EUROPE TECHNOLOGIES
SONATS

FATIGUE LIFE IMPROVEMENT OF WELDED STRUCTURES BY ULTRASONIC NEEDLE PEENING

INNOVATIVE IMPACT SURFACE TREATMENT SOLUTIONS

ULTRASONIC SHOT PEENING
ULTRASONIC IMPACT TREATMENT
ULTRASONIC NEEDLE STRAIGHTENING/FORMING

Revision	Modifications	Date	Author
0	-	2014, Dec. 8th	P.LEFEVRE
1	New results (Fraunhofer study)	2016, June. 14th	P.LEFEVRE
2	New results (Purdue University study)	2018, October. 3rd	P.LEFEVRE
3	AASHTO's recommendations modifications	2019, November. 14th	???

CONTENTS

1. ABSTRACT

Conventional Hammer Peening is a well-known post-weld treatment for fatigue life improvement. This method is applied to the weld toe only.

Ultrasonic Needle Peening (UNP) (also called Ultrasonic Impact Treatment (UIT) or High Frequency Mechanical Impact (HFMI)) is a process achieving the same effect, but with more process control compared to conventional hammer peening. UNP is also faster and far less harmful for the operator.

(See below on figure 1 an UNP equipment.)

Moreover UNP process can be used by any operator after only one day of training. For these reasons many industries have shown a strong interest for this innovative technology.

This document describes SONATS research, in-field experiences and knowledge about Ultrasonic Needle Peening. It is dedicated to any people (Engineers, welders, operators, controllers) who are interested in this process.

Figure 1 : SONATS NOMAD UNP System

NOTE: Many designations are used to describe the process which consists in using high frequency mechanical vibrations to put in movement impactors or needles to throw against the metal surface area to be treated:

- *UIT for Ultrasonic Impact Treatment,*
- *UNP for Ultrasonic Needle Peening,*
- *UP for Ultrasonic Peening,*
- *or HFMI for High Frequency Mechanical Impact treatment).*

In this document we will, most of the time, use “Ultrasonic Needle Peening” or “UNP”.

2. UNP EFFECTS

According to P. J. Haagensen and S. J. Maddox[1], "The weld toe is a primary source of fatigue cracking because of the severity of the stress concentration it produces". For this reason, the weld toe can be considered as a "notch".

Hammer Peening or Needle Peening is an ancestral process, which consisted in striking manually a weld by the means of a hammer, to improve its surface finish and resistance. Later, pneumatic and magnetostrictive tools have been developed to help the operator. Nowadays, the principle is still the same but the equipment design has been improved. The latest technologies are using piezo effect for electrical to mechanical vibration conversion. The vibrating element, named Sonotrode, is then use to provide the kinetic energy to a needle (or impactor). Thanks to those modern tools, the influence of the operator on the process application is close to zero, with little efforts and high treatment speed.

Research about UNP started in the late fifties[2] and sixties in the USSR[3,4,5]. Extensive research have been carried out later in the nineties, on structural steels[6], high strength steel and aluminum[7,8], showing each time a high level of improvement in term of fatigue life. In 1996, the International Institute of Welding published a specification[9] and in 1999 the first "Guide for application of UIT"[10].

On this basis, many industries started to pay attention to this effective and user-friendly post-weld improvement techniques.

The weld toe improvement methods rely on two main principles:

- Weld toe geometry modification,
- and Residual stresses modification.

Ultrasonic Needle Peening acts on both phenomenon to finally achieve high level fatigue life improvement of the treated welded detail.

2.1. Modification of the weld toe geometry

Conventional methods of post weld treatments, such as TIG dressing or weld toe grinding consist of increasing the radius at the transition between the base material and the weld seam. UNP achieves the same effect by the mean of high frequency impacts, able to induce local deformation, and creating a controlled groove at the weld toe.

Figure 2 describes the geometry modification after UNP/UIT compared to "as welded" or other post treatment methods.

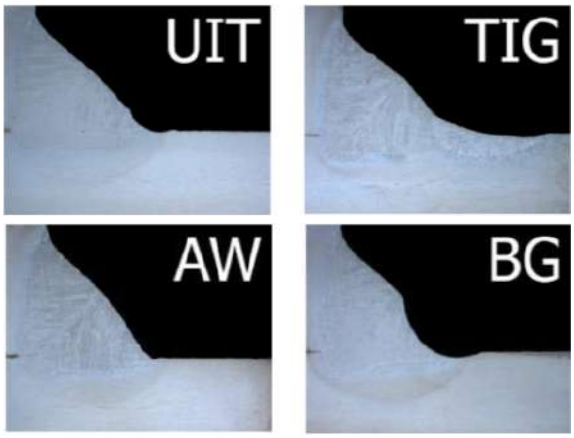


Figure 2: Weld to geometries for "as welded" condition and after post treatment (toe grinding UIT, also called UNP, and TIG dressing)[11]

The treatment should be applied uniformly all along the weld toe without any discontinuities to create a groove by successive impacts. Figure 3 is representing the groove scheme.

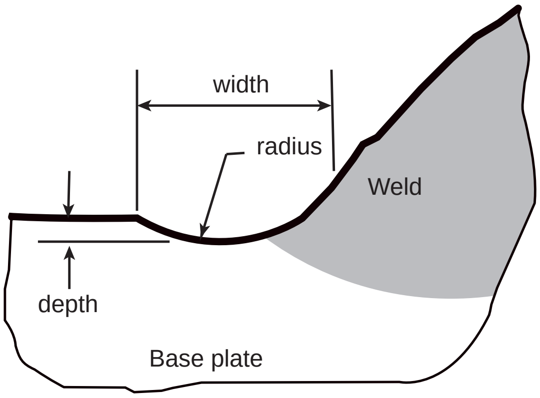


Figure 3: UNP groove scheme

Results observed in the literature, display a wide range of groove sizes. Galtier et al[12] measured after UIT on 2 steel grades, radii from 0.8mm to 2.0mm and depth from 0.17mm to 0.4mm.

Yildirim & Marquis[13] studied the effect of several HFMI tools, the radii were measured, from 1.80mm to 4.55mm, width from 2.39mm to 5.45mm and depth from 0.16mm to 0.29mm.

Yekta and Al[14] describe the following groove sizes for one equipment with several different peening treatment times as shown in Figure 4.

Weld toe geometry measurements					
Group (mm)	Radius		Indent depth (base metal side)		
	x(mm)	s(mm)	x(mm)	s(mm)	max.(mm)
B	1.76	0.36	0.16	0.04	0.19
C	2.09	0.18	0.16	0.06	0.22
D	1.17	1.09	0.17	0.15	0.39
E	1.69	0.27	0.36	0.07	1.10
F	2.37	0.11	0.27	0.07	0.37
Note : x=mean; s= standard deviation					

Figure 4 : Radius (from 1.17 to 2.37mm) and Depth (from 0.16 to 0.36mm) according to several peening conditions[14]

All geometries from these three studies led to a high level of improvement in terms of fatigue life, by using different UNP equipment, treatment procedure and on several materials.

In 2013, Marquis and Barsoum[15] compiled 46 studies from the last decade to define procedures and quality assurance guidelines. In this document, we can read “The HFMI indentation depth following treatment should be 0.2–0.6mm while the resulting width is typically 2–5mm”.

NOTE: These values are given as typical geometries; it results from a complete coverage of the weld toes by impacts (also called 100% coverage).

2.2. Compressive residual stresses

The second effect of UNP is the introduction of beneficial compressive residual stresses. Depending on tool, intensity of the treatment, and material, the level of introduced compression may vary.

Figure 5 describes residual stress profiles after treatment with UNP equipment on S355 ; several set up conditions are characterized. These measurements were performed by X-Ray diffraction at SONATS Laboratory (Carquefou, France).

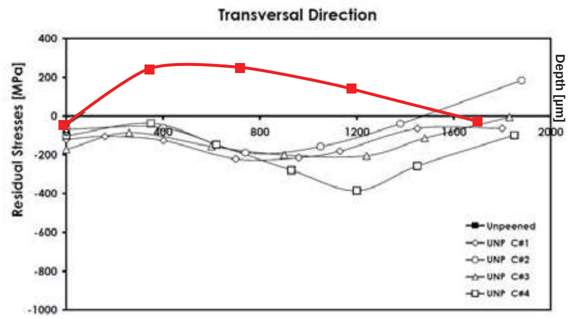


Figure 5: Residual stress distribution (transversal direction) at the surface and into depth, weld toe location

The red curve corresponds to “As welded” specimen, high tensile residual stresses is observed down to 1.6mm.

After UNP, we observe high compressive residual stresses down to more than 1.4 mm for all conditions. As for shot peening (or Ultrasonic Shot Peening), compression is beneficial for the fatigue life improvement, acting against the service loads.

Yildirim & Marquis[13] observe similar results, “tensile residual stresses were found at all of the weld toes measured. Values ranged from +185 to +552MPa. For the HFMI-treated specimens, compressive residual stresses were measured in 31 of the 32 HFMI grooves studied prior to fatigue testing. The single HFMI groove which showed tensile residual stress had a value of only 52MPa. The compressive residual stresses before fatigue testing were −53 to −457MPa for the high-strength steel specimens.”

Authors conclude that UNP imparts compressive stresses in weld toes being treated for all the tested equipment’s.

3. PROCESS PARAMETERS

The UNP/UIT/HFMI process is monitored according to several parameters. Influence of these parameters are discussed in this paragraph.

3.1. Mechanical Vibration frequency and Needle Impact frequency

On an Ultrasonic Peening system, a high voltage electrical signal is created by an Ultrasonic Generator. This signal is then converted to a mechanical vibration at the same frequency, either by a piezo-electrical converter or a magnetostrictive converter.

When the Needle (or Impactor) is in contact with the vibration surface, it gains kinetic energy and is thrown against the part to be treated. Then the needle moves back to the vibrating surface for the next cycle.

Therefore the Mechanical Vibration frequency and the Needle Impact frequency should be dissociated.

Figure 6 describes the acoustic elements and the impactor in the SONATS UNP NOMAD peening head design :

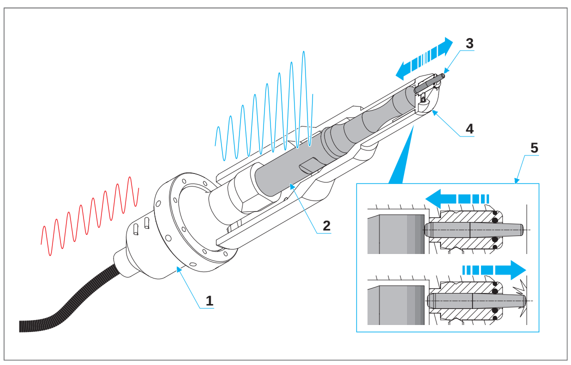


Figure 6 : Acoustic elements inside the UNP peening head (SONATS)

With:
1. Piezo-electrical converter
2. Sonotrode
3. Specific Impactor (Or Needle)
4. End piece (to guide the Impactor)
5. This little scheme illustrates the movement cycle of the impactor inside the end piece

Influence on the results:
The ultrasonic vibration frequency of the sonotrode is the same as the converter but the impactor is uncoupled from the Sonotrode (therefore the impact frequency is lower than the ultrasonic frequency). By pressing the tool on the weld toe, the operator forces the needle to come in contact with the vibrating sonotrode, to finally strike the weld toe with a lower frequency than the vibration frequency of the sonotrode.

For SONATS NOMAD equipment, the ultrasonic vibration frequency is 20 KHz with an impact frequency in a range of 100-400 Hz. The impact frequency depends on the pressure applied by the operator, the amplitude of vibration, the needle geometry, the material and the travel speed along the toe.

Figure 7[17] shows the first equipment developed by E.O. Paton Welding Institute (Ukraine) which worked at 27 KHz.

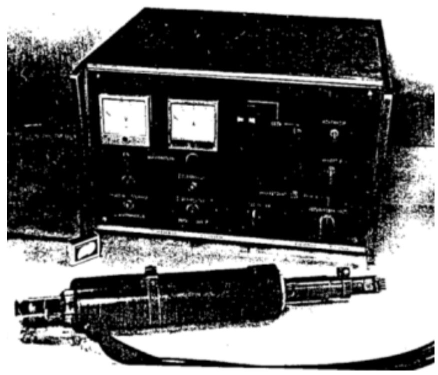


Figure 7 : First UIT tool developed by E.O. Paton Welding Institute (Ukraine)

Later, this tool has been used for many fatigue test programs on laboratory specimens and real structures, showing each time attractive fatigue life improvement [6, 7, 8, 9, 10, 12, 14, 15, 26]. E S Statnikov explained in[18], that 27 KHz equipment produces impacts at 80 to 200Hz. This impact frequency is similar to SONATS observation.

According to Y. Kudryavtsev, a 20KHz piezo-electrical equipment was developed in the early 90'. Fatigue test results showed similar fatigue life improvements as for magnetostrictive 27KHz equipment [19, 20, 21].

In 2013, IIW carried out a round robin test comparing the fatigue life improvement achievable by different HFMI (High Frequency Mechanical Impact Treatment) including 27 KHz equipment, 20 KHz equipment and low frequency (< 1KHz) pneumatic tools[13]. Longitudinal non-load carrying welded specimens were treated by HFMI. Samples were fatigue tested under axial loading. Fatigue test results indicate that all of the HFMI-improved welds using equipment with 3 frequenciesof vibration (27KHz, 20KHz and <1000Hz) satisfied IIW requirements (FAT160 and m1=5).

This round robin test and previous studies clearly show that the vibration frequency has no influence on the fatigue life improvement generated by UNP/UIT process. Important parameter is the frequency of impact, and its reproducibility.

A smooth and complete continuity for the groove should be produced by the operator. Thanks to its consistent peening impact frequency and amplitude, SONATS equipment allows a much quicker process without harmful conditions for the operator. Low frequency pneumatic tools suffer from a lack of control on impact frequency and amplitude, and induce harmful peening conditions which make difficult for an operator to achieve a bright and continuous groove.

3.2. Amplitude of vibration

A vibration is defined by its frequency and its amplitude. Usually, when the frequency of vibration increases, the amplitude decreases. SONATS NOMAD UNP equipment is able to work in the range of 10µm p/p to 60µm p/p.

The Figure 8 describes the basic sinusoidal ultrasonic wave.

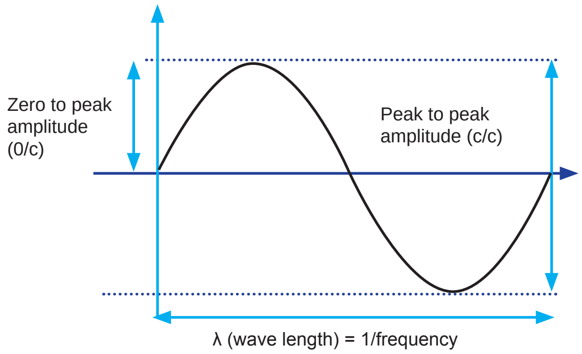


Figure 8 : Sinusoidal wave

The high level of energy to treat the weld toe is obtained thanks to a small displacement at very high speed, inducing a high acceleration of the impactor. Small amplitude is user friendly compared to high amplitude obtained at low frequency by pneumatic equipment (several millimeters of displacement).

The amplitude of vibration should be easily modified depending on the material to treat. To achieve IIW requirements (groove size), SONATS usually uses parameters in Table1:

Frequency		20 000 Hz	
Material	Steel	Aluminium	Stainless Steel
Amplitude (p/p)	30 - 60µm	20-40µm	20-40µm

Table 1 : Typical sonotrode's amplitude of vibration for SONATS NOMAD UNP equipment

SONATS performed fatigue test with 60µm p/p amplitude achieving high level of fatigue life improvement[16]. André Glatier et al[12], used an amplitude of vibration of the sonotrode equal to 40 µm p/p to treat high strength steel. The fatigue life time of the T-Joint specimen was found to be more than twice the"as-welded" life.

The amplitude of vibration is not considered as a key parameter in a large majority of publications. Thus the influence of this parameter on the fatigue life improvement is not studied. Even if the influence of the amplitude is small with respect to the fatigue life improvement, it has a real influence on the treatment speed and equipment drivability, and therefore on the groove continuity and quality. For this reason, a perfect control of the vibration amplitude of the sonotrode is really important.

3.3. Ultrasonic Needle Peening Power

Some studies deal with the power consumption of the ultrasonic equipment. It is the result of the following parameters:

- Converter technology (Piezoelectric or Magnetostrictive)
- Design and Manufacturing quality of the equipment
- Pressure applied by the operator on the tool
- Material to be treated
- Amplitude of vibration

Depending on these parameters the effective equipment power consumption can be multiplied by 10 even identical fatigue life improvement.

SONATS equipment power consumption ranges from 10W (without loads) to 150W (during the treatment), this low energy consumption comes from piezo electrical converter which is very efficient compared to magnetostrictive transducer. For magnetostrictive transducers, a majority of electrical power is converted into heat, that is why liquid cooling is necessary.

For piezo electrical converters which are more efficient, the electrical power is mainly converted into mechanical vibration which is then transmitted to the weld toe. Air cooling is sufficient.

Power consumption of the equipment has no particular signification on the quality of the UNP treatment.

3.4. Geometry and diameters of impactors/both needles

Impactors, also called needles or strikers, are usually made of hardened steel.

The peening head is usually composed of one to four impactors (depending on the supplier). SONATS proposes 3 different types of nozzles for its PM03 peening head as describes in Figure 9.

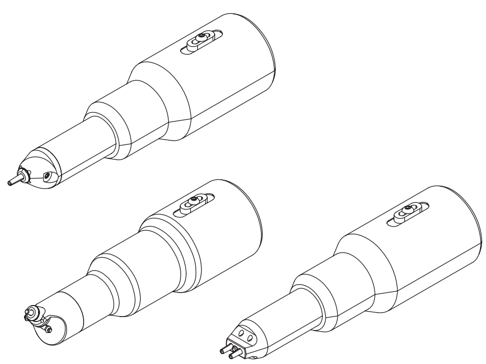


Figure 9 : 1 Impactor, Angled 1 Impactor and 2 Impactors-in-line nozzle for UNP application (SONATS)

To perfectly control the weld toe treatment, SONATS advices to use only one needle. The number of impactors has no influence on fatigue life improvement[16]. 2-impactor-in-line nozzle could be used in the case of a perfect quality weld seam. Angle nozzle is very efficient for treating difficult access toes.

The diameter of the impactors is usually between 3 to 4mm with 1.5 to 3mm impact tip radius.

SONATS proposes 2 geometries of impactors as shown on Figure 10. Thanks to needle types, every acceptable weld toe geometry can be treated on every material.

These needles are made of 100C6 bearing steel. To treat stainless steel or titanium, specific needles can be used.

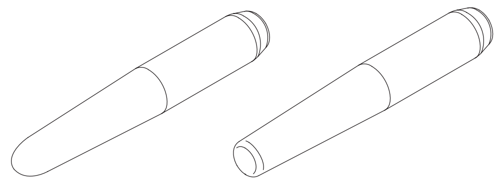


Figure 10 : 1.5 mm radius impactor and 3.0 mm tip radius impactor (SONATS)

4. FATIGUE RECOMMENDATIONS

These paragraphs detail the UNP process recommendations according to International Institute of Welding (IIW), classification societies, and professional associations for transportation infrastructures.

4.1. IIW recommendations

With respect to post weld treatment methods, the following document is considered as reference worldwide:

"IIW Recommendations on Post Weld Fatigue Life Improvement of Steel and Aluminium Structures"[22]

This document has been created in order to standardize the optimum application methods for burr grinding, TIG dressing, hammer peening and needle peening. It also includes design resistance curves based on both nominal stress assessment method and on the structural hot-spot stress method. This IIW guideline does not take into account Ultrasonic Needle Peening method yet. However, in 2013 IIW published a set of 2 complementary documents called:

- Fatigue strength improvement of steel structures by high-frequency mechanical impact: proposed procedures and quality assurance guidelines[15].
- Fatigue strength improvement of steel structures by high-frequency mechanical impact: proposed fatigue assessment guidelines [23]

SONATS strongly advises anyone interested in UNP process, to read both documents.

According to IIW, any supplier which fulfills "The proposed procedures and quality assurance guidelines" can guaranty X1.6 improvement factor (or the fatigue limit, it corresponds to a 4-Fatigue class increase for steels σy <355 MPa). The fatigue class improvement increases with the strength as shown in Figure 11. This guideline gives additional improvement factors to take into account thickness, steel strength and loading effects.

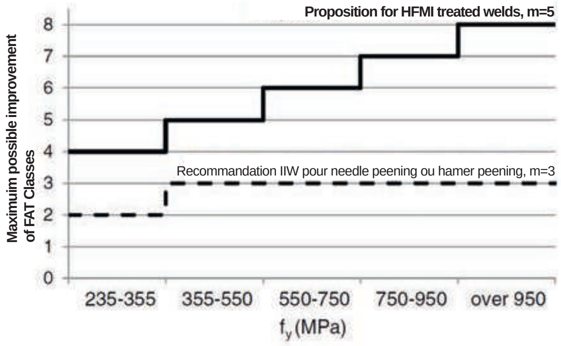


Figure 11 : Proposed (by IIW) maximum increase in the number of FAT classes as a function of the Steel strength

4.2. Classification societies approaches

Most of classification societies have already acknowledged the benefits of UNP methods under certain conditions. This paragraph introduces recommendations and guidelines about UNP.

4.2.1. American Bureau of Shipping – ABS

The American Bureau of Shipping has updated in 2014, a document called "GUIDE FOR THE FATIGUE ASSESSMENT OF OFFSHORE STRUCTURES (APRIL 2003)"[24]. In this document, it is written:

"The finished shape of a weld surface treated by ultrasonic/hammer peening is to be smooth and all traces of the weld toe are to be removed. Peening depth below the original surface is to be maintained at least 0.2mm. Maximum depth is generally not to exceed 0.5mm. Provided these recommendations are followed, when using the ABS S-N curves, **a credit of 2 on fatigue life** may be permitted when suitable toe grinding or ultrasonic/hammer peening are provided. Credit for an alternative life enhancement measure may be granted based on the submission of a well-documented, project-specific investigation that substantiates the claimed benefit of the technique to be used."

4.2.2. Lloyd's Register –LR

The table 2 describes the post-weld methods (including UNP) improvement factor according to Lloyd's registers.

Fatigue Strength improvement factors		
Method	Improvement factor on fatigue life, fL	
Weld toes (see notes 1 to 7)		
Disc toe grinding	1.1	
Burr toe grinding	2.0	
TIG and plasma dressing	2.0	
Full burr grinding with smooth concave weld profile (see Fig 2.4.5)	3.0	
Hammer Peening	1.3	
Controlled Shot Peening	2.0	
Ultrasonic Peening (UP and Ultrasonic Impact treatment (UIT), see note 7	25	minimum yield stress <315 N/mm^2
	35	minimum yield stress <315 N/mm^2
Free edge of parent material (see notes 2.4 and 8)		
Removal of plate corners, see note 8	1.6	Plate thickness, t<22 mm
	1.0	Plate thickness, t>66 mm
	Obtain by linear interpretation	66mm > t > 22 mm

NOTES
1. Fatigue strength improvement factors only may be applied to as-welded transverse butt welds, as-welded T and cruciform welds and as-welded longitudinal attachment welds, see Ship Right Fatigue design Assesment Level 3 Procedure, Table T.2.1 in chapter 7.
2. See Ch 2,2.1.2 for conditions of application of fabrication stage fatigue strength improvement methods.
3. When a factor improvement of above 1.6 is applied to the weld toes, full penetration welds are to be used to eliminate the possibility of cracking the weld root. For a lower improvement factor, partial penetration welds in accordance with the Rules for Ships may be used. See 2.4.2.
4. In way of areas prone to mechanical damage, fatigue improvement may only be granted if these are adequately protected.
5. No improvement factor should results in a fatigue life longer that calculated using the S-N curve given in Table 2.4.7
6. Treatment of inter-bead toes will be necessary for large multi-pass welds. see 2.4.3, 2.4.4 and 2.4.6.
UP and UIT may only be used on single pass electro-gas butt welds for plate thickness in the range from 50 mm to 80 mm.
7. Improved factors may be applied in addtion to the improved free edge S-N curves given in Table 7.1.1 in Chapter 7 of Ship Right Fatigue Design Assesment Level 3 procedure.

Table 2 : Improvement factor of fatigue life for several post-weld improvement methods (including UIT) according to Lloyd's Register

4.2.3. Bureau VERITAS

The following recommendations (Figure 12 and 13) are included in BV document "Rules for the Classification of Offshore Units" [25]

Article 2 Post welding treatment

2.1 Scope

2.1.1 General
In normal design and building conditions, post welding treatments are not applied.

The decision to apply a post welding treatment may be required for specific hot spots, on a case-by-case basis, where the damage ratio is classed to the limit and in case of repair.

2.1.2 Conditions of application
Full penetration welding is to be adopted. Post welding treatment of partial penetrations is not accepted.

The post welding treatment procedure is to be performed according to a recongnized standard and approved by the society.

2.1.3 Mechanical post welding treatment
The following mechanical post welding treatments are accepted:

- grinding
- shot peening
- needle peening
- ultrasonic peening

In principle, hammer peening is not accepted

2.1.4 Thermal post welding treatment
The following thermal post welding treatments are accepted:

- TIG refusion
- plasma refusion.

Figure 12 : Accepted Post welding treatment by Bureau VERITAS

2.3 Fatigue resistance assessment

2.3.1 General
These treatments improve the weld toe and the residual stresses leading to an increase of the S-N curve class. The post weld S-N curve may have a different slope than the as welded S-N curve.

2.3.2 Assessment
The fatigue lifetime of the treated details is to be assessed taking into account the modified S-N curves. The used S-N curves are to be duly justified, by fatigue tests or by a recognized standard.

2.3.3 Experimental S-N curves
When tests are considered to determine the S-N curve, the test program has to be approved by the Society. Attention is to be paid to the necessary number of samples, and the distribution of the results along the stress range axis to allow a correct determination of the S-N curve slope and standard deviation. To be homogeneous with the Rules for as welded joints, the design curve will correspond to a curve, at minus 2 standard deviations, and taking into account confidence intervals of the calculated mean and standard deviation.

Figure 13: Fatigue assessment procedure

4.3. American Association of State Highway and Transportation Officials (AASHTO) and Federal Highway Administration (FHWA) Recommendations

In the United States of America many welded components on existing bridges are prone to fatigue failure. The US Federal Highway Administration (FHWA) estimates that $76 billion is necessary to repair deficient bridges throughout the country.

In 1996, the Federal Highway administration launched a study to measure the benefits of Ultrasonic Impact Treatment, (UIT) on weldments prone to failure. Their findings showed that the fatigue life of welds where UIT was applied was 8 times longer than welds where it was not. Further studies were conducted on welded girders and cover plates yielding similar positive results.

Subsequent research conducted by Purdue University in 2018 has shown that Ultrasonic impact treatment is a highly effective technique for increasing the fatigue life of welded girders. The study was recently extended to prove that equipment manufactured by Empowering Technologies is accepted as a reliable option for UIT application. The “AASHTO LRFD Bridge Construction Specifications” was modified as such in the 2020 Interim Revisions released in September of 2019. Empowering Technologies and their partners are dedicated to supporting the repair of our nation’s bridge by Increasing the fatigue life of weldments and decreasing the cost of future weld repair.

“AASHTO - Interim Revision (2020) to the LRFD Bridge Construction Specifications - 4th Edition 2017”

5. RESULTS WITH SONATS UNP EQUIPMENT

5.1. Published studies

SONATS has more than 20 years of experience in research for impact surface treatment activated by ultrasounds (STRESSONIC® process). Most of these research programs have been conducted under confidential agreements with end-customers.

This paragraph lists some published papers with respect to SONATS NOMAD UNP equipment.

5.1.1. “Fatigue Life Enhancement of Welded Structures using STRESSONIC® Ultrasonic Needle Peening”[16]

The French Institute of Welding, in collaboration with SONATS, carried out a study to evaluate UNP process capability to increase the fatigue life of welded components. The results of this study have been presented at ICSP11 Conference (Indiana, USA - 2011)[16].

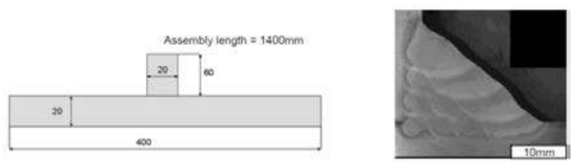


Figure 14 : T-joint geometry and micrograph illustrating the multi-pass

Specimens were needle peened by SONATS according to four combinations of parameters as Table 3. Figure 15 shows a picture of the equipment in process.

Parameters	c#1	c#2	c#3	c#4
Needle quantity	3	3	1	1
Needle Type (tip radius)	S3-15 (3mm)	S3-13 (1.5mm)	S3-15 (3mm)	S3-13 (1.5mm)
Amplitude of vibration	60 µm p/v	60 µm p/v	60 µm p/v	60 µm p/v
Travel velocity	8mm/s	8mm/s	8mm/s	8mm/s
Shifted Pass Quantity	2	2	2	2

Table 3 : Treatment parameters

Figure 15 : Ultrasonic needle peening of the weld toe

Each specimen was fatigue tested using a four points bending machine with stress ratio R=0.1 and 20Hz sinusoidal signal. Additional specimens were produced for residual stress measurement done by X-Ray diffraction and roughness measurements with a 2D profile-meter. 45 specimens were fatigue tested (9 unpeened and 36 peened).

Results:
As expected, the Ultrasonic Needle Peening treatment has created a plastic deformation of the weld toes by generating a groove along the weld toe. For each combination of parameters residual compressive stresses were characterized as shown in Figure 16.

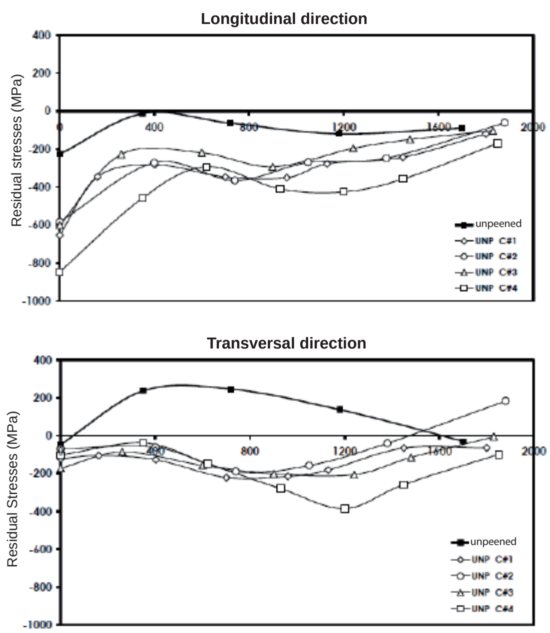


Figure 16 : Residual stress profiles in the longitudinal and transversal direction for as welded and UNP specimens

For each combination of parameters, fatigue life improvement was compared to as welded results as shown in Figure 17.

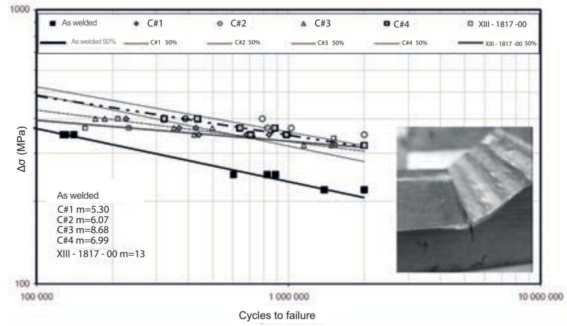


Figure 17 : Fatigue test results for as welded, UNP treated specimens and IIW publication[28]

	As Welded	XIII-1817-00 As Welded	XIII-1817-00 UIT Set2-5mm	C#1	C#2	C#3	C#4
Median	206	188	314	279	319	305	316
Caracteristic curve	197	167	286	251	291	291	298

Figure 18 : Stress range at 2E6 cycles

The results show an improvement up to 50% in stress range at 2 million cycles. Fatigue life was increased at least by a ratio of three and up to five for 350 MPa stress range. The UIT condition, «set 2» from study XIII-1817-00, has been used for comparison and validation of current work. Results are found comparable. Whatever parameter sets, a significant enhancement for all specimens is observed.

This demonstrates the low influence of studied parameters such as needle tip radius and needle quantity.

5.1.2. “Fatigue behavior on HF hammer peened longitudinal attachments”[29]

The objective of this study is to evaluate the fatigue strength of UNP on longitudinal attachment welded joints in bending with a stress ratio R = 0.1.

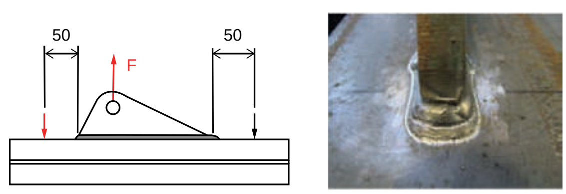


Figure 19 : Specimen geometry and treated weld toe

Six improved specimens and one as-welded were tested at a fixed load level. The results were compared with previous studies on the same specimen type with different weld improvement processes.

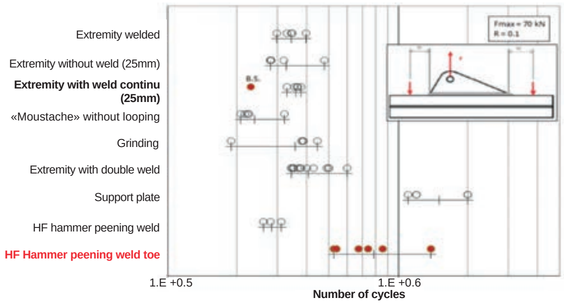


Figure 20 : Fatigue life time observed on longitudinal attachment for different Post-weld treatment including UNP (by SONATS)

As illustrated on Figure 20, and comparing UNP results with "as-welded" results, we observe a mean life time equal to 740.000 cycles for UNP and 320.000 cycles for "as welded" specimens. It corresponds to a 2.3 fatigue life improvement factor.

5.1.3. "Fatigue life improvement of welded structures by Ultrasonic Needle Peening compared to TIG dressing"[30]

Two improvement techniques were studied:

- TIG dressing
- Ultrasonic Needle Peening

These post weld treatments are intended in new structures to increase the fatigue strength as well as for post repair operations or for upgrading existing shipbuilding structures.

Experimental procedures:
The considered material in this work is a hot rolled S355 NL (grade widely used in surface shipbuilding).

The plate's dimensions are 3000mm length, 700mm width and 12mm thickness. Figure 21 describes the geometry of the specimen before machining.

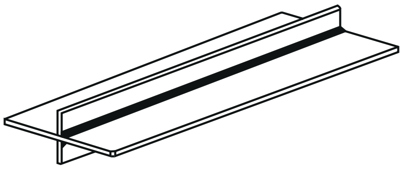


Figure 21: Non-load carrying attachment welded on 12 mm thickness plate

The weld is then treated by SONATS (see Figure 22) before machining the fatigue specimens.

Figure 22 : Ultrasonic Needle Peening equipment and operation by SONATS

Specimens after machining are rectangular plates (400mm length and 80mm width).

Fatigue tests were conducted on TIG and UNP treated specimens under axial loading on electrohydraulic machines at 5-10Hz in function of the maximal stress applied.

Results:
Residual stress measurement was performed in the UNP treated area (see Figure 23).

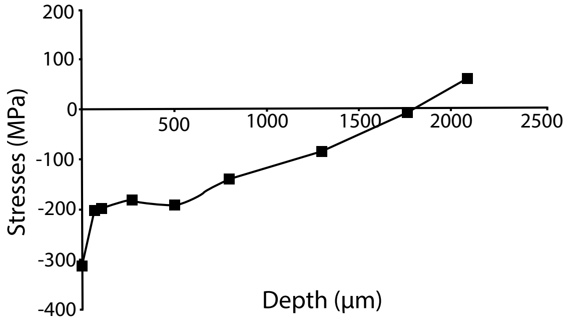


Figure 23 : Residual stress measurement by XRay diffraction

Residual compressive stresses are observed in depth down to 1.7mm after treatment by UNP.

Figure 24 summarizes the Δσ-N curves at 2 sdtv for the two post-weld treated and as-welded specimens. Results are obtained in traction-compression R = -1. The red line corresponds to the design curve FAT 100MPa according to IIW recommendation.

High level of improvement is observed for both methods, better results are obtained with UNP.
The calculated FAT for as welded specimen is

137MPa, 254MPa for TIG Dressing and 357MPa for UNP.

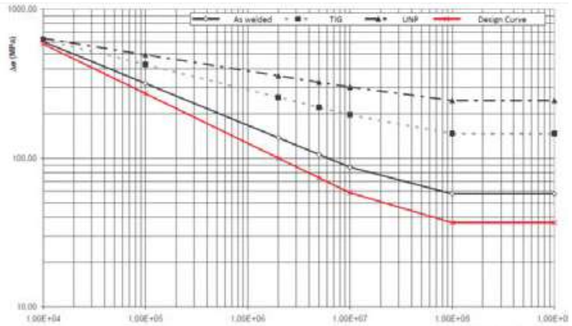


Figure 24 : Δσ-N curves for as welded, TIG dressed and UNP treated specimens

5.1.4. US Navy: «Systematic review of the UIT parameters on residual stresses of sensitized AA5456 and field based residual stress measurements for predicting and mitigating stress corrosion cracking»[31]

This thesis focuses on the use of x-ray diffraction to measure residual stresses around welds in aluminum ship structures both in the laboratory and in the field. Tensile residual stresses are often generated during welding and, in sensitized aluminum structures, can cause extensive stress corrosion cracking. Peening techniques, such as ultrasonic impact treatment (UNT by SONATS), can mitigate and even reverse these tensile residual stresses. This research uses x-ray diffraction to measure residual stresses around welds in AA5456 before and after UIT. In particular, the importance of UIT parameters such as peening amplitude and pin size is studied. All combinations of UIT parameters removed the tensile residual stresses and resulted in compressive stress several hundred microns below the weld surface. The exact level of compressive residual stress was sensitive to the pin size used with a low dependence upon the displacement amplitude.

5.1.5. Fatigue testing of welded steel and aluminium specimens (2015)

FRAUNHOFER IWM (Freiburg, Germany), investigated UNP on structural steels and aluminum alloys. Fatigue tests were carried out in FRAUNHOFER's lab on butt-weld specimens made of S355J2+M (See Figure 25), S690QL and EN AW5754 (AlMg5). Fatigue tests were performed at R=0.1 constant amplitude and under uniaxial load.
S355 Specimens

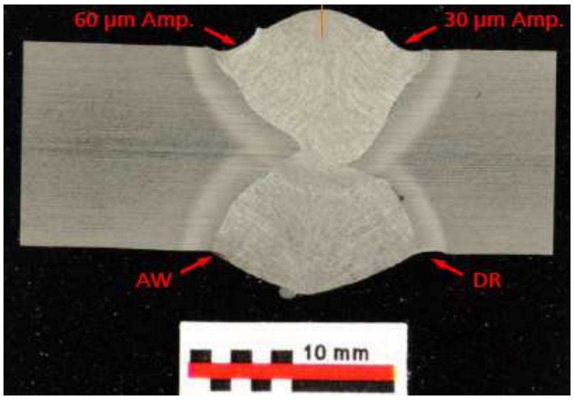


Figure 25 : Cross section view of a butt weld joint treated at 60 µm of amplitude, 30µm of amplitude, with double radius and as welded.

On S355 specimens, standard treatment using 3mm diameter needles was compared to a new needle geometry called «double radius peen». Fatigue curves are shown in Figures 26 - 30.

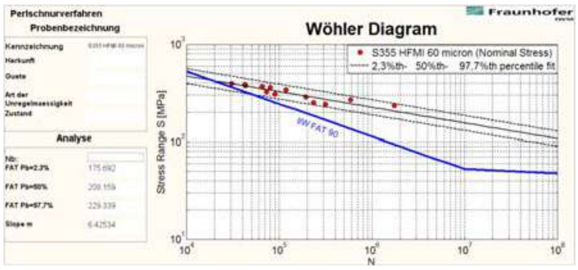


Figure 26 : Fatigue Curve on S355, as welded

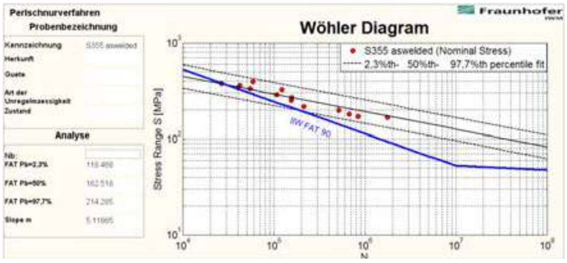


Figure 27 : Fatigue Curve on S355, UNP with standard parameters

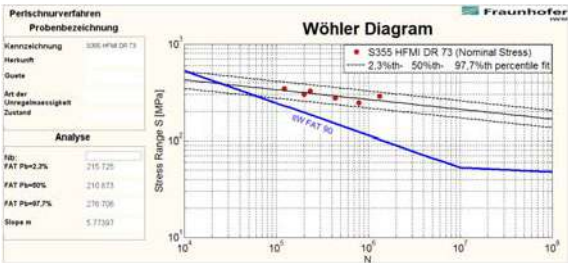


Figure 28 : Fatigue Curve on S355, UNP with «Double Radius Pin»

Table 4 sums up the FAT obtained on S355 specimens according to the post weld treatment.

S355J3+M	FAT (+2.3%)	% of FAT Improvement (to AW)
IIW Recommandation	90 Mpa	-
As welded	118 Mpa	-
With UNP (Standard Parameters)	176 Mpa	49%
With UNP (Double radius Peen)	216 Mpa	83%

Table 4 : Summary of FAT on S355

S690 Specimens

At the as welded stage, the steel strength has few influence on the fatigue limit of the welded assembly. However, when a post weld treatment such as UNP is applied, the improvement in fatigue strength increases with the steel strength, see Figure 29 and 30. The level of the improvement should be higher for S690 than for S355.

FRAUNHOFER tested the Ultrasonic Needle peening on butt welds made of S690. Fatigue results are presented in Figure 29 and 30.

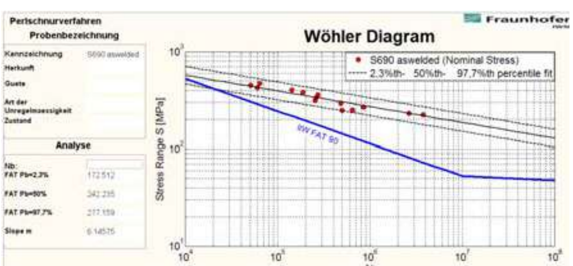


Figure 29 : Fatigue Curve on S690, As welded

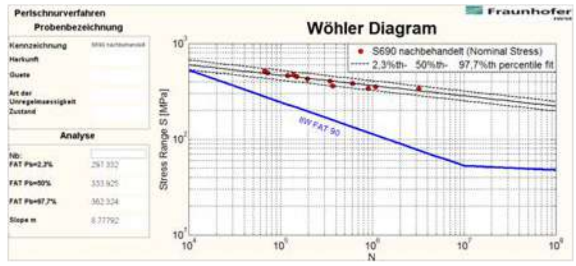


Figure 30 : Fatigue Curve on S690, UNP with standard parameters

EN AW 5754 Specimens

Effect of HFMI treatment on steel joints was widely studied in the last 30 years. For Aluminum, only few studies were carried out.For this reason SONATS and FRAUNHOFER tested the effect of UNP on butt welds made of EN AW 5754.

Fatigue curves are shown in Figure 31 and 32.

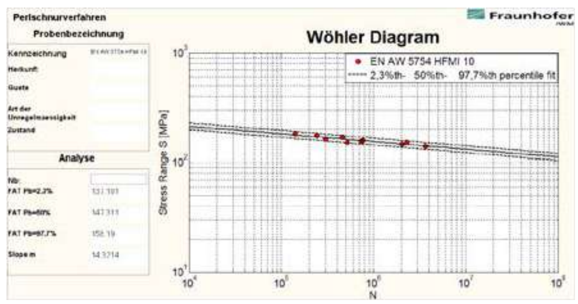


Figure 31 : Fatigue Curve on EN AW 5754, UNP with standard parameters

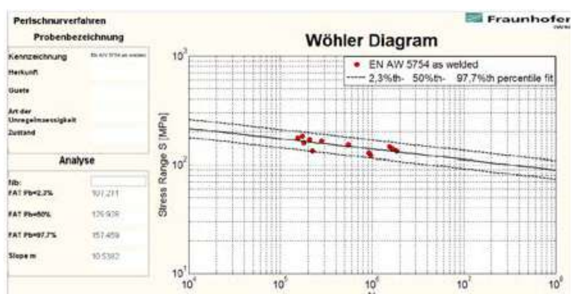


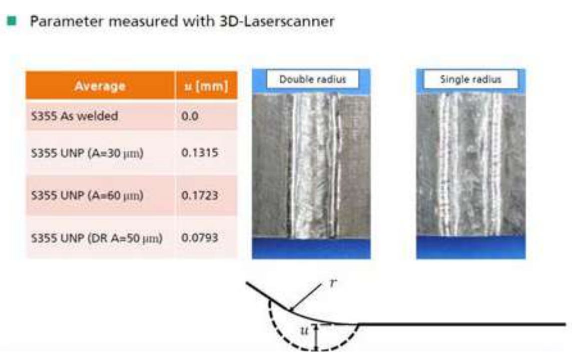
Figure 32 : Fatigue Curve on EN AW 5754, As welded

Compared to the AW joints, we observed 70% of FAT(2.3%) improvement after Ultrasonic Needle Peening on S690. The scattering is also reduced.

Thanks to UNP, 28% of fatigue strength improvement was obtained on EN AW 5754 butt weld specimens. The scatter also drastically decreases by using this post weld treatment.

Conclusions
Fatigue tests were carried out by FRAUNHOFER, on 3 different materials, high fatigue strength improvement was observed for S355J2+M, S690QL and EN AW5754 (AlMg5).

Double radius peen shows a larger improvement than standard needles. The reason for this higher improvement is probably the low penetration in the weld toe combined with a very low surface roughness in the groove (as observed in Figure 33).



Average	u [mm]
S355 As welded	0.0
S355 UNP (A=30 µm)	0.1315
S355 UNP (A=60 µm)	0.1723
S355 UNP (DR A=50 µm)	0.0793

Figure 33 : Surface indention depth after needle peening according to several parameters and surface (DR = Double Radius)

5.1.6. Fatigue Life Improvement of Welded Girders with Ultrasonic Impact Treatment[32]

The fatigue life of welded connections can be improved by a variety of post-weld treatment methods. One of the most effective methods is HFMI treatment. This technology may be applied during shop fabrication, but the greatest benefit comes from field retrofitting applications. Prior research has demonstrated the effectiveness of 27 kHz UIT systems for improving the fatigue life of welded bridge girders (Fisher and Roy, 2003).

In collaboration with Purdue University, SONATS conducted a project to demonstrate the effectiveness of SONATS process on transverse stiffener and cover plate termination welds using 20 kHz impact frequency. In this study, fourteen full-scale girders with welded attachments are subjected to constant amplitude fatigue loading to determine the improved fatigue resistance due to SONATS HFMI equipment.

The test matrix considered variables of stress range and minimum stress. Fatigue test results show:

- Transverse stiffener welds improved from AASHTO Category C' to Category B
- Cover plate termination welds improved from AASHTO Category E' to Category C

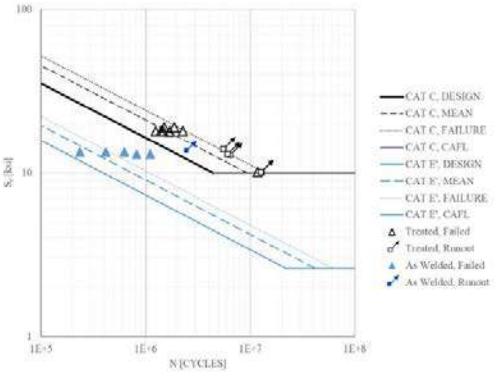


Figure 34a: Figure 1: S-N Diagrams for T cover plates

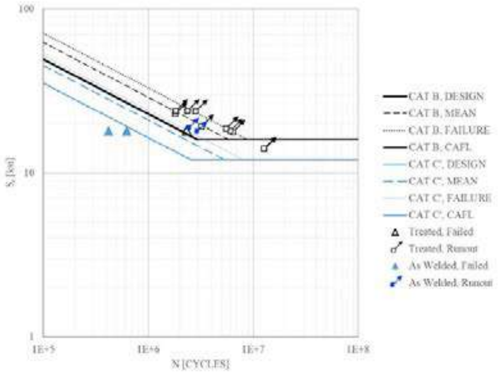


Figure 34b: S-N Diagrams for Transverse stiffeners

This results expand the alternatives available to bridge owners seeking solutions for extending the life of their aging steel bridge inventory.

5.2. Studies in Progress

5.2.1. Société Nationale des Chemins de Fer - SNCF - France

As presented in the IIW Document" XIII-2545-14"[33], SNCF is leading an important study. It aims to establish the fatigue criteria for UNP fillet welds under frequently observed service loads. Specimens made of fine-grained steel are tested using two stress ratios. The program will be ended by performing fatigue tests on real size components.

5.2.2. «Mechanisms understanding of hammer peening effect in welded structure under fatigue loading»

In collaboration with CETIM (Centre Technique des Industries Mécaniques), and other companies, SONATS is involved in a research program to characterize the UNP effect in welded structures.

Some questions still arise:

- What is the HFMI peening efficiency for the different domains of fatigue (low cycles, limited endurance or high cycles)?
- What are the influencing parameters (residual stress, geometry of the weld toe, hardening ...)?
- What are the involved mechanisms?

In summary, the on-going study is: "Why, how and under which conditions of solicitations, HFMI peening is effective in welded structure?".

5.2.3. Fatigue behaviour of arc welded assemblies: paths of improvement[34]

In order to take advantage of Ultra High Strength Steels (AHSS) in the automotive industry, ARCELORMITAL would like to propose to its customers an efficient and robotized post weld treatment method. The thickness of the tested samples is 2 mm (as currently observed in automotive industry).

In a first step, several post-weld improvement methods are tested, TIG dressing and UNP by SONATS have been selected due to the efficient fatigue life improvement observed after treatment with these techniques. Additional tests are ongoing in order to confirm previous results.

6. SONATS' EXPERIENCE

SONATS was founded in 1991 and has more than 20 years of experience in residual stress measurements and surface impact treatments activated by ultrasound for fatigue life improvements. This paragraph describes some chosen examples of our experience on UNP featured projects.

6.1. Civil engineering structures

NOMAD UNP offers a portable solution easy to use and has been accepted by the Port Authority of New York to extend the life of the George Washington Bridge's upper level structural steel deck (2014). Extensive UNP operations have been conducted by the contractor American Bridge during about one year, as shown on Figure 34a and 34b. (See American Bridge Journal - AB Connections, Summer 2012 on www.americanbridge.net)

Beside this remarkable example, NOMAD UNP has been used on bridge repairs, or new bridges, in USA, Canada, Europe and Asia. SONATS and ETI provide peening services or/and NOMAD UNP equipment leasing after dedicated training for bridge work.

Figure 35a : George Washington Bridge

Figure 35b : George Washington Bridge

6.2. Heavy machinery

SONATS and EMPOWERING TECHNOLOGIES (ETI) have provided solutions for manufacturers of heavy construction equipment. It ensures that optimum weld Quality Assurance was maintained on critical structures and weld joints, with very positive results, see below an example of a wheel loader part.

UNP was added by end-customers into their specifications as a method of fatigue strength and life enhancement.

Figure 36 : Example of Wheel loader part

6.3. Shipbuilding

Manufacturers engaged SONATS and ETI to ultrasonically needle peen the critical welded area on several Nordic seas tankers rudders to improve fatigue strength and fatigue life.

Figure 37 : Nordic Sea Tanker Rudder repair

SONATS provided UNP service onsite to prevent cracking from fatigue and tensile stress. Treatment has been very efficient since no more cracks have been observed.

Beside this repair project example, SONATS and its US Subsidiary EMPOWERING TECHNOLOGIES, were engaged to treat numbers of new or used ship structures (both for Steel or Aluminum). ETI is a qualified UNP/UIT supplier for the US Navy.

6.4. Energy

SONATS Engineering Services team was called to evaluate the feasibility to impart beneficial compressive stresses on critical welded areas.

Objective was to increase the maximum load resistance on a defined design of Wind turbine. SONATS deployed Engineers and UNP operators to treat weld connections on a nacelle with hard accessible work environments (see Figure 37).

Figure 38 : Wind turbine nacelle

6.5. Defense

SONATS developed a unique device able to needle peen very large welded area on aluminum frames of amphibious motor vehicles. Treatment results to a high surface finish quality and improve resistance to stress corrosion cracking.

Figure 39 : Aluminium frame of an amphibious military heavy equipment

6.6. Automated peening solutions

SONATS / ETI is developing a robotic device in order to apply UNP technology in an automated, controlled and repeatable process (see Figure 39).

Figure 40 : Robotic UNP on automotive chassis

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