Fatigue Life Enhancement of Welded Structures using Ultrasonic Needle Peening

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ABSTRACT

Ultrasonic Shot Peening technique is nowadays recognized as a mature process currently covered by 2 aerospace industries specifications (BNAE and SAE/AMS), and used worldwide for improving the resistance of high-value components. Ultrasonic Activation of media principle is also used for Needle Straightening and Forming of Metal sheet components.

A recent development is the Needle peening of Welds (also called Ultrasonic Impact Treatment), a reliable, well-controlled and efficient technique for strengthening welded assemblies, especially as regards to fatigue damage due to cyclic loads encountered during service. Ultrasonic Needle Peening (Ultrasonic Impact Treatment) has been shown to bring significant life enhancement thanks to the introduction of beneficial Compressive Stresses combined with weld toe geometry reshape [2, 3, 4]. The process is able to increase the number of fatigue cycles before crack initiation by factors of ten. This process is also an alternative of toe grinding or TIG dressing.

Target end-user applications are found or expected in a large range of industries, such as Transportation, Energy, Mining Exploitation, Oil & Gas, Heavy Industries and Infrastructures.

In this article, we will describe experimental fatigue tests and characterization results [1] obtained on S355 steel welded specimens, that demonstrate and confirm life time enhancement. The ultimate goal of this program is to establish best practices to guarantee process repeatability and reliability whatever manual and automatic operations.

KEYWORDS

Ultrasonic Needle Peening (UNP), Ultrasonic Impact Treatment (UIT), Fatigue Life Enhancement, Welds, Residual Stresses, S355

INTRODUCTION

The **U**ltrasonic **N**eedle **P**eening (UNP) also called **U**ltrasonic **I**mpact **T**reatment (UIT) is a process using vibrating tool to throw needles or indenters onto part surface. The treatment creates dimples inducing compressive residual stresses and reshapes weld toes. This technique uses a generator providing an electrical sine signal with 10 to 60 kHz to a piezoelectric or magnetostrictive transducer which converts it into a mechanical displacement. The sonotrode vibrating displacement (vibration amplitude) is commonly set from 10 to 200µm p/v.
The hand held peening head is terminated by an end piece which encapsulates needles. These needles can vary according to their size, geometry, material and hardness.

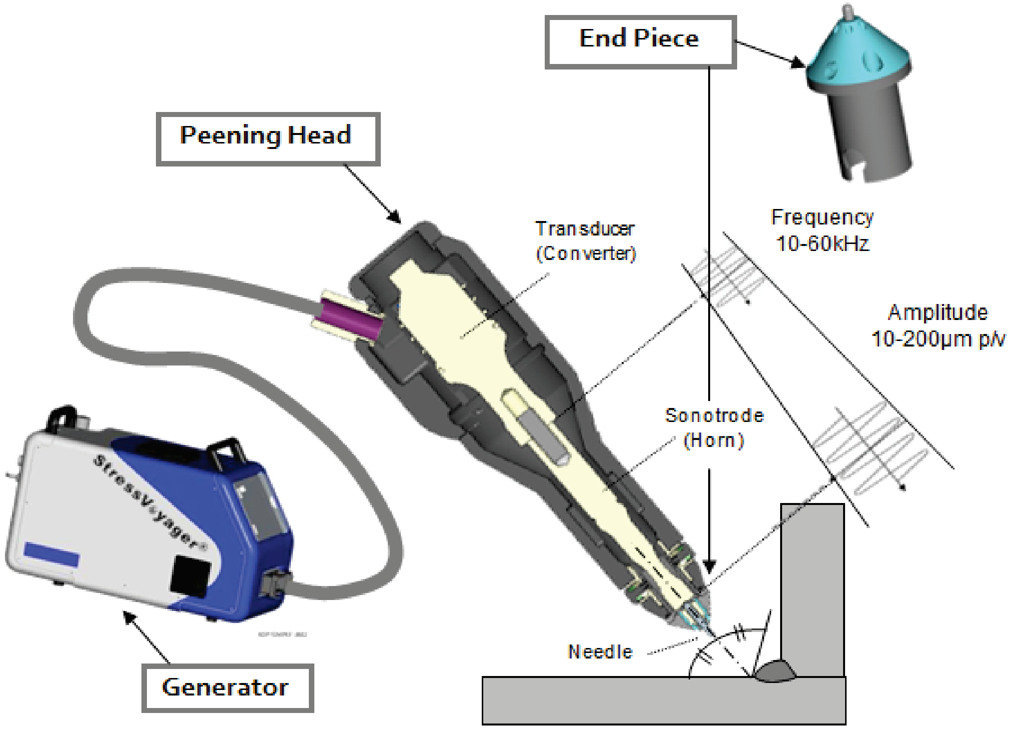


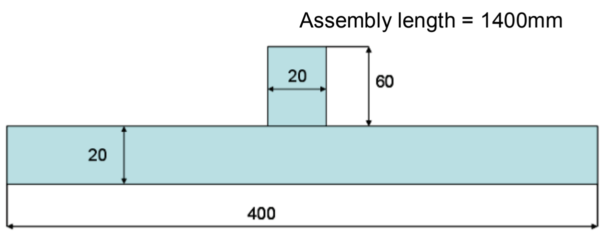
Fig. 1: Ultrasonic Needle Peening Process Principle

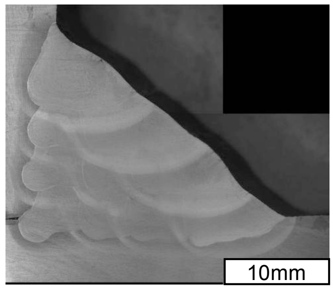
Ultrasonic Needle Peening is a post weld treatment mostly used as a manual operation but largely predicted in the future as an automatic process in the order to get the full benefit of material strength of welded components (For example, on high strength steel used in the automotive industry for car body and frames).

This process is easy to manage and environmentally friendly. It is reliable and provides a very cost effective post weld technique for new and repaired components.

EXPERIMENTAL DETAILS

The specimens: the program has been developed using steel MAG welded specimens. The specimens have been specifically made of S355K2+n steel with a UTS=532MPa and YS=417MPa. Prior welding, the plate scale was removed by grinding on approximately 60mm on each side of the vertical plate. To increase the consistency of the results the welds have been achieved by a robotic arm applying 20 passes with 310A under 30V with 420mm/min travelling velocity. Welds have been filled using G3Si1 (SG6) filler metal and shielded with M21 gas. Due to the required number of passes to create the large join, weld passes have been alternatively applied on each side of the stringer to limit assembly distortion while welding. In addition, the specimens have been stabilized at the 200°C between passes.





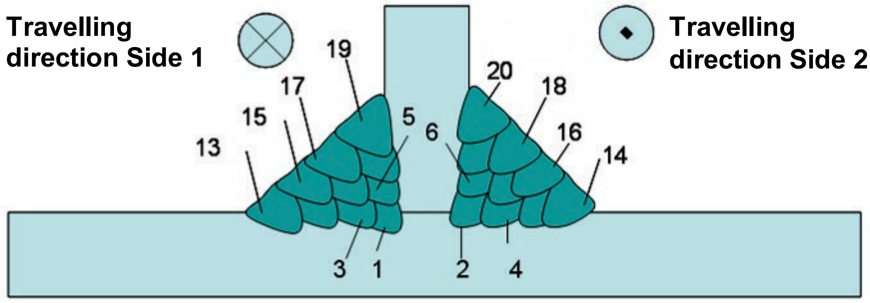
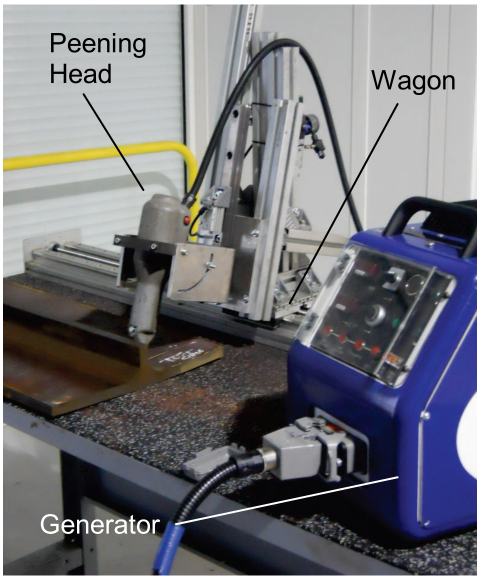


Fig. 2: Welded assembly and specimens



The Ultrasonic Needle Peening Equipment: A portable equipment called StressVoyager®-UNP was used and associated with a motorized travelling wagon to perform the peening along the specimen weld toes. The wagon also includes a cylinder pipe to apply a permanent tool pressure against the specimen. This 70N load was evaluated as equivalent to an operator pressure during a manual operation. The StressVoyager®-UNP is a 20kHz version using a 1000W generator, CR20A piezo-electrical transducer and a SO-PT-15-Ac-00 steel sonotrode. The end piece, needles and process parameters were varied according to the test matrix.

Fig. 3: Ultrasonic Needle Peening device built with a StressVoyager®-UNP and a motorized wagon.

The peening head was tilted at 17° to correctly orientate the needle at the medium angle created by the weld and the base plate. The fatigue testing of the specimen is a 4 point bending testing which creates tensile stresses in the weld bottom. Only the bottom toes have been ultrasonically needle peened. As references, nine (9) unpeened specimens have been tested and compared with a literature referenced XIII-1817-00 [2]. 36 other specimens have been tested under 4 parameter combinations as described in the following table.

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

S3-13 and S3-15 are shrouded needles with Ø4mm and Ø3mm diameters.

The 2 passes have been shifted to enlarge the groove created by the indenters. The second pass partially overlapped the first one. The target was to reproduce a typical groove width observed when the operation is performed manually.
Before testing the specimen edges (at the weld toe) was ground to avoid premature failures. Each specimen has been testing using a 4 point bending machine with stress ratio of R=0.1 with 20Hz sinusoidal signal. Additional specimens have been produced for residual stress measurements done by X-Ray diffraction and roughness measurement with a 2D profile-meter.

RESULTS

As expected, the Ultrasonic Needle peening treatment has created a plastic deformation of the weld toes by generating a groove along the weld. Characterizations of each peened samples have demonstrated that the needle peening introduced deep compressive stresses in the toe. Maximum compressive stresses have been observed at the specimen surface and they affected the material down to 2.5mm deep. In the figure 4 are shown the residual stresses profiles on both directions: longitudinal and transversal. Conditions: C#1, C#2 and C#3 are significantly similar while the C#4 shows a better compressive stress improvement with a superficial stress reaching -850MPa. It is suspected that this difference can be issued from another physical aspect and subject to particular additional characterizations (in progress). As an important fatigue life aspect, the surface finish of grooved toes was also characterized. The figure 5 shows the roughness measurements achieved for the longitudinal and transversal direction next to the toe or groove. The roughness is significantly improved after needle peening especially for transversal direction which is the most critical direction for crack initiations. The conditions using 3mm tip radius needles have smoother surface roughness than conditions using 1.5mm tip radius needles. As in our test matrix, all needles are thrown with the same velocity, the sharpest needles (R=1.5mm) have a deeper penetration in the toe and create deeper dimples resulting in a higher roughness.

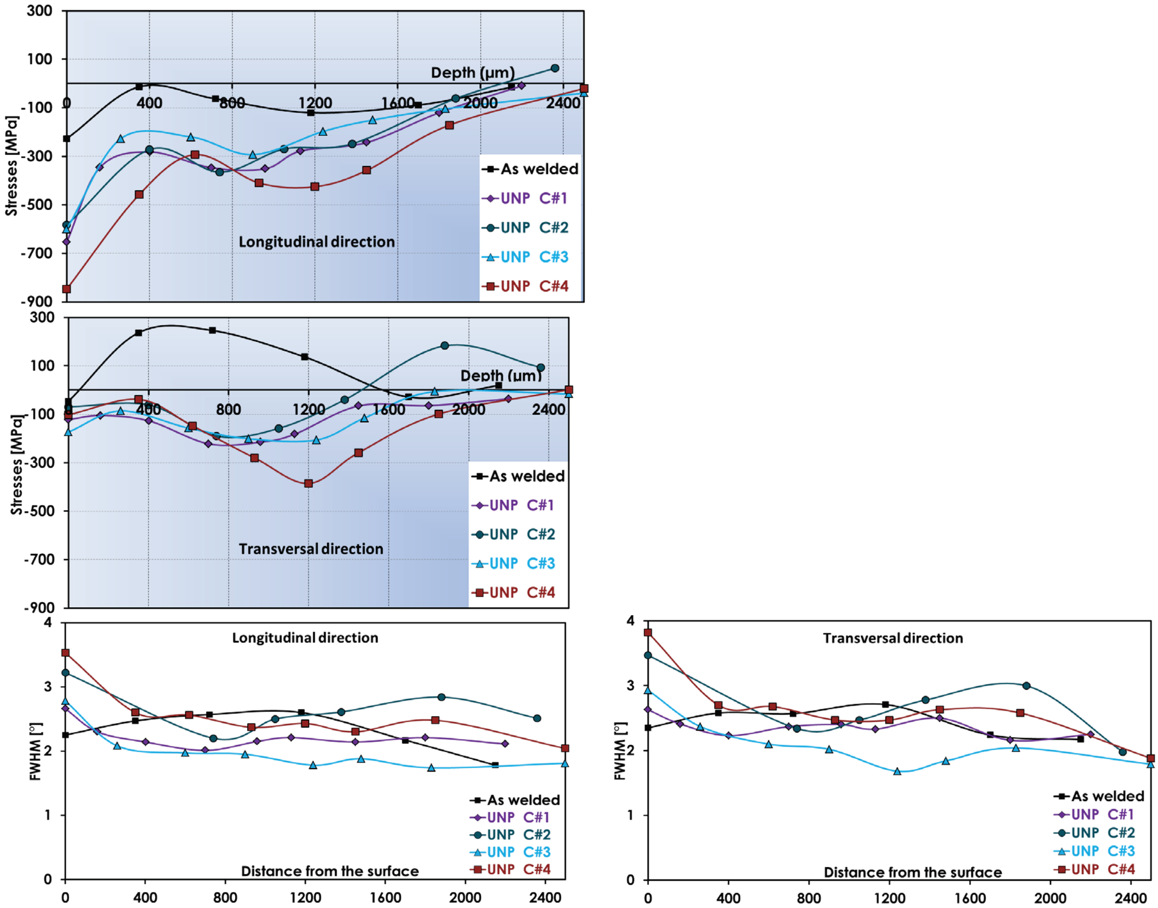


Fig.4: Residual stress distribution in both directions at weld toes for unpeened and ultrasonically needle peened specimens.

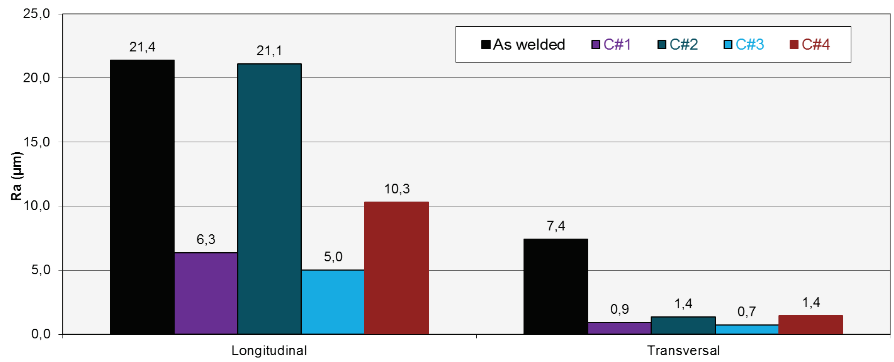


Fig.5: Roughness measurement - longitudinal and transversal to the weld

The 45 specimens have been fatigue tested (9 unpeened and 36 peened). 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 3 and up to 5 for 350Mpa stress range. The UIT condition set 2 from study XIII-1817-00 has been used for comparison and validation of current work. Between both studies results are found comparable. Whatever parameter sets, we still observed a significant enhancement for all specimens. This demonstrates the low influence of varied parameters as needle size and needle quantity. We observed better results on condition #2 which will require to be carefully analysed to highlight the dominant parameter.

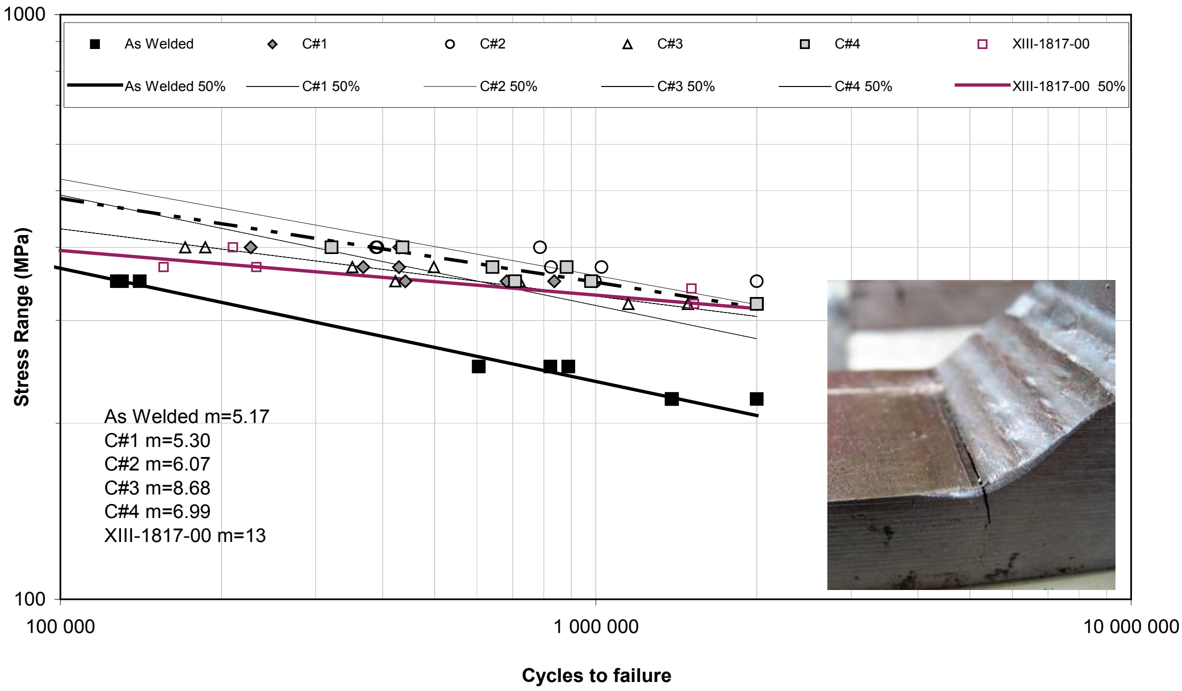


Fig.6: Fatigue S/N curves conducted up to 2 million cycles

	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**

Fig.7: Stress Range at 2e6 cycles

The figure 8 shows the distribution of failures next to the toe. As expected, for untreated specimens, failures were located in the weld toe(F) which is the most stressed area and for the all series no failure was observed on the groove weld side (E) and on the root, Peened samples mostly break in the same area but, some failures are located in base material, showing that the weld joint is no longer the weakest point of the assembly.

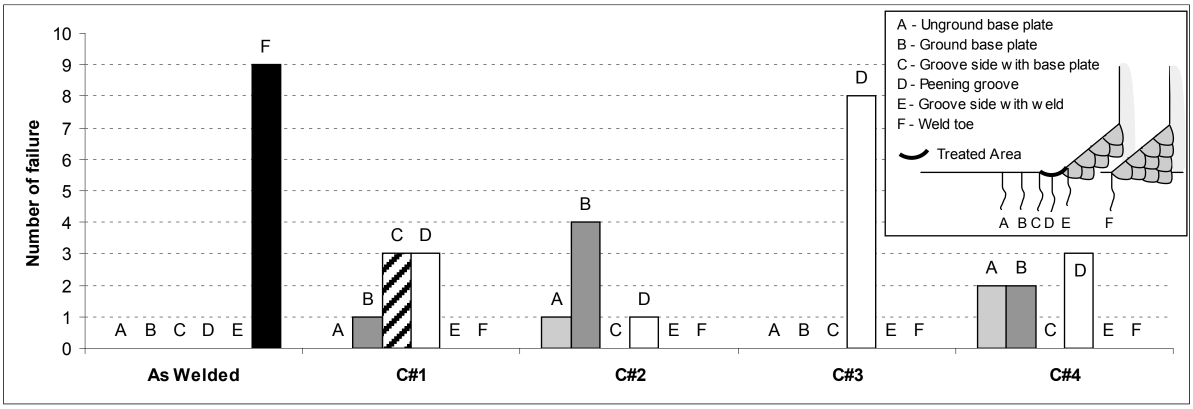


Fig.8: Failure location distribution next to the weld toe

CONCLUSIONS AND PROGRAM CONTINUATION

In this study, we investigated the influence of ultrasonic needle peening on S355 steel components. The results show and confirm that the ultrasonic needle peening bring significant fatigue life improvement on welded components. The process improves the residual stresses distribution, the transversal roughness and reduces the notch effect.

This study also demonstrates the limited influence of first order parameters compared to their influence in similar ultrasonic peening process as ultrasonic shot peening. Conditions #2, #3 and #4 show an equivalent benefit while condition #1 is slightly less. The fatigue limit at 2.10^6 cycles was increased by 50%. Those results validate the current work in order to engage further testing to highlight best parameters and working practices.

This test program is still running to evaluate and clarify best operating practices. The key point of this process remains in the process control to limit and avoid variability due to the manual operation. Additional testing and characterization are scheduled for other parameters combinations and fatigue solicitations (loads and cycles).

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