Fatigue Strength Improvement of Aluminum and High Strength Steel Welded Structures using High Frequency Mechanical Impact Treatment

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Abstract

Most structures and components are fabricated using welded joints. A very high percentage of all fatigue failures locally occur at welded locations due to high tensile residual stresses and stress concentrations resulting from the weld process. High frequency mechanical impact (HFMI) treatment has been increasingly used as an effective post-weld treatment technique to improve fatigue strength of welded structures. Fatigue tests have been conducted for as-welded and HFMI treated 5083-H321 grade aluminum and ASTM A514 steel welded specimens to investigate the effects of the HFMI treatment under constant amplitude $R = 0.1$ and variable amplitude loading. This paper presents fatigue test results including local properties (residual stresses) of welded specimens under the as-welded and the HFMI treated conditions. Test results showed that the HFMI treatment significantly improved fatigue life performance of the aluminum and steel welded specimens under both constant and variable amplitude load conditions. Therefore, the HFMI treatment is a quite promising post-weld treatment technique and its potential applications on the fatigue design of welded structures and components can lead to lighter structures and products, in which components and structures can be down-sized and optimized to reduce weights.

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1. Introduction

Welding is one of the most widely methods for joining structural components because of its low cost, structural strength and geometric flexibility. However, fatigue failures tend to occur at weld joints due to irregular geometries, material imperfections and flaws, and tensile residual stresses induced by welding. Therefore, the weld joints are considered to be critical areas from a fatigue design point of view. A large number of experimental research studies have been conducted to develop post-weld treatment technologies to improve fatigue strength of welded joints and structures and avoid fatigue failure. These treatments aim to reduce stress concentrations by modifying local geometries of the weld toe and/or introduce compressive residual stresses by plastically deformation the weld toe in order to increase fatigue life of the welded structures [1]. These treatment methods are generally divided into two categories: weld profile modification methods, and residual stress modification methods. As for the weld profile modification methods, the main goal is to reduce the local stress concentration due to the irregular weld profile by achieving a smooth transition between the base plate and the weld area. Some of the most well-known weld profile modification methods are machining or grinding of weld seam and toe, and re-melting the weld toe by TIG or plasma dressing. On the other hand, the main goal for the residual stress modification methods is to eliminate the high tensile residual stresses and induce compressive residual stresses at the weld toe. Hammer and needle peening are two of the well-known residual stress modification methods. In addition to the previously discussed weld treatment methods, high frequency mechanical impact (HFMI) treatment, which is a term introduced by the IIW in 2010 has gain considerable attention as a post-weld treatment method in recent years [2]. HFMI treatment uses cylindrical rods, which impact the weld material at high frequency (18000-27000 Hz) to induce locally plastic deformation resulting in re-shaping weld toe geometry and modifying residual stress state in the region of the weld toe. This study was conducted to examine fatigue performance of welded specimens of 5083-H321 aluminum and ASTM A514 high strength steel subjected to HFMI treatment.

2. Experimental Fatigue Test

The current study was undertaken to investigate fatigue performance of aluminum and high strength steel welded specimens subjected to high frequency mechanical impact (HFMI) treatment. Fatigue tests of welded specimens were conducted to quantify the fatigue performance improvements resulted from the HFMI treatment.

2.1. Test Specimens

Specimens were fabricated from 3/8” (9.5 mm) thick aluminum (5083-H321) and high strength steel (ASTM A514) plates. Transverse stiffeners were welded to the plates and welded plates were inspected to check the quality of the welds. No weld quality problems were observed. Following the fabrication of 12” wide welded plate samples, samples were treated manually by a HFMI tool as shown in Figure 1. The 12” wide samples were then cut into 2” wide strips, which were subsequently machined to their final “dog bone” shape (see Figures 2) using a computer numerical control machine. The geometry and dimensions of specimens are shown in Figure 3.
Figure 1: HFMI treatment of 12” long high strength steel weld.

Figure 2: Aluminum specimen after machining to final shape.
2.2. Test Program

The fatigue tests were carried out in a 100 kN MTS testing frame shown in Figure 3 at varying frequencies associated with the loading level but testing frequencies did not exceed 100 Hz. The tests were monitored and run until specimen complete fracture. In general, tests were stopped and abandoned if fatigue cracking was not observed after ~4 million cycles, and those test were recorded as a “runout”.

Table 1 shows the summary of the fatigue test matrix describing the material type, loading type, the treatment and the number of specimens. The testing program consisted of fatigue testing of 48 welded specimens. Of these, 24 were to be fabricated of aluminum and 24 of high strength steel. Half of the specimens were to be tested in their “as-welded” (AW) state and half were to be HFMI treated. Two loading histories were used in this study: constant amplitude (CA) loading at a stress ratio, $R = S_{\text{min}} / S_{\text{max}}$, of 0.1 and variable amplitude (VA) loading using the history shown in Figure 4.
Table 1: Fatigue testing matrix.

| Material | Loading | Treatment | Number of Specimens |
|----------|---------|-----------|---------------------|
| Steel    | CA      | AW        | 6                   |
|          |         | HFMI      | 6                   |
|          | VA      | AW        | 6                   |
|          |         | HFMI      | 6                   |
| Aluminum | CA      | AW        | 6                   |
|          |         | HFMI      | 6                   |
|          | VA      | AW        | 6                   |
|          |         | HFMI      | 6                   |

3. Fatigue Test Results

The results of the fatigue tests can be seen from Figures 4 and 5 for ASTM A514 steel and 5083-H321 aluminum specimens respectively. The specimens for these two materials were divided into the as-welded (AW) and HFMI treated groups. Each specimens group was tested under the constant amplitude (CA) and variable amplitude (VA) loading conditions. Fatigue test data (S-N) for ASTM A514 steel and 5083-H321 aluminum were plotted in Figures 5 and 5 respectively. The figures show the effect of the HFMI treatment on the fatigue lives of the welded specimens. In these figures, the as-welded specimens are indicated with blue symbols and the HFMI treated specimens are indicated in red. A filled symbol indicates that the specimen failed, whereas a hollow symbol indicates that the test was a “runout”.

In all cases, the red symbols showing HFMI fatigue data are shifted to the right, indicating that an increase in fatigue life in varying degrees has resulted from HFMI treatment. In general, the fatigue life increases are more substantial for the high strength steel than for the aluminum weld specimens. In fact, there is one load level for the aluminum (under VA loading) where the as-welded and treated data overlap slightly. This result can be attributed to the natural scatter of the test data and the minimal benefit of HFMI treatment for the aluminum at the higher stress ranges. When comparing the test data, it is important to recognize that the horizontal axis in these graphs is a logarithmic scale, so a small shift to the right can represent a fatigue life increase of several hundred percent.

For the CA test results, the plotted stress range, $\Delta S$, is simply $S_{\text{max}} - S_{\text{min}}$. The stress is simply the nominal stress, or the load divided by the corresponding cross section area. For the VA tests, there is a step load histories consisting of large and small stress blocks. It was therefore necessary to calculate and equivalent stress range based on Miner’s sum, i.e.:

$$\Delta S_{eq} = \left( \frac{\Delta S^m_1 \cdot N_1}{N_{tot}} + \frac{\Delta S^m_2 \cdot N_2}{N_{tot}} \right)^{1/m}$$

Where $\Delta S_1$ is one stress range and $\Delta S_2$ is the other. For the loading history in Figure 4, $N_1 = 50$ large cycles, $N_2 = 950$ small cycles and $N_{tot} = 1000$ cycles. $m$ in Equation (1) is the slope of the constant amplitude S-N curve. In accordance with recognized North American structural design codes for steel and aluminum [3,4], $m$ was taken as 3.0 for steel and 3.64 for aluminum for the tested transverse stiffener detail, which is commonly classified as “Detail Category C”.

The purpose of the VA loading tests was to study the effectiveness of HFMI treatment under a loading history that is known to be particularly severe for impact treated welds. Specifically, loading histories with periodic “underload” cycles, where the minimum stress level is significantly lower than the other cycles tend to result in
lower fatigue lives for impact treated welds, since the underload cycles can have two negative effects [5]: 1) reducing the crack closure stress level, and thus increasing the portion of each cycle that causes fatigue damage, and 2) relaxing the residual stresses, due to the cyclic plasticity that results at the weld toe. Looking at the VA loading results in Figures 4 and 5, it can be seen that a significant fatigue live increase resulted due to HFMI treatment, even under this particularly severe loading history.

The fatigue life increase resulting from HFMI treatment depends on the stress range. At the lower stress ranges, the fatigue life is greater — in some cases in fact, the treatment results in an infinite life. At the higher stress ranges, the fatigue life increase is generally less, but still significant relative to the as-welded state.

![Fatigue Test Results](image1)

![Fatigue Test Results](image2)

Figure 4: CA (top) and VA (bottom) fatigue test results for ASTM A514 steel welds
3.1. Statistical Analysis of Fatigue Test Results

In order to better understand the fatigue strength improvement resulting from HFMI treatment, a statistical analysis for the CA fatigue test data was performed, using the method recommended by the International Institute of Welding (IIW) [6]. It was assumed that the results of the fatigue tests had a characteristic of the Gaussian log-normal distribution. According to this method, the fatigue life, \( N \), is treated as the dependent variable, which varies depending on stress range, \( \Delta S \). Given the test results and the number of data points, the S-N curve slope and vertical
position can be established for a given survival probability. In Figure 6 and Table 2, results are summarized for the mean curve (50% survival probability) and a “design” curve. The IIW normally assumes a survival probability for the design curve of 95%. The S-N curve defining the number of cycles to failure expressed as follows:

\[ \text{LOG}(N) = \text{LOG}(C) - m \cdot \text{LOG}(\Delta S) \]  

where \( C \) and \( m \) are constants determining the vertical position and slope of the S-N curve by linear regression analysis taking stress range, \( \Delta S \) as the independent variable. In Table 2, the values of these constants are given for the mean (\( m \)) and design (\( k \)) curves.

![Figure 6: Mean and design curves based on IIW statistical analysis of constant amplitude (CA) loading results for steel (left) and aluminum (right).](image)

| Material | Treatment | \( m \) | LOG(C)m | LOG(C)k |
|----------|-----------|--------|----------|---------|
| Steel    | AW        | 2.3876 | 10.9215  | 10.4907 |
|          | HFMI      | 5.6091 | 20.1075  | 19.2281 |
| Aluminum | AW        | 6.0658 | 17.2391  | 16.9451 |
|          | HFMI      | 7.3534 | 20.2544  | 19.6216 |

It can be observed from Figure 6 and Table 2 that a significant increase in the fatigue lives obtained for both the materials, regardless of whether the mean or designs S-N curves are compared. In order to quantify the fatigue life improvement associated with HFMI treatment, Table 3 was generated utilizing Equation (2) and Table 2. To do this, the stress range (\( \Delta S \)) associated with an as-welded (AW) fatigue life of \( N = 1 \cdot 10^5 \) or \( 2 \cdot 10^6 \) was first obtained. The number of cycles to failure at the same stress range was then calculated for the HFMI treated weld and then used to calculate a fatigue life increase ratio (HFMI/AW). Looking at these ratios, it can be seen that the fatigue life increase due to HFMI for the steel weld specimens was 15.7-21.3 times at the higher stress level (associated with an AW fatigue life of \( N = 1 \cdot 10^5 \)) and 895 to 1214 times at the lower stress level (associated with an AW fatigue life of \( N = 2 \cdot 10^6 \)). The fatigue life increases for the aluminum specimens were more modest but still significant: 1.4-2.6 times at
the higher stress level and 2.6-4.9 times at the lower stress level. In general, the fatigue life increase ratio was similar if the design S-N curves were compared as opposed to the mean S-N curves.

Table 3: Fatigue life increase (HFMI/AW) for several stress ranges.

| Material | S-N Curve | ΔS (MPa) | AW     | HFMI   | HFMI/AW |
|----------|-----------|----------|--------|--------|---------|
| Steel    | Mean      | 302      | 1.00E+05 | 1.57E+06 | 15.7    |
|          |           | 86       | 2.00E+06 | 1.79E+09 | 895     |
|          | Design    | 199      | 1.00E+05 | 2.13E+06 | 21.3    |
|          |           | 57       | 2.00E+06 | 2.43E+09 | 1214    |
| Aluminum | Mean      | 104      | 1.00E+05 | 2.61E+05 | 2.6     |
|          |           | 64       | 2.00E+06 | 9.87E+06 | 4.9     |
|          | Design    | 93       | 1.00E+05 | 1.38E+05 | 1.4     |
|          |           | 57       | 2.00E+06 | 5.22E+06 | 2.6     |

3.2. Residual Stress and Weld Geometry Measurements

Although HFMI treatment has a significant impact in modifying the weld toe geometry and thus reducing the stress concentration at the weld toe, the HFMI method is classified as a residual stress modification method. Therefore, residual stress measurements were performed by Proto Manufacturing, an external laboratory, using a procedure of electropolishing and x-ray diffraction. The measurement results are plotted in Figure 7. Measurements were taken on untested as-welded and HFMI treated specimens. Figure 8 shows some scatter in the residual stresses. However, in general, HFMI treatment introduces a compressive residual stress near the surface of the treated weld toe on the order of 300-600 MPa for the high strength steel specimens and 75-200 MPa for the aluminum specimens. The scatter in the measured residual stress is significant – for one of the aluminum welds, the near surface residual stress after HFMI treatment was seen to be almost zero. Since measured residual stress results are very sensitive to the precise location of the measurement spot, measurements for the precise same spot for different specimens are quite difficult to obtain. Considering the significant fatigue life improvement that was observed in the test results, it is suspected that these residual stress variations occur over short distances along a weld, so that if a crack initiates in a region of low compressive residual stress, it is arrested in the adjacent regions were the residual stress magnitude is higher. Further measurements would be needed, however, to confirm this assumption.

Weld toe geometry measurements were also taken using a method of silicon impressions and photographing. Figure 8 shows a photograph of the silicon impression (left) and the definitions of the dimensions measured (right). Figure 8 (right) also shows three different ways of measuring indent depth from the base metal side ($D_b$), the weld side ($D_w$) and the average of the base metal and weld side ($DAVG$). Figure 9 shows a silicon impression slice photograph and the dimensions after treatment being measured. The geometry measurements for the weld toe are summarized for ASTM A514 steel and 5083-H321 aluminum specimens in Tables 4 and 5 respectively.
Figure 7: Residual stress measurements on steel (left) and aluminum (right) weld samples.

Figure 8: Silicon impression of 5083-H321 aluminum specimen after HFMI treatment (left) and definition of indent depth (on the weld side and base metal side) and radius.

Figure 9: Silicon impression of steel Specimen A, Cut 1 before (left) and after (right) treatment.
Table 4: HFMI indent geometry ASTM A514 steel.

| Specimen | Cut | $D_a$ (mm) | $D_w$ (mm) | $D_{AVG}$ (mm) | $R$ (mm) |
|----------|-----|------------|------------|----------------|----------|
| A        | 1   | 0.0512     | 0.176      | 0.114          | 1.98     |
|          | 2   | 0.0917     | 0.179      | 0.135          | 2.15     |
|          | 3   | 0.1420     | 0.0850     | 0.114          | 1.86     |
| E        | 1   | 0.130      | 0.165      | 0.148          | 1.76     |
|          | 2   | 0.172      | 0.245      | 0.209          | 1.78     |
|          | 3   | 0.142      | 0.157      | 0.150          | 2.23     |
| G        | 1   | 0.148      | 0.0864     | 0.117          | 1.77     |
|          | 2   | 0.292      | 0.188      | 0.240          | 1.93     |
|          | 3   | 0.159      | 0.0996     | 0.129          | 2.55     |
| H        | 1   | 0.236      | 0.228      | 0.232          | 1.75     |
|          | 2   | 0.362      | 0.111      | 0.237          | 1.69     |
|          | 3   | 0.202      | 0.225      | 0.214          | 1.70     |
| Average: |     | 0.177      | 0.162      | 0.170          | 1.93     |
| Std. Dev.: |   | 0.086      | 0.056      | 0.052          | 0.26     |

Table 5: HFMI indent geometry 5083-H321 aluminum.

| Specimen | Cut | $D_a$ (mm) | $D_w$ (mm) | $D_{AVG}$ (mm) | $R$ (mm) |
|----------|-----|------------|------------|----------------|----------|
| B        | 1   | 0.107      | 0.102      | 0.105          | 2.35     |
|          | 2   | 0.219      | 0.167      | 0.193          | 2.23     |
|          | 3   | 0.218      | 0.0706     | 0.144          | 2.35     |
| C        | 1   | 0.0719     | 0.0664     | 0.069          | 2.43     |
|          | 2   | 0.0889     | 0.123      | 0.106          | 2.23     |
|          | 3   | 0.233      | 0.17       | 0.202          | 1.76     |
| D        | 1   | 0.182      | 0.211      | 0.197          | 1.86     |
|          | 2   | 0.106      | 0.106      | 0.106          | 2.44     |
|          | 3   | 0.124      | 0.150      | 0.137          | 2.35     |
| F        | 1   | 0.180      | 0.155      | 0.168          | 2.38     |
|          | 2   | 0.203      | 0.144      | 0.174          | 2.25     |
|          | 3   | 0.203      | 0.172      | 0.188          | 1.89     |
| Average: |     | 0.161      | 0.136      | 0.149          | 2.21     |
| Std. Dev.: |   | 0.058      | 0.044      | 0.044          | 0.24     |

To gain an understanding of the statistical variations in the weld toe geometry dimensions, impressions from four aluminum and four steel specimens were taken before and after HFMI treatment. The impressions taken before treatment mainly served to confirm that the notch before treatment was sharp (i.e. with a radius too small to measure accurately with <10x magnification images taken with a digital camera) and to establish the angle, $\theta$, between the weld surface and the base metal surface (see Figure 9 (left)). The impressions taken after treatment at the same location were then used to measure the weld toe radius, $R$, and the indent depths on the weld and base metal sides of the weld toe, $D_w$ and $D_b$. To perform the measurements, the images were imported into the software AutoCAD (see
Figure 9 (right)). Each of the four impressions was sliced and photographed at three locations to see the parameter variations along the same weld toe.

In general, HFMI treatment resulted in an indent with a radius of ~2 mm and a depth (average of depth on weld side, $D_w$, and base metal side, $D_b$) of ~0.15 mm. An effort was made to achieve the same indent depth in both materials, by varying the power settings on the treatment tool. This was essentially achieved, with the indent depth for the high strength steel specimens being only a few hundredths of a mm greater, on average.

4. Conclusions

Based on the presented research, the following conclusions are drawn:

- The HFMI treatment resulted in a reliable fatigue life increase in both aluminum (5083-H321) and high strength steel (ASTM A514) weld specimens, under both constant amplitude (CA) loading at $R = 0.1$ and variable amplitude (VA) loading.
- In general, the fatigue life increase due to HFMI treatment was greatest for the high strength steel specimens. The actual increase depends on the stress level.
- A statistical analysis confirms that the fatigue life increase can be seen when comparisons are made over a range of survival probabilities (50% or 95%).
- The HFMI treatment results in the introduction of a significant compressive residual stress near the surface (i.e. to a depth of ~1 mm) of the treated weld toe.
- HFMI treatment results in the reliable introduction of a weld toe radius of ~2 mm.

Results of the research study are quite promising for the implementation of the HFMI method in welded engineering structures. Therefore, it seems that HFMI treatment has strong potential as a reliable means for reducing the weight of fatigue critical welded components and structures fabricated out of aluminum or high strength steel.

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References

[1] G. Marquis, Z. Barsoum, A guideline for fatigue strength improvement of high strength steel welded structures using high frequency mechanical impact treatment, Procedia Engineering 66 pp.98 – 107, 2013, doi: 10.1016/j.proeng.2013.12.066.
[2] Haagensen, P. J., Maddox, S. J.: IIW Recommendations on Post Weld Fatigue Life Improvement of Steel and Aluminium Structures, Woodhead Publishing Ltd., Cambridge, 2013.
[3] Canadian Institute of Steel Construction (CISC), Handbook of Steel Construction: 9th Ed., Toronto, 2006.
[4] Aluminum Association. ADM-10: Aluminum Design Manual – Specifications and Guidelines for Aluminum Structures, 2010.
[5] S. Walbridge, Fatigue analysis of post-weld fatigue improvement treatments using a strain-based fracture mechanics model, Engineering Fracture Mechanics, 75:5057-5071, 2008.
[6] A. Hobbacher, Recommendations for fatigue design of welded joints and components, International Institute of Welding: Doc. XIII-1965-03/XV-1127-03, 2005.