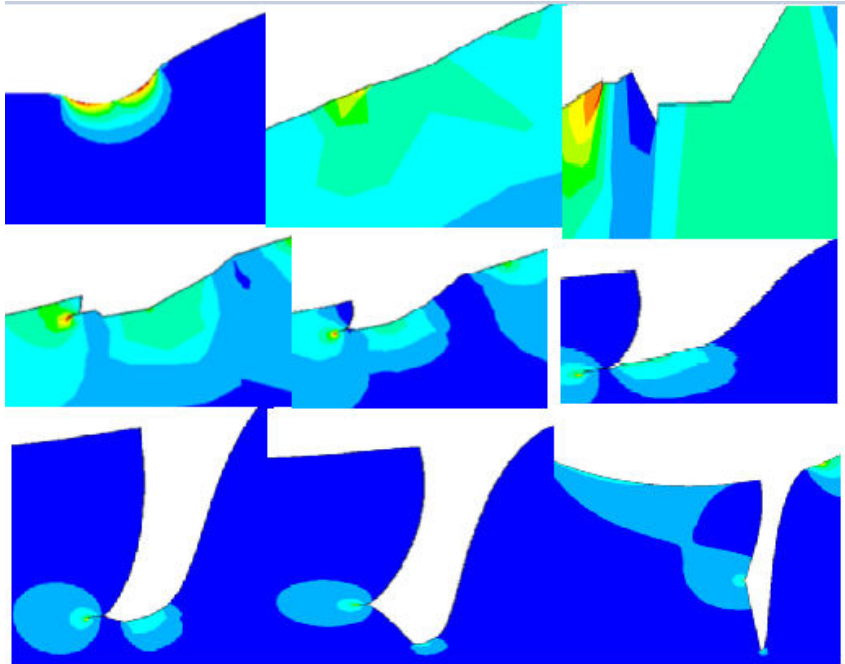


Figure 8: Cracks with different depth (0.01, 0.02, 0.05, 0.1, 0.3, 0.5, 0.8 and 1.2mm) behaviour under peening [12]

The fatigue fractography photos in figure 9 show the difference between fracture surface when peening is performed on as-welded (left) and pre-fatigued (right) butt welded specimens. A fracture of stamp-like impression (given by the arrow) shown in the left figure is caused by repeated extrusion of two opposite surfaces of extending fatigue cracks. These impressions are called by the author 'Tire tracks' and they tend to extend perpendicularly to the direction of crack propagation[12]. On the other hand, in pre-loaded specimen (29% of the as-welded fatigue life), the small fatigue cracks already exists before peening and the treatment will form a series of parallel plastic deformation traces, this is shown in the right side of figure 9.

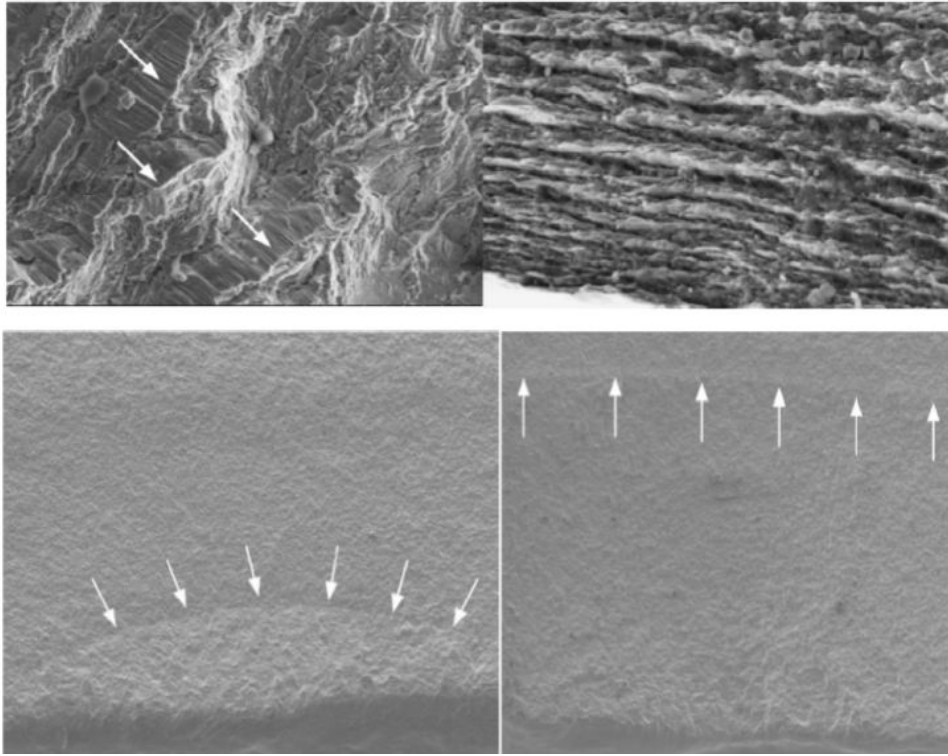


Figure 9: UL: The fracture surface of as-welded peened specimen. UR: The fracture surface of pre-fatigued peened specimen[12]  
 D: Beach marking showing the extended fatigue damage under a pre-fatigue loading of 43,57% of as-welded fatigue life respectively[12]

If the peening is applied after long pre-fatigue loading stage, the cracks will be deeper and peening will not be able to create these parallel plastic deformation for the whole cracked zone. The depth of the crack is remarkable because of the formation of beach marks. These marks are the results of changing the stress level from tension to compression locally. See figure 9 which shows the beach marking at different pre-fatigue loading stages. It's noteworthy that this kind of beach marking is not useful for crack detection purposes since they are shown on fractured specimens.

One of the signs of the success of the peening treatment is the appearance of cracks away from the weld toe, this means that treatment makes the detail stronger than locations where cracks weren't expected (e.g: The root or base metal). In [15, 16] the cracks originated from the root in most of the specimens, while in [26] only the specimens loaded with low stress ratio shows root failure. In [21–23] some of the specimens cracked from outside the artificially created slit, which means the treatment raised the strength of the pre-cracked region even more than the pre-cracked one similarly to the case studied in [11].

In some cases, peening is applied while the structure is under static tensile stresses. Despite of the resulting high stress ratio, the benefit of peening was equal [15] or even higher [26] than peening under no static tension. Different explanations are proposed by Maddox et al, one of them is the high welding tensile residual stress which makes the further increase in the nominal stress range due to static tension not significant [15]. Another possible explanation is that peening under loading will partially prevent the relaxation of compressive residual stress after peening since

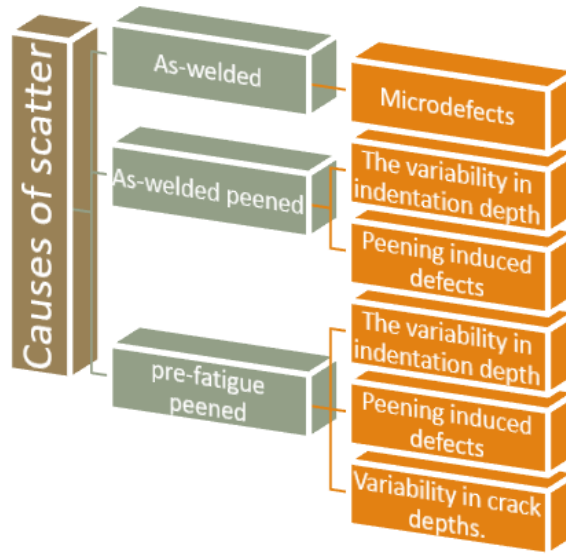


Figure 10: The causes of fatigue strength scatter in as-welded and peened structures.

part of the load (The static part) is applied before peening [26]. Another possible explanation is that peening while structure is under tension allows for crack opening and expands the weld toe region, that gives better chances for the indenter to hit the targeted zone.

It is conspicuous that the scatter of results is higher for pre-fatigued peened specimen in comparison with as-welded and as-welded peened specimens, the scatter is attributed to the variability of the crack sizes, especially when the crack detection doesn't yield a specified crack depth value [12, 15, 16, 25, 26]. However, if the treatment is applied in early stages when the crack is small, the results is less scattered because of the removal of local micro-defects existing in the weld toe of as-welded specimens which cause the variability of their strengths. The causes of scatter is summarized in figure 10.

It was reported in [35] that peening can also be used as remedial treatment if the original treatment ( By grinding or welding) isn't optimum and the crack tip isn't fully removed. In this case, the remaining crack tip will be exposed to the compressive residual stress field generated by peening. The following conclusions can be drawn from the literature review about peening of cracked specimens:

1. The effectiveness of peening is lost when the crack becomes deeper. The allowable crack depth is a function of residual stress distribution after and possibly before treatment, the peening parameters and other factors. But most of the papers recommended not to use it for a crack deeper than 1.5-2mm.
2. No correlation is found between the original FAT and the gain factor.
3. The peening parameters, base metal strength, the weld toe radius and loading level affect the peening effectiveness for both new and cracked structures.
4. The peening can result in change of the crack growth direction from vertical to horizontal with respect to the applied loading direction, and this will cause crack growth retardation.
5. The fracture surface of pre-loaded fatigued structure shows parallel plastic deformation which looks different from the tire tracks shown in as-welded peened structures fracture surfaces.

6. High stress ratio is harmful for the peening. However, if Peening is performed under high mean stress it can be beneficial.
7. The scatter of fatigue life becomes higher if the treated cracks are deeper.

Table 2: Comparison between the specialists analyses for life extension by the mean of peening

Research	Lienter	Branco	Takahashi	Houjou	Fisher	Maddox
References	[20]	[17–19]	[21, 22]	[21, 23]	[25, 26]	[15, 16]
Published	2016	2004	2014-18	2014-18	1974	2011
Base metal	S355	St 52-3	SU316	SM490④	A36④	355J2+N
Yield strength (MPa)	355	400	307	371	250	390
The stress ratio	0.1	0.1	0	0.05	0.075-0.15⑥⑩	0.5-0.69⑩
Stress range(MPa)	300,200	350	320	450	83,128,171	55-120
Detail type	longitudinal	T-Joint	Butt weld	Butt weld	Cover plate	longitudinal
Type of loading	Axial	Bending	Bending	Bending	Axial	Axial
Plate thickness(mm)	5	12.5	5	20	14	30
Toe radius (before/after)	0.05/?	3.56/3.05	?	?	?	?
RS before/after peening	-250/?	?/-355	100/-350	-70/-550	?/?	?
Depth where RS=0(mm)	0.06/?	?/?	0.2/1.4	>2/>2	?/?	?
Peening method	HMFI	HP	NP	NP	UIT	UIT
Kt before/after	?/?	?/?	2.67/1.5	2.33/2	?/?	?
Hardness before/after	?/?	?/320	160/400	280/304	?/?	?
Gain factor in cycles or strength when a=1mm①	Gn= 1-1.6⑦	Gn=11 Gs=1.2	Gs ≥ 2⑤	Gs ≥ 1.8⑤	Gs=3	Gn=4 ×
Studied crack sizes	1	2.4-4③	0-1.5	0-1.6	1.3-3.8③	≤1 (L=2-8))
Detection method	SG	SG	X②	X②	UT	DP
Aspect ratio a/c⑨	0.7	0.25-1.1③	1	1	0.13-0.42③	0.4-0.5②
Initial defect size a.	0.1	0.1	?	?	?	?
Allowable a (mm)	0.5-1	≤2.5	≥1	≥1.2	≤3	≤ 1.5 (L≤ 8)
FAT (MPa)⑧	71	100	100	100	50	63
Toe failure ○	Always	Always	usually	usually	Often	Rarely

?: These values are not specified in the corresponding papers.

①: Gn: The gain in fatigue life including the pre-fatigue life and Gs: The gain in fatigue strength.

②: No crack detection is taken place since crack is created artificially.

③: The range is because different specimen was loaded to different crack sizes.

④: The marked materials have proof strength and no yield strength.

⑤: The marked cells have higher gain factor because the given number doesn't include the life before treatment.

⑥: Here, two minimum stress were used: 14,70MPa.

⑦: Different gain factors because the cracked specimen were tested for different stress ranges.

⑧: The fatigue resistance class given by [36].

⑨: The given aspect ratios is before treatment.

⑩: The stress ratio is high because the peening is taking place while the structure is under loading.

○: In some cases the failure starts from the root or other positions.

×: High gain factor, However its the average of highly scatter results.

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### 1.3.2 TIG remelting

TIG remelting is aimed to remove the weld toe flaws by remelting the material at the weld toe. It also reduces the stress concentration locally by increasing the radius of the toe. This will provide smoother transition between the base plate and the weld face [1]. TIG is widely used treatment method in the literature for new structures[37–46].

Unlike peening and grinding, the treatment in TIG remelting is thermal instead of mechanical, usually the heat input of this kind of treatment is lower than that in welding and has more local effect [39]. Three geometrical parameters are expected to change after TIG remelting as shown in figure 11: The weld toe radius, is the most relevant one and it plays vital rule in reducing the stress concentration. That explains why the IIW[1] has specified 3mm to be minimum radius after treatment. The second factor is the weld height which usually decreases after TIG, that has a positive effect in decreasing the stress concentration. The last factor is the undercut formation which has a higher possibility to form after TIG remelting depending on treatment quality as shown in figure 11. The formation of undercuts has detrimental effect because of the resulted higher stress concentration.

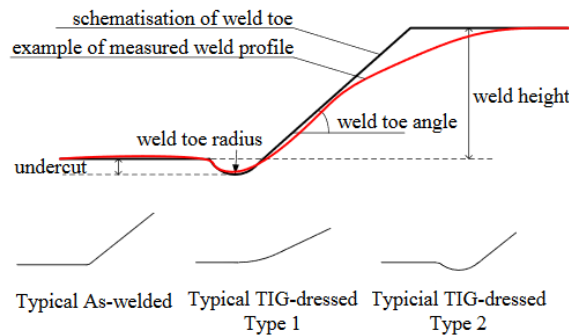


Figure 11: Typical weld toe profiles before and after TIG[46]

In most of the cases, TIG remelting causes an increase in hardness value locally where crack formation is expected, that causes an increase in crack initiation life. However, the hardness increase might lead to faster crack propagation once the crack exists[47]. Softening behaviour is expected for ultra high strength steel, this implies that TIG isn't preferred method for this kind of steel [44, 46].

Unlike peening, the enhancement from TIG remelting is not dependant on the applied stress level [39]. This is explained with the fact that the treatment efficiency in TIG doesn't rely on the introduced residual stress, although it changes the residual stress from the as-welded state (positively or negatively).

Moreover, TIG remelting can be used for retrofitting existing cracks at the weld toe region; this is because the thermal treatment creates a fusion zone (FZ) where the heat causes a complete change in the material properties. This zone is bounded by heat affected zone (HAZ) which is bounded by the unaffected zone of the base metal (BM), the different mentioned zones are shown in figure 12. The diffused zone will be free from any crack since the original cracked material is replaced with new material by diffusion.

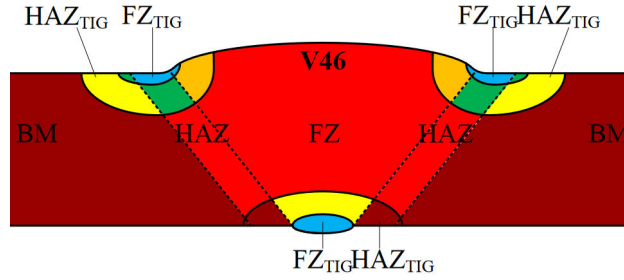


Figure 12: Fusion zone created by TIG remelting (blue colored)[46].

Fewer papers are found in the literature concerning retrofitting crack by TIG remelting [25–28]. The common factor between these papers is the drawn conclusion that the crack depth prior to treatment is the major decisive factor on determining treatment’s effectiveness. Some different aspects between the mentioned papers are shown in table 3. Noticeably, most of the papers were written longtime ago (seventies and eighties); which explains the uncertainty in crack detection methods and the large scatter in estimated crack sizes found especially in [25–27]. In [27], the difference between the used two detection methods estimation (UT, PT) reaches 500%.

The most important factors affecting the efficiency of TIG remelting process are:

1. The depth of the fusion: When the flow of heat in the treated zone is high, the treatment reaches deeper region. This makes the probability of retrofitting crack tip higher. The heat input is controlled by three factors: the voltage (V), the input current (A) and the remelting speed (S). The slower treatment with high voltage and current ensures deeper fusion and better results. If the toe is free from cracks, the heat input has reversed effect on fatigue life [48]; this is because increasing the heat input reduces the cooling rate and results in coarser micro-structure. However, the benefit of high heat input (for cracked structures) found to be higher than the reduction in fatigue life due to this reversed effect.
2. The existing crack prior to retrofitting: Deep crack (which are not fully fused) have the potential to grow again after treatment. However, it’s found that even if the crack is not fully removed, some degree of fatigue life extension is still achieved depending on the remaining crack shape. Ramalho et al. found an average of 20% extension in fatigue life for incomplete fusion [28], similar gain factor is found by Miki et al. for remaining crack depth between 1.5-8mm [27]. The position of the remaining crack tip with respect to weld toe is also important; if the crack tip is so deep, the local stresses will be similar to the nominal stresses ( $K_t \approx 1$ ) and the crack is not likely to grow.

The remaining subsurface crack usually grows toward the toe, that is because of two reasons: the first is the higher stress concentration around the weld toe because of the closeness to the weld toe. The second is the increase in hardness due to fusion which results in faster propagation rate[47].

The interaction between the two mentioned factors (depth of crack and fusion depth) is summarized in figure 13. Notice that even for relatively deep cracks ( $h=3\text{mm}$ ), the fatigue life can be extended by  $10^5, 10^6$  cycles (30%,300% of the as-welded fatigue life) if the fusion depth reaches 2, 3mm deep respectively.



Table 3: Compassion between the specialists analyses for life extension by the mean of peening

Research	Ramalho	Miki <sub>1</sub>	Miki <sub>2</sub>	Fisher
References	[28]	[27]	[27]	[25, 26]
Puplished	2010	1987	1987	1974
Base metal	St 52-3	SM58	SM58	A36
$\sigma_y$ or $\sigma_{0.2}$ (MPa)	400	590	590	250
R	0.05	0.1	0.1	0.075-0.15
$\Delta$ Sn (MPa)	?	280	280	55-120
Detail type	T-Joint	Longitudunal	Transversal	Cover plate
Type of loading	Bending	Bending	Bending	Axial
Plate thickness (mm)	12.5	15	15	14
RS before/after TIG	-90/-80	?/?	?/?	?/?
Toe radius before\after	4.11/6.25-12 ①	0.7/5	?/?	?
Kt before /after	?	2.5/1.4	2.5/1.4	?
Gain factor in cycles	Gn1 $\leq$ 1.2 ① Gn2=2.45	Gn1 = 1.1 ④ Gn2 $\gg$ 2	Gn1=1.3-1.5 ④ Gn2 $\gg$ 2	Gn $>$ 2
Gain factor in cycles or strength when a=1mm	Gn $>$ 2.5	Gn $\gg$ 3	Gn $\gg$ 3	Gn $\gg$ 2
Crack detection method*	SG	DP	DP , UT	UT
Aspect ratio a/c	?	0.16	0.15	0.13-0.42
depth of fusion (mm)	$\approx$ 1.62	3-4	3-4	1.5-7.1
Heat input (KJ/mm)	1.93	2.07	2.07	2.12-3.46
Position of TIG from the toe		0-1	0-1	
Initial defect size a.	0.15	?	?	?
Studied crack size	2.2-6.9 ① $\leq$ 2.5	L= 2-32	3-10 ⑤ L=10-50(2-50)	1.5-3 L=3-6
Allowable a (mm)	2.5	Depends on $d_f$	Depends on $d_f$	5
FAT (MPa)	100	71	100	50
Toe failure	Always	Often ②	Always	usually ③

①: Two series were studied, the first with deeper cracks allowed.

②: The crack sometimes starts from the other weld leg and propagates through the reinforcement.

③: Half of the specimens show root failure.

④: The first raw is for partial fusion.

⑤: The depth is estimated by UT, while the length is estimated by both UT,PT (PT estimation is between parenthesis).

\*: See table 1.

The depth of fusion shown in the figure 13 isn't the maximum fusion depth but the depth of fusion at the maximum crack depth level. That explains why TIG remelting is the most demanding retrofitting method in term of the required expertise to reduce the difference between maximum crack level and maximum fusion level.

In comparison to peening, the fusion usually reaches deeper regions than the compressive residual stress layers caused by peening .That makes TIG more capable of retrofitting deeper cracks than peening. However, if the crack is retrofitted successfully by peening it results in longer fatigue life due to the effect of compressive residual stress. On the other hand, TIG remelting requires higher quality control since the position of treatment is so crucial in crack fusion and reducing the stress concentration. If the treatment quality is low, the position of maximum fusion depth will not coincide with the position of maximum crack; that causes a reduction in allowable crack depth.

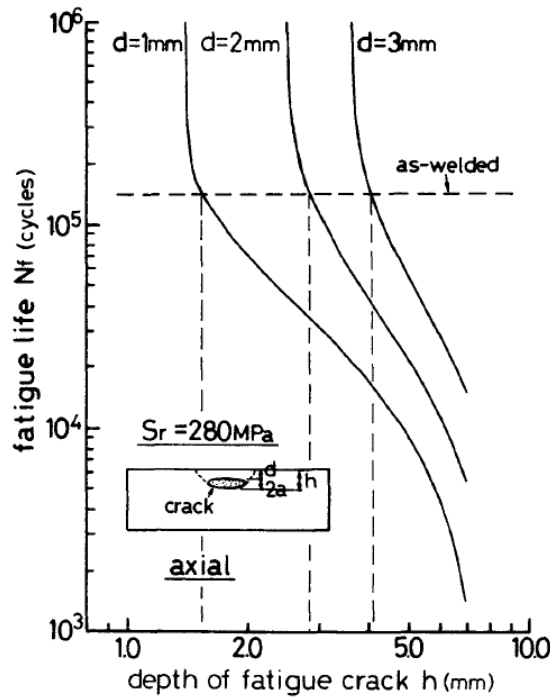


Figure 13: Fatigue life of joints with remaining cracks after incomplete penetration of TIG remelting[27].

It can be concluded from the literature review on retrofitting cracks by TIG remelting that:

1. Unlike peening, the efficiency TIG remelting isn't sensitive to high stress ratio or maximum stress [26].
2. There are two factors affecting the treatment efficiency: The fusion depth and the depth of existing cracks before treatment[27].
3. An incomplete crack fusion can be harmful because of the potential for propagation [28]. However, even in such a case an increase of the fatigue strength (>20%) may still be obtained depending on the remaining crack depth.
4. The higher heat input increases the fusion depth (see table 3).
5. The required expertise and quality control in TIG are high and can have an influence on the maximum allowable crack.

## 2 The use of fracture mechanics in the literature

Linear elastic fracture mechanics (LEFM) is widely used method for estimating the fatigue propagation life of welded structure because of its simplicity. Nonlinear fracture mechanics is not needed for HCF since the plasticity around the crack tip is limited to small zone. Hence, LEFM is simpler and more appropriate for crack-like imperfection. This approach is to be used for crack propagation phase, the initiation phase is harder to be computed analytically.



## 2.1 Gain factor concept

The gain factor concept (mentioned in tables 2 and 3) is developed to assess the success of the fatigue life extension techniques, the concept is used in [17–20, 28]. The gain factor in fatigue life is defined by the following relations and illustrated in figure 14:

$$N_1 = N_i + N_{pb} + N'_{pa} \quad (1)$$

$$N_2 = N_i + N_{pb} + N_{pa} \quad (2)$$

$$N_3 = N_i + N_{pbFM} + N'_{paFM} \quad (3)$$

$$N_4 = N_i + N_{pbFM} + N_{paFM} \quad (4)$$

Where:

$N_1$  : The experimental fatigue life for the as-welded detail.

$N_2$  : The experimental fatigue life for the treated detail ( Including the life before treatment).

$N_3$  : The predicted fatigue life for the as-welded detail.

$N_4$  : The predicted fatigue life for the treated detail ( Including the life before treatment).

$N_i$  : The number of cycles causing crack initiation ( experimentally evaluated).

$N_{pb}$  : The number of cycles causing crack propagation before crack detection.

$N_{pa}$  : The number of cycles causing crack propagation after crack detection and treatment.

$N'_{pa}$  : The number of cycles causing crack propagation after crack detection (No treatment).

$N_{pbFM}, N_{paFM}, N_{pbFM'}, N_{paFM}'$ : Same as  $N_{pb}, N_{pa}, N_{pb'}, N_{pa}'$  but evaluated analytically by fracture mechanics.

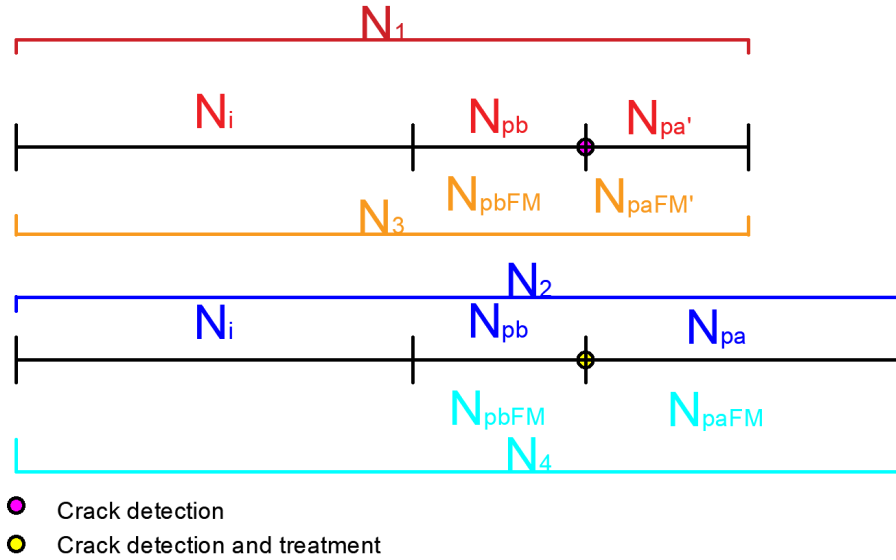


Figure 14: Illustration for equations 1, 2, 3 and 4.

And the gain factor is then calculated by :

$$g_N = \frac{N_2}{N_1} \quad g_{N_{FM}} = \frac{N_4}{N_3} \quad (5)$$

Where:

$g_N$ : The experimentally obtained gain factor.

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$g_{N_{FM}}$ : The gain factor obtained by fracture mechanics.

The main two equations used in crack propagation analysis which forms the backbone of fracture mechanics are:

$$K = F \times \sigma \times \sqrt{\pi \times a} \quad \frac{da}{dN} = C \times (\Delta K)^m [34] \quad (6)$$

Where:

$F$ : A factor accounting for crack geometry and crack size, detail geometry, loading and boundary conditions.

$\sigma$ : The nominal stresses.

$a$ : The crack size.

$K$ : Stress intensity factor.

$C, m$ : Paris law parameters.

$da/dN$ : Crack propagation rate.

The factor 'F' is a multiplication of different factors shown in equation 7:

$$F = F_e \times F_t \times F_g \times F_S \quad (7)$$

$$F = F_e \times F_t \times F_g \times F_{el} \quad (8)$$

Where:

$F_e$ : Factor accounting for crack configuration.

$F_t$ : Factor accounting for plate thickness and width.

$F_g$ : Factor accounting for the stress concentration.

$F_S$ : Factor accounting for surface crack.

$F_{el}$ : Factor accounting for crack exists close to the surface.

Equation 7 is applicable for cracks originated from the surface, while equation 8 applies for subsurface cracks. If the treatment is not complete and crack remains (Incomplete crack remelting by TIG or In complete crack forging by peening), the second part is applicable. These equations are mainly applied for predicting crack propagation in depth direction. However, they can also be used for crack propagation in weld direction but without plugging in  $F_S$  or  $F_{el}$ .

## 2.2 Weight function approach

Because of the complexity resulted from evaluating all of the functions in equation 7, another approach called '**Weight function**' can be used. This approach is defined as the stress intensity resulting from a simple load configuration. Its mainly used for semi-elliptical crack shape which is the case in weld toe fatigue cracks. The equations used in this approach are shown in figure 15.

$M_1, M_2$  and  $M_3$  are factors dependant on the crack aspect ratio. Notice that the residual stress effect can be included in the effective stress ratio evaluation. Moreover, the effect of stress concentration is taken into consideration in  $\sigma$ , which is the local stress for the un-cracked plate. The mechanical material proprieties ( $\sigma_y, \sigma_u, \sigma_{fl}$ ) are proportional to the harness [23], so they can also be accounted for when the stresses are evaluated. For example, if the welding causes a 30% increase in hardness and peening or remelting causes further 10% hardness increase at the weld toe, the yield, ultimate and fatigue strength values are increased by a factor 1.43

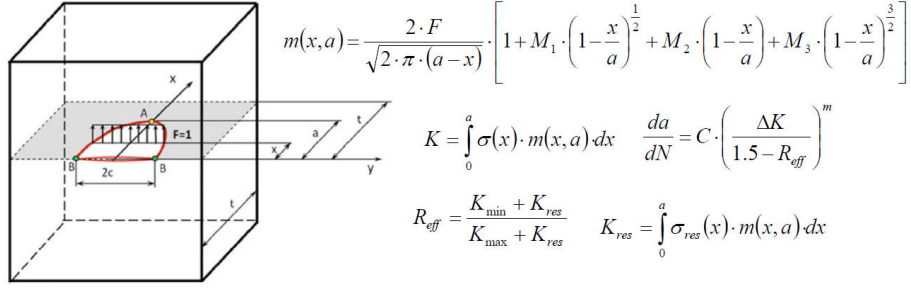


Figure 15: The weight function approach equations[20].

(1.1 × 1.3). This emphasizes the importance of hardness distribution for base metal, for as-welded and for treated conditions. However, hardness effect is only to be used when the crack is completely removed and the lower integration limit in evaluating  $K$  is zero.

On contrary to the conventional fracture mechanics formula which is capable of accounting for the residual stress, hardness and stress concentration at only single point, weight function approach takes the distribution of these factors in region around the crack into account. That's substantial because the residual stress gradient is too steep around the toe [20], and the same for hardness [18] and stress concentration factors [23, 27]. One of the problems associated with this method is the incapability of analyzing the sub-surface cracks. Moreover, The multiple close cracks and crack coalesce aren't accounted for in weight function approach. More details about this approach can be found in [49].

### 2.3 Threshold stress intensity factor

Crack in its early stages is dependant on the micro-structure. It propagates faster within the grain physique and slower close to the grain boundaries, as shown in figure 16. The use of Paris law isn't accurate to estimate short crack growth until crack becomes long enough. The applicability of Paris law is a function of the crack size. but a general rule of thumb is to use Paris law for cracks deeper than 1mm [50].

The very early stage of fatigue life (initiation life) isn't problematic since the weld already contains defects which consumes part of initiation life. However, the intrinsic value of crack size is between 0.05-0.15mm [20] which is much lower than the drawn limit ( $\approx 1\text{mm}$ ). That makes the evaluation of the threshold value of stress intensity essential; in order to know when Paris law is applicable and when the crack is referred as short or long. However, the use of Paris law after to study propagation after treatment is more complicated since the crack size isn't known then or there is no existing crack. This point will be discussed in detail later.

The threshold value of stress intensity  $\Delta K_{th}$  is a function of the crack size, this dependency is given by Kitagawa diagram, and can be expressed by the following equations [23, 49] :

$$\Delta K_{th} = \frac{1}{\sqrt{(\Delta K(L)_{th})^{-2} + \left(\frac{1}{\alpha \Delta \sigma_{w0} \sqrt{\pi a}}\right)^2}} \quad \alpha = 1 + 1.464(a/c)^{1.65} \quad (9)$$

Where:

$\Delta K(L)_{th}$ : The threshold stress intensity for long crack, For steel  $\Delta K(L)_{th} = 8.4\text{MPa}\cdot\sqrt{\text{m}}$ .

$\Delta\sigma_{w0}$ : The fatigue limit for as-welded specimen.

$\alpha$ : A shape factor dependant on the crack aspect ratio.

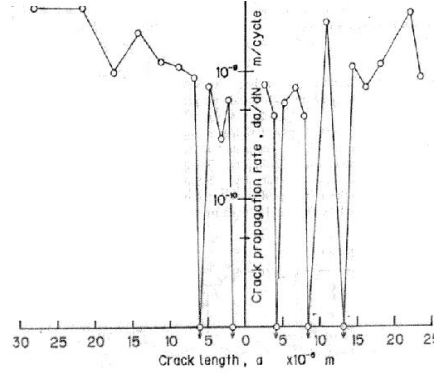


Figure 16: Crack propagation in early stages is dependant on micro-structure [50].

The improvement of residual stresses and stress concentration can be included in the evaluation of stress intensity  $\Delta k$ . The threshold value of stress intensity  $\Delta k_{th}$  is calculated using equation 9; then the values of  $\Delta k$  and  $\Delta k_{th}$  are compared. If  $\Delta k_{th}$  is larger, the crack is arrest and doesn't have the potential to propagate which implies that the treatment succeeded. This methodology says nothing about the gain in fatigue life, it only assesses the arrest of the crack propagation. In comparison with the use of Paris law, this methodology gives only qualitative assessment for the fatigue life and not quantitative like Paris law.

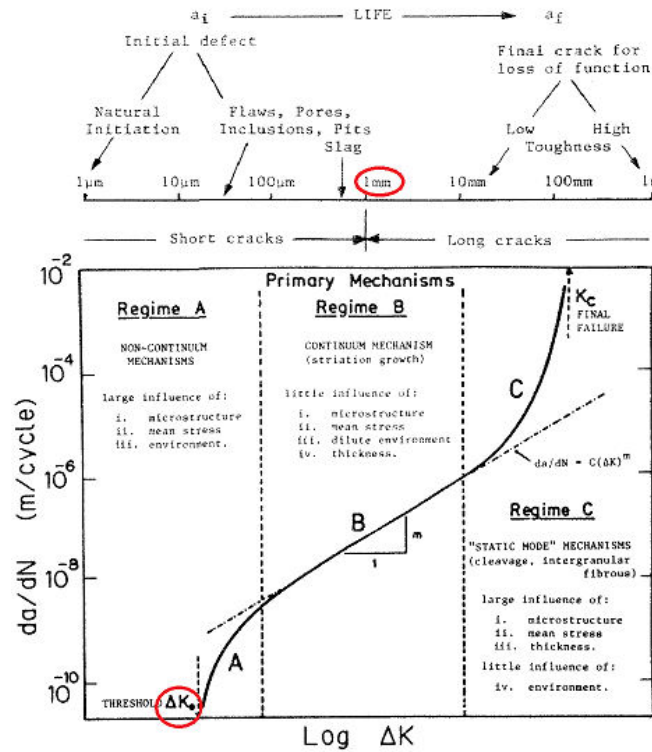


Figure 17: Crack propagation curve and the applicability of Paris law [50].

Table 4: U: The disconformity in as-welded conditions. L:The disconformity in peening conditions. [18]

Specimen	$a_0$ (mm)	$c_0$ (mm)	$a_m$ (mm)	$c_m$ (mm)	$N'_{bm}$ (1)	$N'_{bmp}$ (2)	Ratio (1)/(2)	$N'_{am}$ (3)	$N'_{amp}$ (4)	Ratio (3)/(4)
22	0.1	0.912	1.67	15.224	310000	356992	0.87	356992	59230	6.03
23	0.1	0.698	3.862	26.947	123600	105601	1.17	105601	18665	5.66

Specimen	$a_0$ (mm)	$c_0$ (mm)	$a_H$ (mm)	$c_H$ (mm)	$N'_{bH}$ (1)	$N'_{bHp}$ (2)	Ratio (1)/(2)	$N'_{aH}$ (3)	$N'_{aHp}$ (4)	Ratio (3)/(4)
24	0.1	0.222	2.413	5.357	202306	217984	0.93	1130853	76992	14.69
26	0.1	0.575	3.18	18.292	42321	42485	1.00	38934	7202	5.41
27	0.1	0.271	2.85	7.717	88458	105845	0.84	132115	28283	4.67
28	0.1	0.23	4	9.2095	109237	146011	0.75	170344	21558	7.9
29	0.1	0.176	3.3	5.8065	427107	414061	1.03	894786	96768	9.25
53	0.1	0.829	1.441	11.959	38746	24692	1.57	405064	8407	48.18

a: The crack depth. c: The crack length. N:Experimental life N': Predicted life.  
The Lowercase key: 0: Initial m: marking H: Peening b:Before a: After P:Predicted.

### 2.3.1 Critical view on the literature use of fracture mechanics in fatigue life extension applications

For fatigue life extension of welded steel structures, fracture mechanics is used in different forms. Conventional parameters approach, weight function or threshold stress intensity assessment are the methods used in literature. They are summarized in table 7. It can be seen from the table that both the parametric and weight function methods aren't applicable for short cracks. That explains part of the disconformity with test results found by Branco et al.[18]. In addition to that, the welding and peening residual stress weren't taken into consideration in the mentioned study.

The ratio (1)/(2) gives the difference in fatigue life between experiment and fracture mechanics estimations before crack detection, while the ratio (3)/(4) give the difference after crack detection. Notice that the ratio (1)/(2) can be above or below one, this is expected because of the high scatter behaviour of short cracks due its dependency on the micro-structure. the disconformity becomes larger when the crack is longer because Paris law parameters are not evaluated for the heat affected zone where the long cracks have reached. The disconformity becomes greater after peening, that is because the peening residual stresses wasn't accounted for in that analysis.

Further disconformity between fracture mechanics prediction and experimental results for TIG remelting by Ramalho et al.[28] is shown in table 5.

The huge gap between  $N_p$  and  $N'_{reab}$  which is shown in table 5 might be explained by the simplifications considered in that analysis:

1. The residual stress and hardness aren't introduced in the fracture mechanics analysis.
2. Paris law parameters are obtained for the whole structure, and not for each part separately (HAZ, Base and weld metal), that's why the expectations in table 5 is less accurate than the one shown in table 4.
3. The predicted values are estimated for crack propagation until 0.6 of the plate thickness, but the experimental results is given for the final fracture.

Leitner et al. [20] have included the welding residual stress in the fracture mechan-

Table 5: The gap between the predicted and experimental results for TIG remelting [28]

Specimen	$a_{reab}$	$\Delta\sigma$	$N_p$	$N_{exp}$	$N'_{reab}$	G
PDR2	2.20	203.4	16843	3504512	1185720	1.33
PDR3	5.18	176.6	1487	6858123	988050	1.14
PDR4	4.83	226.7	1007	2093198	615786	1.29
PDR5	5.43	294.4	310	604693	127110	1.21
PDR6	4.74	289.1	617	659213	550079	1.83
PDR7	5.94	364.5	134	278782	311338	2.12
PDR8	5.06	349.7	279	266504	178495	1.67
PDR10	5.80	393.0	116	153245	116388	1.76

$a_{reap}$ : The crack depth at marking.  $\Delta\sigma$ : The nominal stress range. G: Gain factor.

$N_p$ : The predicted fatigue propagation life from  $a_{reab}$  crack to 0.6 of the plate thickness.

$N'_{reab}$ : The experimentally obtained total fatigue life of the treated specimen has  $a_{reab}$  crack.

$N_{exp}$ : The total life of the as-welded specimen subjected to equal stress range as the repaired one.

Table 6: Weight function and parametric approaches fatigue life prediction before treatment [20]

height	Nominal stress range $\Delta\sigma_n[MPa]$	$N_{exp}$	$N_{WF}[-]$ (Incl. RS)	$N_{WF}[-]$ (Excl. RS)	$N_{PE}[-]$ (Excl. RS)
100		2.1e7	1.5e7	1.3e6	194000
200		748000	537000	164000	24000
300		95000	100000	48000	7000

ics analysis (weight function approach) for predicting the propagation life before treatment. Noticeably, the prediction becomes closer to the experimental results as shown in table 6. The third and fourth columns give the fatigue life calculated using weight function approach (denoted by WF in the figure) with and without considering welding residual stress respectively. The last column is for the parametric method (denoted by PE in the figure) excluding residual stress. Obviously the residual stress should be included. However, there is a still gap between the prediction (third column) and experimental results (second column). That could be explained by the use of Paris law parameters for the whole structures and the use of weight function for short crack growth estimation (Out of Paris law validity zone) see table 17.

Paris law parameter (C,m) are so intricate especially in weld; since they are not only material proprieties, they are dependant on the stress ratio [34]. That's why they should be always collected carefully from the literature, another challenge with these parameters is their potential to change after treatment which makes the parameters (C,m) a function of treatment quality.

Because of the mentioned challenges associated with crack propagation quantitative analysis, Takahashi [23] seek only qualitative assessment about the allowable crack size. The effect of residual stress and stress concentration are incorporated in the evaluation of the stress intensity. Then the evaluated stress intensity  $\Delta K_t$  is compared with the threshold stress intensity  $\Delta K_{th}$  which is a function of the crack size, see figure 18. This methodology is used for both carbon and stainless steel butt welded joints and the errors in allowable crack size estimation are smaller than 15%.

As mentioned before, the use of fracture mechanics to study crack propagation after treatment is complicated; since the effect of treatment (especially peening) on crack size, shape and orientation is difficult to measure. It can be concluded from the literature that there are three possible alternatives for using fracture mechanics

in this case:

1. Assuming that crack size isn't affected by the treatment, and continue propagating in the same direction. Herein, The treatment effects are only included in the geometry and residual stress improvement. This way of implementing fracture mechanics is used in [22, 23]. This assumption isn't necessarily correct, but it can't be rejected since the crack behaviour after treatment isn't really known. However, in the three mentioned papers, the estimations were conservative in comparison with the experimental results, which implies that this assumption is adding to the disconformity reasons mentioned before.
2. Assuming that the crack is completely healed after treatment. This assumption is more valid in TIG remelting because the depth of fusion is larger than indentation depth of peening. Using this assumption will give rise to new crack initiation period. Herein, the crack might initiate from other zones which was subjected to damage due to pre-fatigue loading and didn't heal by treatment because of their remoteness. Fracture mechanics can be used to study crack propagation from the initial defect size exists in material to final fracture. Contrary to the previous assumption, this assumption may result to non-conservative prediction of fatigue life because the crack may not completely heal (especially in peening). However, the use of fracture mechanics for studying short crack results in conservative predictions (See the results in [18, 28] as examples), so these effects opposed each other.
3. Using Paris law with trial and error to optimize the lower integration limit of Paris law. That makes the model semi-analytical because of its dependency on experimental results to optimize the crack size. However, this method has the potential to give highly accurate results. Martin et al. used this methodology to optimise the initial defect size, the weld toe radius and the crack aspect ratio [20].

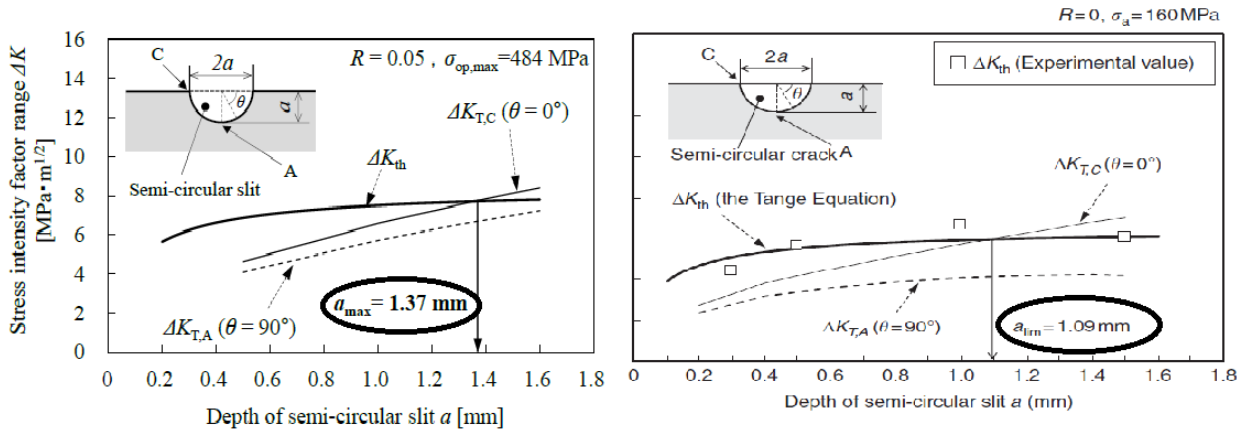


Figure 18: The prediction of maximum allowable crack size for stainless and carbon steel respectively [22, 23]

The following conclusions can be drawn about the fracture mechanics use in fatigue life extension literature:

1. Three approaches are found in literature to apply fracture mechanics: Parametric method, weight function approach and the use of stress intensity threshold to assess crack safety.
2. Incorporating the welding and treatment residual stress found to increase the accuracy of prediction. However, they are not always known.



3. The disconformity between prediction and experiment is attributed to: the use of Paris law out of its validity zone, the difficulty in obtaining Paris law parameters, the disregarding of hardness and residual stress distribution in the analysis and the ambiguity of crack size after treatment.
4. The use of threshold stress intensity found to be the best method for crack safety assessment. However, it gives only qualitative assessment.

Table 7: Comparison between fracture mechanics approaches used in literature for fatigue life extension of welded structures.

Method	Parametric method	Weight function	Threshold stress intensity
Description	The crack shape function (F) is defined by multiplication of different factors to account for crack shape, crack geometry and crack position, then the propagation rate is evaluated	The stress intensity is evaluated by an integration of stress times the weight function around the crack region. Then the propagation rate is evaluated	The active stress intensity is compared to the threshold stress intensity, then the crack safety is assessed
References	[20, 27]	[18, 20]	[22, 23]
parameters	C,m, F parameters	C,m	$\alpha, \sigma_{w0}$
Nature	Quantitative	Quantitative	Qualitative
Equation	Equation 7	Figure 15	Equation 9
Strength	<ol style="list-style-type: none"> <li>1. Ability to deal with surface or sub-surface crack.</li> <li>2. Stress concentration is accounted for directly in the shape function.</li> <li>3. The effect of residual stresses and hardness can be included</li> <li>4. Simple to use.</li> </ol>	<ol style="list-style-type: none"> <li>1. Relatively simple.</li> <li>2. The stress intensity is evaluated by integration around the crack and not in single point</li> <li>3. The effect of residual stress, stress concentration and hardness can be included.</li> </ol>	<ol style="list-style-type: none"> <li>1. Very simple and cheap</li> <li>2. Show high conformity with test results.</li> <li>3. The effect of residual stress, stress concentration and hardness can be included</li> <li>4. Applicable for short crack</li> </ol>
Weakness	<ol style="list-style-type: none"> <li>1.The parameter are very expensive.</li> <li>2. Paris law parameters for weld, base metal and heat affected zone must be evaluated.</li> <li>3. The stress intensity is evaluated for single material point.</li> <li>4. Not applicable for short crack</li> </ol>	<ol style="list-style-type: none"> <li>1. Paris law parameters for weld, base metal and heat affected zone must be evaluated.</li> <li>2. Inability to account for irregular crack shapes.</li> <li>3. Not applicable for short crack</li> </ol>	<ol style="list-style-type: none"> <li>1. No quantitative assessment of crack propagation.</li> </ol>



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### 3 Ideas inspired from the state of the art

#### 3.1 Crack detection by strain drop

It was shown that the measurement of local strains at the weld toe is substantial method for determining the crack depth. The use of multiple strain gauges is important when long weld line is under study so the drop can be notable even for small cracks. However, that requires calibration by FEM analysis for welded details containing crack. The sensitivity of crack location with respect to the gauge should be taken into account in the analysis. That's important in defining upper and lower boundaries of the crack size can be obtained using this methodology which results from the possibility of crack formation between the gauges or at the gauge center respectively. The concept is illustrated in figure 19, if the strain gauge shows 40% drop in all of the shown gauges, this indicates that  $a_1$  is deeper than  $a_2$  because  $a_1$  will be sensed earlier.

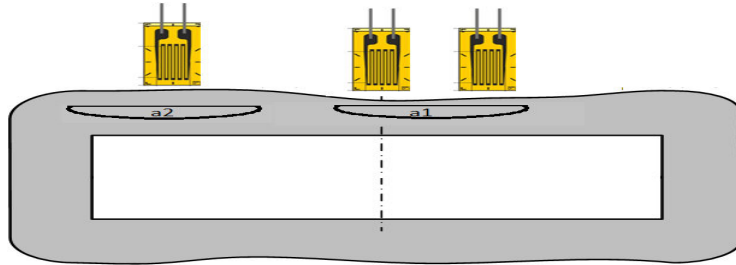


Figure 19: Illustration shows crack originated between two gauges ( $a_1$ ) and crack appears at the gauge level ( $a_2$ ).

#### 3.2 Crack behaviour after treatment

As shown in figure 8, the crack behaves differently when compressed by peening depending on its depth. The real behaviour can be obtained by observing the cracks after peening. Milling is to be done perpendicular to the weld direction to enable the observation. The crack could change its orientation fully or partially, it's also possible that the crack will be completely forged. Milling enables studying the relation between crack depth and its behaviour, an illustration is shown in figure 20. Notice that the crack can be easily distinguished after milling because the dye applied before peening is staining the crack surface and all the cracks will appear below the indentation depth (which is marked by grey color in the figure).

The first section shown in the figure is for short crack which is completely forged by the compressive stresses resulted from peening. The second section is for deep crack, peening in this case might change the crack orientation but since the crack is long, the influence zone will be limited. The third section is for short crack which changes its orientation completely due to peening.

This methodology is applicable for TIG remelting. As mentioned before, TIG's fusion zone is deeper than peening's indentation depth. Herein, the crack isn't expected to change its orientation so it's more suitable to mill the specimen parallel to weld direction as shown in the illustration in figure 21. The purpose of this kind

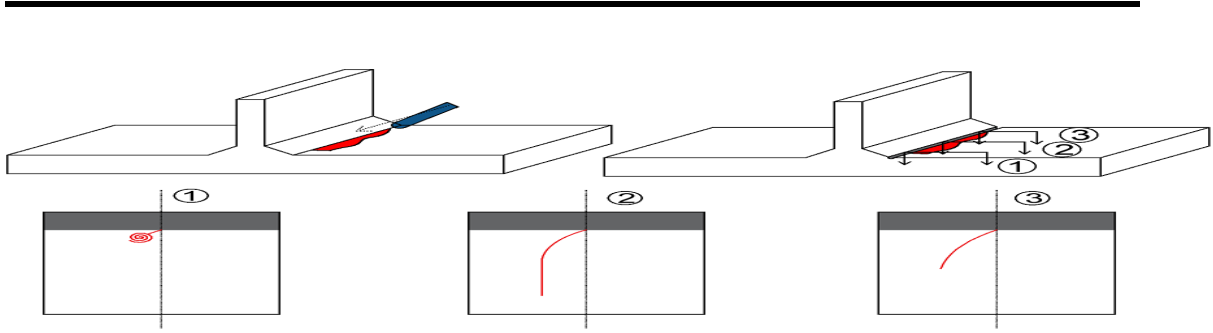


Figure 20: Illustration on peening effect on existing crack (The crack is donated by red color and peening indentation by grey color)

of milling is to figure out if the crack remains (as shown in the figure) or completely removed.

The results of these experimental analyses (Milling the peened and remelted surfaces) are used as inputs for fracture mechanics and crack propagation analyses by controlling the lower limit of Paris law integration. Besides, this analysis is decisive for hardness effect inclusion (It shouldn't be included if the crack remains).

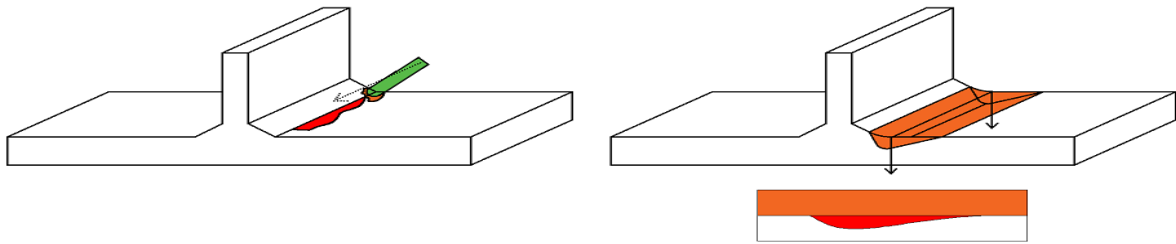


Figure 21: Illustration on TIG remelting effect on existing crack (The crack is donated by red color and fusion zone by brown color)

### 3.3 Crack initiation measurement

Aykel et al.[31] have used the crack initiation life as an indication of the treatment quality. Strain gauge's drop is usable for detecting the crack depth. However, if the initiation life ( $N_i$ ) is defined as the life required to create one or more cracks shorter than 0.5mm, strain gauges can be used to define  $N_i$ . Otegui et al.[51] have used multiple strain gauges close to the toe, and it's reported that 50% drop in any of the gauges corresponds to crack less than 0.5mm, the positions of the strain gauges are shown in figure 22. A relation can be drawn between the crack depth before treatment and the resulted  $N_i$  after treatment, if  $N_i$  is long, the crack depth before treatment is reparable and vice verse. Strain gauge analysis Strain gauge is a device used to measure strains on object. It is widely used in the mechanical and structural engineering worlds because of its capacity to describe the variation of stresses and strains. One of its application is the detection of crack and measuring its dimensions as mentioned in chapter 1; this methodology was intensively used in this project. Series of strain gauge signals generated during fatigue testing accompanied with finite element analysis are used to create a toolbox can be used to read any strain signal used in fatigue testing and interpret it correctly.

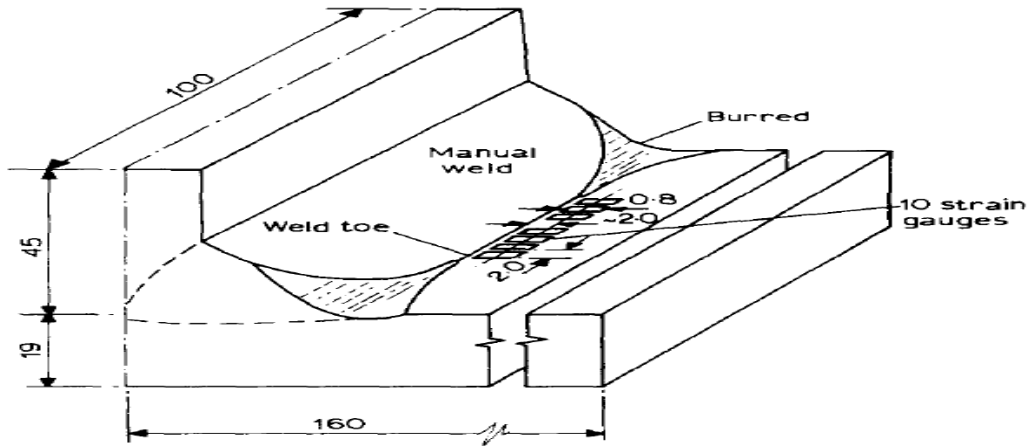


Figure 22: The positioning of the strain gauges used for crack initiation marking [51].

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