Diode laser weld toe re-melting as a means of fatigue strength improvement in high strength steels

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Abstract

Re-melting of weld toes to improve the surface profile and thus reduce stress concentrations is a known fatigue improvement technique. In the study reported here, a novel approach was taken, using a diode laser as heat source. Different diode laser treatment conditions were tested, using the diode laser power, spot size and shape, and the travel speed as main parameters. Fillet welded samples in S690QL and S960QL in 10 mm thickness were treated and fatigue tested with constant amplitude loading. In response to those initial results, further samples were welded and treated and variable amplitude fatigue testing was undertaken.

Keywords: weld toe re-melting, diode laser, high strength steels, fillet welds, fatigue improvement

1. Introduction

1.1. Background

In fusion welds, a sharp transition from the weld metal to the heat-affected zone/parent metal is often found, particularly in those with considerable overthickness/excess weld metal. This transition acts as stress raiser and can thus impair the weld’s performance, in particular the fatigue performance. The transition at the toe can be characterised by the toe angle and radius (both of these are illustrated in Fig. 1), with a small toe angle and radius being detrimental.

One of the well-established ways of improving a weld’s fatigue performance is therefore via smoothing of the transition between the base metal/HAZ and the weld metal (at the weld toe) via mechanical (e.g. grinding or peening) or thermal (via re-melting (dressing) of the weld toe area) means. Traditionally, toe re-melting or dressing is performed using TIG or plasma welding with the suitability of both of these processes resulting from their ability to create just a small amount of molten metal (and this fairly superficially) without the need for filler metal addition to run the process. However, both are generally performed manually and are very sensitive – TIG in particular – to the torch-to-workpiece distance which controls the voltage and thereby significantly affects the process. In addition, the achievable travel speeds tend to be limited to a few hundreds of millimetres per
minute, which is generally slow in comparison to welding travel speeds used for example for MAG welding. Re-melting can then become a bottleneck in production, lowering productivity and raising manufacturing costs.

Fig. 1. Macro-section of a bead-on-plate MAG weld with drawn on it the toe angle (left) and toe radius (right).

1.2. FatweldHSS RFCS project

In the framework of the ‘FatweldHSS’ collaborative European Research Fund for Coal and Steel (RFCS) project on fatigue improvement techniques for welds in high strength steels, diode laser weld toe re-melting was tried. The interest in this power source had a number of reasons. Firstly, the laser is a very scalable tool in terms of power and power density and may therefore open up a larger range of employable parameter sets including travel speeds, potentially increasing productivity. In the ideal case, travel speeds similar to welding travel speeds would be achievable, meaning in-line treatment can be considered. Secondly, diode lasers can easily be used with different focused spot sizes and geometries (in particular circles and rectangles), which is a means of changing the heat distribution in the processing zone. This should be reflected in the shape and dimension of the area that is molten and may therefore impact on the profile and fatigue improvement achievable. Lastly, within the laser family, diode lasers are relatively efficient laser sources, often cheaper to purchase and run in terms of cost per kilowatt than traditional high power lasers (CO₂, Nd:YAG and nowadays fibre and disc lasers).

1.3. Laser weld toe re-melting: state-of-the-art

There are not many publications in the public domain on the use of lasers for weld toe re-melting. Some mentions were found suggesting the use of lasers for weld toe re-melting (e.g. [1]), even if they were not supported with experimental data. However, there was some experimental work reported in the 1980s on aluminium alloy A5083P-O by Masumoto et al. [2] and on steels at the University of Illinois at Urbana-Champaign (US) [3-5]. At the latter, it was found that laser re-melting gave fatigue improvement less than that of shot peening, but better than that of TIG dressing and the technique was thus seen as very promising. A much more recent publication reports on work on the use of fibre lasers for toe re-melting [6]. In this paper, the development of beam-shaping optics to allow deep penetration fibre laser welding and toe dressing of the weld to be performed in a single pass is discussed.

2. Experimental approach and set-up

2.1. Materials

Trials were made on welds in two high strength steel grades: S690QL and S960QL (both in 10 mm thickness), although some of the preliminary investigations were performed on arbitrary steels. The samples for fatigue testing were large tensile specimens, with longitudinal attachments welded to both the specimen surfaces at the mid-position. The attachments (circled by the dashed line in Fig. 2) were MAG fillet welded all around in a multi-pass procedure. Welding was performed by robot to maximize repeatability. It was the lower weld toe that marks the boundary between the weld metal and the main plate that was treated.

Fig. 2. Schematic of the samples used for fatigue testing; the position of the attachments is circled by the dashed line (dimensions in millimetres).
2.2. Diode laser re-melting set-up

Introductory trials for proof of concept and to select suitable optics were performed at German manufacturer of diode lasers Laserline GmbH in Mülheim-Kärlich (Germany). For these trials, runs were made on flat plate and on bead-on-plate MAG welds. For the main body of work, a Laserline 6 kW LDF 6000-100 fibre-delivered diode laser source was rented and installed for a two-month period at OCAS NV at its facility in Zelzate near Gent (Belgium). In addition, later in the project further samples were treated at Laserline for variable amplitude fatigue testing.

The laser used operates in the wavelength range of 900-1070 nm with a beam parameter product of 110 mm*mrad, allowing it to be used in combination with a 1 mm diameter fibre optic cable for beam delivery. Different collimating and focusing optic combinations were used, giving focused spot sizes of approx. 5x6 mm and 10x13 mm for rectangular and 5 mm, 3 mm and 2.5 mm diameter for circular spots. The focusing optics at OCAS were mounted on a Panasonic TAWERS arc-welding robot for following the 2D shape of the weld toe. The axis of the laser beam was at 20° to the normal to the sample surface (so in welding terms, approx. the PB position). Because of the complexity of movement required from the robot arm (exacerbated by the long distance from the tool centre point to the last robot axis), the travel speed for toe dressing was limited to 2 m/min. During the experiments at Laserline (both campaigns), a gantry system was used that allowed only vertical beam orientation (and therefore the laser beam was kept perpendicular to the main plate surface). Shielding gas was generally not used, although some of the introductory experiments were performed using a shielding gas flow of 20 l/min of helium.

2.3. Re-melting experiments

Re-melting procedure development aimed at developing different parameter sets, for example focusing on the depth of re-melting, or on the travel speed and thus productivity. Evaluation of the performance was in first instance done via external visual appearance followed by cross-sectioning for promising parameter sets. The main evaluation criterion was smoothness of the treated weld toe with a secondary criterion being minimization of the amount of molten material and heat input, and maximization of the travel speed. In addition, hardness testing, residual stress measurements and 3D surface measurement before and after fatigue testing were periodically performed.

The developed procedures were then tested for their suitability for fatigue improvement on a fillet weld. Initially, two treatment conditions per steel grade were fatigue tested using constant amplitude loading. The best performing parameter set was then repeated and tested using variable amplitude loading.

2.4. Fatigue testing

2.4.1. Constant amplitude loading

For the constant amplitude loading (CAL), sixty specimens comprising the two high strength material grades (S690QL and S960QL) and five treatment conditions denoted C1 to C5 were fatigue tested in air under ambient conditions at a stress ratio, R, of 0.1. Tests were conducted in load control using both servo-hydraulic and resonant fatigue testing machines at frequencies in the range of 3.5 to 80 Hz.

2.4.2. Variable amplitude loading

To establish the fatigue performance of treated specimens under variable amplitude loading (VAL), a series of ten specimens each were tested from the two grades. All specimens were in the C2 treatment condition which had performed well in the CAL experiments. The stress-time history for the loading spectrum employed comprised 200,000 turning points at fully reversed (R = -1) stress ranges, as shown in Fig. 3.

In order to compare fatigue test results obtained under both CAL and VAL, it is useful to define the constant amplitude stress that is equivalent in terms of fatigue damage to the applied variable amplitude stress spectrum. For an applied stress spectrum consisting of n, cycles at stress range $s_i$, and assuming that Miner’s rule [7] is correct, this is given by:

$$ S_{eq} = \left[ \frac{\sum_{i=1}^{n} (s_i^m n_i)}{\sum n_i} \right]^{1/m} $$

(1)

where $m$ is the slope of the constant amplitude S-N curve for the detail concerned, expressed in the form:

$$ S^m_{max} = A $$

(2)
where $S$ is the constant amplitude stress range and $A$ is a constant.

It should be noted that the above definition of the equivalent stress is based on the assumption that the constant amplitude $S$-N curve with a slope of three extends to the lowest stress ranges in the spectrum. Good agreement between constant and variable amplitude test results with the latter expressed in terms of the equivalent stress range would indicate that Miner’s rule was correct for the weld details and stress spectrum considered, whereas disagreement would indicate that Miner’s rule was not accurate.

3. Results

3.1. Laser diode re-melting

3.1.1. Introductory diode laser re-melting experiments on flat plate and bead-on-plate welds

The main parameters varied for the initial trials on flat plate and bead-on-plate melt runs performed at Laserline were the laser power, travel speed and focused spot shape and dimensions. The ranges investigated were 2 to 6.5 kW of laser power (measured at the laser source) and 0.25 to 1.5 m/min travel speed. The focused spot shapes and dimensions were as listed above (cf. section 2.2). In addition, some trials were performed whereby first a low power pass was used to pre-heat the treatment area, followed by the actual re-melting pass. This was done since it was found that a certain amount of heat is required to have the molten metal flow and wet properly, creating the desired smooth surface. When the heat input is insufficient, for example resulting from a high travel speed, the molten metal can ball up, rather than spread and wet (Fig. 4). Obviously, this would not be optimal for the fatigue performance.

However, with proper parameters, weld toe smoothing could be achieved consistently, an example of which can be seen in the cross-section in Fig. 5. This weld was treated using a 5x6 rectangular spot with a laser power of 2 kW but a travel speed of only 0.25 m/min.

3.1.2. Laser diode re-melting for weld toe and root finish

Fig. 3. Variable amplitude loading spectrum used in this project

Fig. 4. Top view of two bead on plate laser dressing passes (left and right in the photograph) where insufficient heat caused poor wetting leading to an irregular surface.

Fig. 5. Example of a cross section of a bead on plate MAG weld of which the weld toe on the left has been re-melted using a diode laser.
3.1.2. Procedure development on fatigue samples

During the trials at OCAS, it quickly became apparent that parameter settings developed on bead-on-plate welds on flat plate were not directly transferable to the fillet welds on the fatigue samples, most likely due to the more inclined weld top bead surfaces. The actual procedure development was therefore performed on welded samples that had been rejected for fatigue testing because of weld irregularities and/or imperfections. Five re-melting parameter sets were developed, which can be found in Table 1. As can be seen in the table, in most cases different travel speeds were specified for the straight parts of the trajectory and the movement around the corners. This was in response to the finding that – even though one travel speed was programmed – the robot did not manage to keep the speed around the corners. It was then attempted via setting of different speeds for the straight parts and corners, and timing of the robot to get an even speed and movement all along the weld.

Table 1. Re-melting parameters used for constant amplitude fatigue testing samples in S690QL & S960QL.

<table>
<thead>
<tr>
<th>Trial ID</th>
<th>Focal length [mm]</th>
<th>Focused spot shape, size [mm]</th>
<th>Laser power [kW]</th>
<th>Travel speed [m/min]*</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>300</td>
<td>Rectangular, 13x10</td>
<td>3</td>
<td>0.75</td>
</tr>
<tr>
<td>C2</td>
<td>300</td>
<td>Circular, 3</td>
<td>2</td>
<td>0.75</td>
</tr>
<tr>
<td>C3</td>
<td>250</td>
<td>Circular, 5</td>
<td>2</td>
<td>0.50</td>
</tr>
<tr>
<td>C4</td>
<td>150</td>
<td>Rectangular, 5x6</td>
<td>2</td>
<td>1.50</td>
</tr>
<tr>
<td>C5</td>
<td>250</td>
<td>Circular, 5</td>
<td>2</td>
<td>1.50</td>
</tr>
</tbody>
</table>

* Travel speed was set so as to maintain near constant speed all around the weld

3.2. Characterisation of treated welds

Treated weld cross-sections for some of the different spot sizes can be seen in Fig. 6. The cross-sections were taken in the plane through the middle of the welded attachments which in the pictures b) to d) can be seen on the left, above and below the central plate. It can be seen from the photographs that, for the parameters used, the largest spot size (13x10 mm rectangular) gave a very fine layer of melting, resulting in the tendency to ball up and thereby not giving the smoothest weld profile. Better results were achieved with the smaller circular spot sizes.

![Macro-section location](image1)
![S960QL-C1: 13x10 mm](image2)
![S960QL-C2: 3 mm Ø](image3)
![S960QL-C3: 5 mm Ø](image4)

Fig. 6. Macro-sections of laser re-melted welded fatigue samples using different spot sizes (re-molten zones are indicated by the arrows on the cross-sections).

Hardness testing (HV0.2) was performed on the macro-sections shown in Fig. 6, with traverses taken just below the surface (at approx. 0.1 and 0.3 mm from the surface; direction of traverse illustrated in Fig. 7). The results can be seen in Fig. 7b) to d) and show hardening in the re-solidified part of the laser dressed area. The hardness varies for the different conditions, but is lowest for the 10x13 mm spot size (with the maximum ~475 HV0.2) and higher for the smaller spot sizes (3 mm and 5 mm diameter circular) where the hardness reaches ~500 HV0.2.
Fig. 7. Hardness measurements just below, but following, the surface - see a) - for welds seen in Fig. 6.

Fig. 8. Stress measurement direction (a) and results (b) on as welded and laser re-melted specimens.

3.3. Fatigue testing

3.3.1. Constant amplitude loading test results

The results for the CAL fatigue tests are presented in the form of an S-N diagram with double logarithmic axis in Fig. 9. The I1W design curve FAT63 [8] and the Class F2 mean and mean -2sd (design) curves from BS 7608 [9] are also given. Also presented in Fig.9 is the as-welded mean curve for the S690QL and S960QL material which was also derived in the FatweldHSS collaborative project.
The fatigue failure mode for the tests performed was as expected, consisting of fatigue crack growth through the plate thickness from one or more of the weld toes. Least squares linear regression was used to fit the mean S-N curve for the data set with only specimens failing at the welded joint being included in the analysis. Specimens exceeding \(10^7\) cycles were excluded from the analysis and termed a ‘run out’.

The fatigue performance of the laser re-melted joints represented by their mean S-N curve in Fig. 9 was significantly greater than that of the as-welded mean S-N curve. The life increase factor (LIF), defined as the ratio of the fatigue endurance of laser re-melted joints to that of the as-welded joints, was 2.75.

Each data set and condition was also analysed by linear regression so that the fatigue strength at \(2 \times 10^6\) cycles could be established, the results of which are given in Table 2.

<table>
<thead>
<tr>
<th>Material grade and condition</th>
<th>Free slope</th>
<th>Fatigue strength @ (2 \times 10^6) cycles for free slope [MPa]</th>
<th>Fatigue strength @ (2 \times 10^6) cycles for slope of 3 [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S690QL C1</td>
<td>2.77</td>
<td>87</td>
<td>85</td>
</tr>
<tr>
<td>S690QL C2</td>
<td>2.99</td>
<td>146</td>
<td>146</td>
</tr>
<tr>
<td>S690QL C3</td>
<td>3.60</td>
<td>126</td>
<td>115</td>
</tr>
<tr>
<td>S690QL C4</td>
<td>3.68</td>
<td>137</td>
<td>123</td>
</tr>
<tr>
<td>S690QL C5</td>
<td>3.63</td>
<td>142</td>
<td>120</td>
</tr>
<tr>
<td>S960QL C1</td>
<td>2.59</td>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>S960QL C2</td>
<td>3.43</td>
<td>134</td>
<td>124</td>
</tr>
<tr>
<td>S960QL C3</td>
<td>3.43</td>
<td>122</td>
<td>113</td>
</tr>
<tr>
<td>S960QL C4</td>
<td>4.30</td>
<td>131</td>
<td>105</td>
</tr>
<tr>
<td>S960QL C5</td>
<td>2.72</td>
<td>96</td>
<td>106</td>
</tr>
<tr>
<td>All</td>
<td>2.85</td>
<td>106</td>
<td>109</td>
</tr>
</tbody>
</table>

It can be seen from Table 2 that for both material grades, condition C2 gave the greatest fatigue strength, whilst C1 gave the lowest. The conditions identified represent a significant difference in terms of spot shape and size, cf. Table 1.

Whilst the mean of the data set suggests a 40% increase in fatigue strength at \(2 \times 10^6\) cycles, under condition C2 the increase in strength is around 87% for S690QL and 59% for S960QL. This is based on a fatigue strength of 78MPa for the as-welded data set at \(2 \times 10^6\) cycles. For condition C1, although this condition has shown the lowest fatigue strength, some measurable benefit is also gained with a \(\sim9\)% increase over that of the as-welded condition.
3.3.2. Variable amplitude loading test results

The results of the VAL fatigue tests are presented in Table 3. As noted in Section 2.4, a convenient way to consider variable amplitude fatigue test results is in terms of the equivalent constant amplitude stress range, $S_{eq}$. This value is included in Table 3 and used to plot the test results in Fig. 10. Also shown are the constant amplitude test results (excluding run outs) used to define the S-N curve and the Class F2 mean curve. The corresponding value(s) of the Miner’s rule summation ($\sum n/N$) at failure, calculated using N values from the mean constant amplitude S-N curve are also included. The class F2 mean curve was selected as an appropriate choice on the basis that it represents the same weld detail and is in good agreement with the mean constant amplitude data presented in Fig. 9.

Table 3. Results of laser re-melted fatigue tests performed under variable amplitude loading.

<table>
<thead>
<tr>
<th>Material grade and condition</th>
<th>Maximum stress range in spectrum [MPa]</th>
<th>Percentage of yield stress in tension</th>
<th>Equivalent stress range, $S_{eq}$[MPa]</th>
<th>Endurance (cycles) at failure</th>
<th>$\sum n/N$ at failure based on the mean constant amplitude S-N curve</th>
<th>$\sum n/N$ at failure based on the Class F2 mean S-N curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>S690QL C2</td>
<td>759</td>
<td>55</td>
<td>183</td>
<td>845,532</td>
<td>1.98</td>
<td>4.21</td>
</tr>
<tr>
<td></td>
<td>828</td>
<td>60</td>
<td>200</td>
<td>492,120</td>
<td>1.50</td>
<td>3.20</td>
</tr>
<tr>
<td></td>
<td>897</td>
<td>65</td>
<td>216</td>
<td>1,548,720</td>
<td>5.96</td>
<td>12.68</td>
</tr>
<tr>
<td>S960QL C2</td>
<td>1152</td>
<td>60</td>
<td>278</td>
<td>332,863</td>
<td>4.29</td>
<td>9.13</td>
</tr>
<tr>
<td></td>
<td>1056</td>
<td>55</td>
<td>254</td>
<td>264,845</td>
<td>1.66</td>
<td>3.53</td>
</tr>
<tr>
<td></td>
<td>960</td>
<td>50</td>
<td>231</td>
<td>506,100</td>
<td>2.38</td>
<td>5.07</td>
</tr>
<tr>
<td></td>
<td>768</td>
<td>40</td>
<td>185</td>
<td>1,810,777</td>
<td>4.38</td>
<td>9.31</td>
</tr>
<tr>
<td></td>
<td>672</td>
<td>35</td>
<td>162</td>
<td>5,176,949</td>
<td>8.40</td>
<td>17.88</td>
</tr>
</tbody>
</table>

All specimens exhibited identical modes of failure to those previously observed under constant amplitude loading. The summation at failure given in Table 3 was found to be well above unity with an average value of ~7.4 (based on the Class F2 mean curve).

It can be seen in Fig. 10 that the results for the variable amplitude tests performed are subject to some degree of scatter. This is typically a factor of 2 on life for identical tests performed. However, the degree of scatter is lower than that for a similar stress range under constant amplitude loading (~4 on life). It should also be borne in mind that the results formed are from a statistically small data set.

Fig. 10: Fatigue endurance data for laser re-melted specimens tested under variable amplitude loading at $R=-1$.

Under the FatweldHSS collaborative project, a small number of as-welded tests were also performed using the variable amplitude spectrum (included in Fig. 10). Again considering the Class F2 mean curve, the average damage summation for the tests performed was ~3.7, therefore suggesting a LIF for the laser re-melted specimens under variable amplitude loading of ~2.
4. Discussion

4.1. Diode laser re-melting

In the experiments described here, smooth dressed weld toes could be achieved with very little heat input and at appreciable travel speeds using a diode laser. However, the trials also showed some caveats with regard to the employment of diode laser re-melting in practice.

Firstly, there is the issue of sample temperature. It was found in the experiments that the sample needs to be sufficiently hot to allow the shallow molten zone around the weld pool to wet the base material properly, thereby creating the desired smooth transition from base to weld metal (avoiding stress concentrations). This heat can either be introduced via the chosen diode laser re-melting parameters, but this tends to also reduce the travel speed. If re-melting is performed on a hot sample – as would be the case with the diode laser head travelling directly after a welding torch – diode laser re-melting tends to give good results even at lower heat inputs and/or higher travel speeds. The sample could also be made hot by having a low heat input diode laser pass prior to the actual re-melting pass, but this will impact severely on the productivity and was therefore not further investigated. Although in a sense it is good that laser re-melting performs well when performed on a hot sample, because this means an inherent suitability for welding and dressing in a single pass, it also means that if for whatever reason re-melting would have to take place after the sample has (fully) cooled, different parameters would have to be used. This means parameters depend on the sample temperature.

Secondly, because of the required heat input, it was found that even with the diode laser, re-melting was most comfortably performed at travel speeds that are not that far above those often used for TIG or plasma dressing (in the range of a few tenths of metres per minute) when used on a weld at room temperature. In spite of this fact, some re-melting parameters were also found that used higher travel speeds (in this project up to 1.5 m/min), but this also requires higher laser power levels, with an associated higher cost. In terms of the optics to choose, particularly when aiming for higher travel speeds, best results were found when using a small, circular spot, indicating that it is not the size of the treated zone that is important, but mostly the sheer fact that the angle and radius are increased at the weld toe.

The type of weld treated also had a significant influence which was noticed when trying parameter settings that worked well on bead-on-plate welds in the PA position on fillet welds in PB to PC position. The parameters proved not directly transferable, possibly indicating the influence of weld surface orientation or heat sink.

Lastly, although not a technical issue, there is the health and safety aspect of laser radiation. Particularly at the multiple kilowatt power level, a laser beam is hazardous. Direct exposure to the beam can result in severe burns and blindness, but even stray or reflected radiation can be of sufficient intensity to cause blindness and/or burns. In this project, this issue was overcome by using the laser in an enclosed cell in which the sample was furthermore placed inside a sheet steel enclosure to contain the reflected radiation. In industry, unless the components to be treated are amenable to such containment, the laser re-melting option will not be practicable.

4.2. Fatigue performance of laser diode dressed welds

In both the current British Standards and recommendations given by the IIW, weld toe grinding is assumed to improve the fatigue strength by a factor of 1.3, which is equivalent to a factor of 2.2 on life [9,10]. Based on the mean of the current results for laser re-melted specimens, the fatigue strength under constant amplitude loading increased by around 1.4 resulting in a LIF of 2.75, significantly above that assumed in the current guidance. It should be noted, however, that the current guidance referred, is based on conventional weld toe improvement techniques such as burr grinding, peening and TIG dressing.

Improvement techniques have been widely studied in the context of welded steel joints but less so in aluminium alloys, although the general principles should be applicable to both. In a review by Hobbacher [11] on the benefit of improvement techniques on welded aluminium joints this was confirmed, and a conclusion made that a strength improvement factor of 1.4 was applicable to all techniques including that of laser re-melting. This indicates that the general level of improvement between melting techniques (TIG and laser dressing) is therefore the same regardless of whether the material is aluminium alloy or steel. The LIF determined in the current programme is therefore in good agreement with the findings by Hobbacher.

A number of re-melting parameters have been developed for optimising the re-melting conditions. It has been shown that condition C2 offers the greatest benefit in weld toe improvement for the materials considered, and condition C1 offering the least amount of benefit. Whilst the mean of the data suggests a 40% increase in fatigue strength, it is interesting to note that the increase in yield strength does not result in an increase in benefit.
Spectrum loading has resulted in high summation values for the tests performed. This may on one hand suggest that Miner’s rule was not accurate, but also that the spectrum employed contained favourable load sequence effects resulting in the retardation of fatigue cracking, thus generating longer lives. By comparing the laser re-melted data with those corresponding to the as-welded condition, under variable amplitude loading, it is apparent that the beneficial effect generated by the improvement technique, whilst slightly lower than under constant amplitude loading, are still offering a significant level of benefit for the spectrum considered.

5. Conclusions

The work performed has allowed the following conclusions to be drawn:

- Diode laser re-melting of weld toes can be performed successfully, using different focused spot shapes and dimensions and parameter sets. However, it became apparent that in order to create a smooth profile, a certain heat input/heat concentration is required, favouring smaller spot sizes.
- Weld toes treated with suitable parameters in macro-section showed a smooth profile and hardness testing showed hardening in the re-melted zone to values of 450-500 HV0.2.
- Residual stress measurements on a sample treated with the best performing procedure showed decreased tensile stresses up to 10 mm near the weld toe, and comparable stress levels further away from the weld toe.
- Fatigue tests of treated samples performed under constant amplitude loading have demonstrated a life increase factor (LIF) of 2.75 over that of the as-welded condition, resulting in a 40% increase in fatigue strength at $2 \times 10^6$ cycles. This indicates a significant benefit for welded joints treated by the laser re-melting process.
- The greatest fatigue benefit was found for condition C2 using a small, circular spot and the lowest benefit for condition C1, using a large, rectangular spot.
- For the materials considered, the increase in benefit found does not relate to an increase in yield strength.
- Under variable amplitude loading, the degree of scatter in results was within that found under constant amplitude loading.
- A LIF of 2 was determined under variable amplitude loading for laser re-melted tests compared with the as-welded condition, indicating that under the applied spectrum, a significant benefit in life was achieved.

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References