Characterising the surface, hardness and residual stress effects from high-rate machining and fatigue strength improvement of circumferential welds in wind turbine support structures

Technical Report

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Supported by:

The project was supported by the EU and the Danish Board of Business Development through a Manufacturing Academy of Denmark (MADE) demonstration project (Materials)

Projektet er medfinansieret af EU og Danmarks Erhvervsfremmebestyrelse.

Medfinansieret af Den Europæiske Union

Danmarks Erhvervsfremmebestyrelse

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1. Preamble

Grant: The project was supported by the EU and the Danish Board of Business Development through a Manufacturing Academy of Denmark (MADE) demonstration project (Materials).

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Timeframe

Start: 1. November 2023

End: 30. June 2024

2. Purpose

The purpose of this document is to collect, interpret and discuss the results obtained in the collaborative MADE project with DTI, Force Technology and MAXARS. Results from the microscopic, macroscopic, hardness and residual stress analyses are considered. This document will serve as the technical output on which further dissemination can be based on.

3. Introduction

This project was supported by the EU and the Danish Board of Business Development through a Manufacturing Academy of Denmark (MADE) demonstration project (Materials).

by Manufacturing Academy of Denmark (MADE) and consisted of Danish government-approved Research and Technology Organisations (RTO) Force Technology, Danish Technological institute and automation machinery developer Maxars A/S. The purpose of the project was to apply previously unexplored analysis methods to the Maxars concept of automatic weld toe milling in offshore wind turbine support structures. This concept consists of a robot that has been developed to automatically follow a weld line and remove the weld toe via a milling process. The technology includes an integrated system for collecting chips and dust from the milling.

Geometric improvement of welds by way of removing the weld cap and weld toe is integral to improving the fatigue limit of steel structures and this is considered in the most applied standards for offshore steel structures: DNV-RP-C203 and Eurocode 3. They specify a factor 3-5 longer fatigue life by removal of the weld toe. This removal process is conventionally performed manually via a grinding process. By applying the automatic weld toe removal, efficiency can be increased 20-25 times and require little manual interference. Automation will also provide a similar result every time as a robotic solution is not prone to human error.

The work in this project consisted of a comparative study of the properties of welds in carbon steel with different post-weld treatments. The analyses were comprised of visual inspection, residual stress analysis, hardness testing, surface roughness measurements and metallographic analysis. A comparison of welds treated with conventional manual grinding and with the Maxars automatic weld toe milling, as well as the standard post-weld treatment sandblasting has been performed.

4. Samples

A list of 'dog bone' samples included in the project is given in Table 1. The included dimensions are the surface after treatment relative to the original surface. Selected images of samples are included in Figure 1.

Table 1: List of samples and applied processes.

Sample #	**Treatment**
2	None. Baseline specimen.

3	Manual grind to 0 mm via 60-80-100
4	Milling to 0 mm. coarse.
5	Milling to 0 mm. fine.
6	Milling to -0.5 mm. coarse.
7	Milling to -0.5 mm. fine
8	Manual grind to 0 mm + sandblasting.
10	Milling to 0 mm coarse + sandblasting.

Sample 3 – manual grind

Sample 4 – milling, coarse

Sample 7 – milling -0.5mm fine

Sample 10 – milling + sandblast

Figure 1: Images of selected samples included in the study.

5. Results & Discussion

5.1. Macroscopic

Macroscopic images of cross-sections from all samples are given in Figure 2. Sample 2, the baseline specimen is distinct from the other specimens as there has been no weld toe removal performed. A difference is seen compared to sample 3-5, where grinding or milling has been done to achieve a surface in the same height as the original surface. In the macroscopic analysis, no significant differences are observed between the fine and coarse milling or the ground specimen.

Sample 6 and 7 were milled to a nominal -0.5 mm below the original surface. Again, no macroscopic difference between the coarse and fine milling is observed. The nominal depth of the milling was achieved and a smooth transition from the original surface can be observed.

This is beneficial regarding fatigue life of any treated components, as sharp edges/transitions can act as locations of stress concentration and thereby crack initiation sites. It should be noted that all geometric features from the milling are similar, indicating a stable automated process.

Samples 8 and 10 are sandblasted after weld toe removal. This is done for comparison as it is a standard process required in the wind energy industry, as it both introduces compressive residual stresses and increases the surface roughness to allow for coating. Upon close inspection of the treated surface, it is clear that the surface quality is worsened after sandblasting, which may be problematic for certain applications.

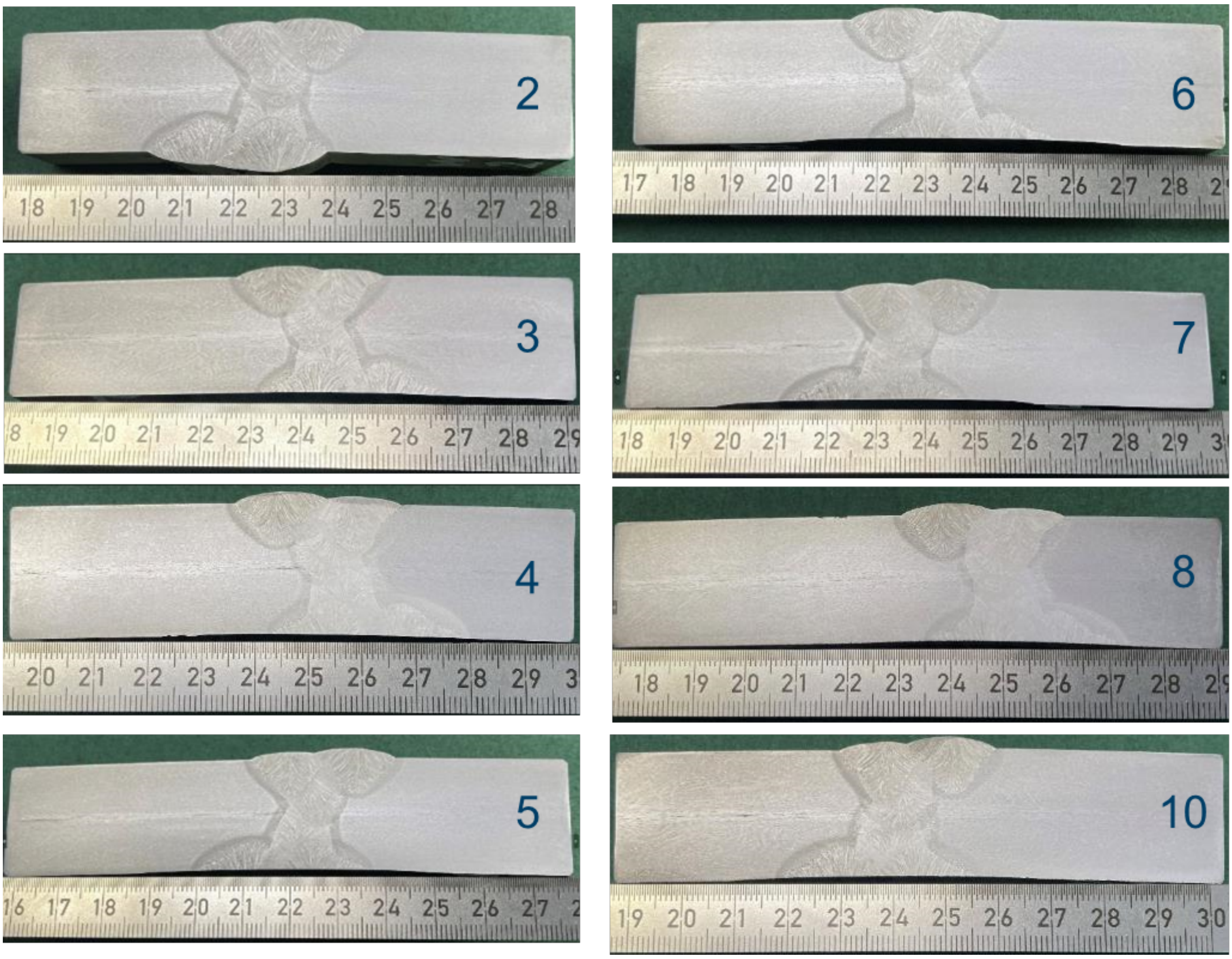


Figure 2: Macroscopic images of the weld cross-section for all included samples.

5.2. Roughness

Roughness measurements may highlight differences in quality between post-weld treatments. Several factors impact the fatigue life of a steel structure, and critical surface factors includes residual stress and surface roughness. All roughness values are presented in Table 2.

Table 2: Measured Ra roughness values for all samples.

Sample #	**Roughness Ra [µm]**	
	x	**y**

2	4.326	1,787
3	0,613	0,138
4	1,248	0,154
5	1,471	0,262
6	1,439	0,111
7	0,846	0,287
8	11,79	9,779
10	11,94	14,15

Considering sample 3-5 relative to sample 2, there is a significant decrease in surface roughness. However, the roughness measurement method is not suited to measure the macroscopic peaks and valleys that are found in the weld toe, so the reduction is higher than what is indicated from the measurements. There is no notable difference between the fine and coarse milling process in either direction. The grinding process achieves a finer surface in both directions than the milling, most significantly in the X-direction. The difference is about 0.5 µm. This indicates that if the manual grinding process is performed correctly, the finer abrasive will result in a slightly finer surface. In the Y-direction, the roughness is very low for both processes and the difference can be argued to be negligible. Similar results are achieved when milling below the original surface, but as observed for sample 7, the fine milling can in this case achieve a surface roughness similar to that of grinding.

As is standard in the wind industry, most large steel structures are coated and this requires a certain surface roughness for sufficient adhesion. Therefore, samples 8 and 10 have been sandblasted. The surface roughness after sandblasting is significantly higher (≈11 µm), so the process had the desired effect on both specimens.

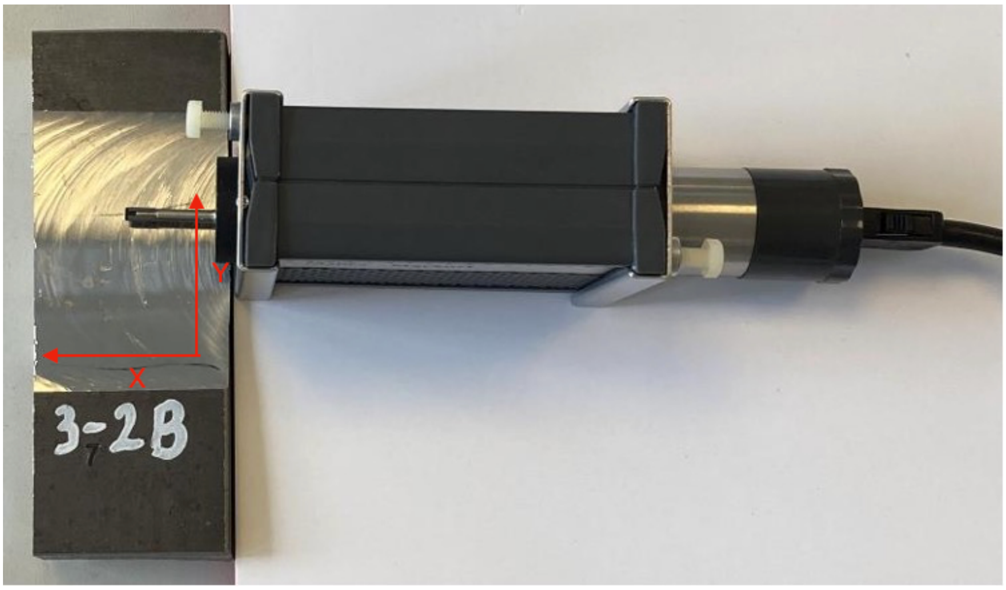
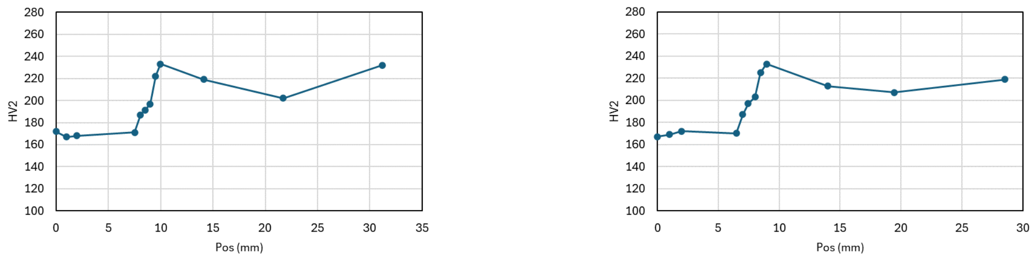


Figure 3: An image of the roughness measurement setup with indications of the directions where roughness has been measured.

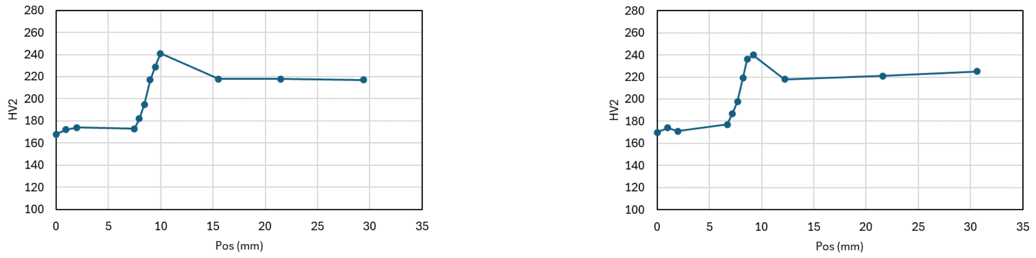
5.3. Hardness

The hardness profiles of all samples are shown in Figure 4. The profiles were measured on the cross-section of the welds and include both the base material, the heat affected zone (HAZ) and the weld material. By observing the hardness values and the shape of the profiles, it is clear that similar hardness is obtained in all specimens, indicating a similar heating during welding. It is also an indication that neither grinding, milling or sandblasting will affect the hardness values in the bulk of the weld.

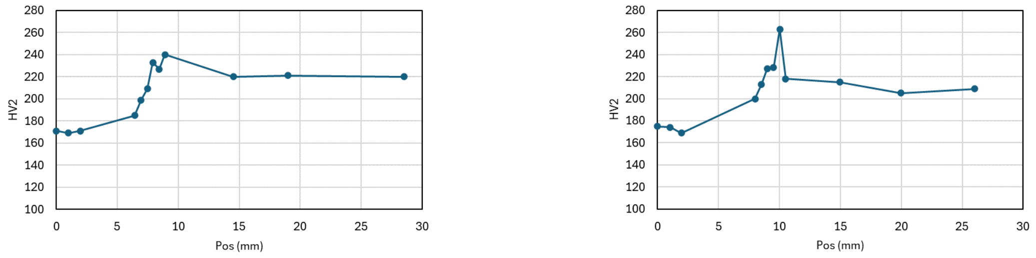
The profiles are measured from the base material into the weld and distinct zones can be seen, likely a result of the thermal history from the welding process. An increase in hardness of about 50 HV is observed in what is likely the transition to the recrystallized zone, that is where the temperature was sufficient for the BCC→FCC phase-transition and recrystallization upon cooling. The hardness values inside the weld (at pos > 9 mm) have similar hardness to the HAZ. Comparing this to the macroscopic and microscopic analyses, the hardness profiles fit nicely to an expected hardness increase at what is visibly the HAZ/weld material.



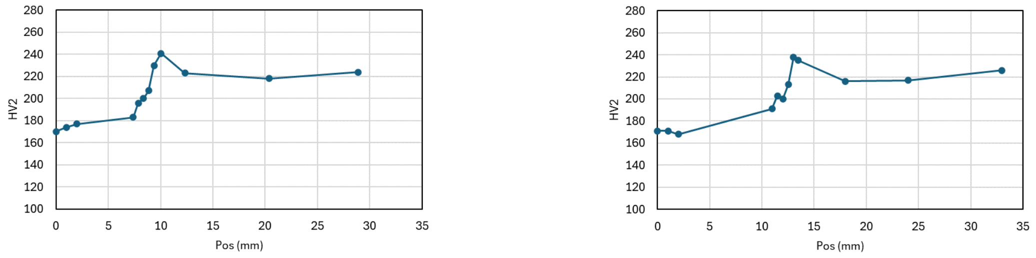
Sample 2 Sample 3



Sample 4 Sample 5



Sample 6 Sample 7

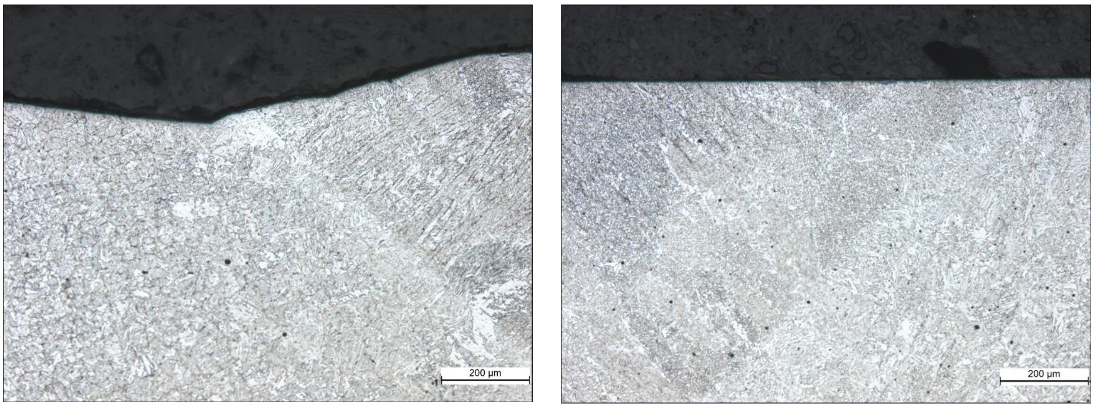


Sample 8 Sample 10

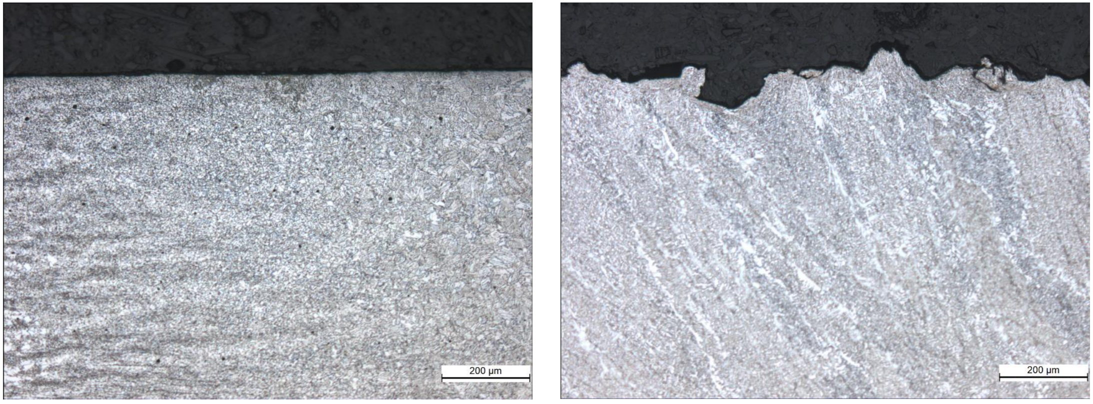
Figure 4: The measured hardness profiles of all included samples.

5.4. Microscopy

Selected representative micrographs captured via light optical microscopy are given in Figure 5, all taken in the interface between the weld and the plate.



Sample 2 – As welded   Sample 3 – Manual grinding



Sample 5 – fine milling   Sample 8 – Manual grinding + sandblast

Figure 5: selected micrographs of etched samples, revealing the surface- and microstructure.

Sample 2 has a clear transition from the base material to the weld, with a gradient in microstructure from the thermal history. This is also seen on the surface height difference. The weld itself exhibits a solidification structure, while the material close to the weld has undergone the BCC→FCC.

Sample 3 and 5, where the weld toe has been removed, shows a generally homogenous microstructure, with the surface-near region being largely similar to the bulk material. Some signs of deformation/heating is evident from the grinding process. From this analysis, it is clear that neither the grinding nor the milling affects the microstructure significantly. Sample 8 exhibits a very rough surface with high rate of deformation from the sandblasting.

5.5. Residual Stress

As the other critical factor for the fatigue life of welded steel structures is residual stresses in the surface, the residual stress state from the different processes has been compared. In Figure 6, the surface residual stresses in the base material and in the area where the weld toe was previously, is compared between all the processed specimens. The residual stresses are evaluated via X-ray diffraction using the BCC 211 peak and a Cr-anode. This results in contributions from the first 2-5 µm of the surface.

As seen on Figure 6, both the milling and the grinding resulted in tensile residual stresses, likely due to local heating of the processed surface and subsequent cooling on a cold substrate. The residual stress from the milling process approaches the yield strength, while the residual stress from the grinding process is also tensile, but only as high as 200 MPa. A slight trend in difference between the coarse and the fine milling can be observed, as it appears that the coarse milling may result in slightly higher tensile stresses.

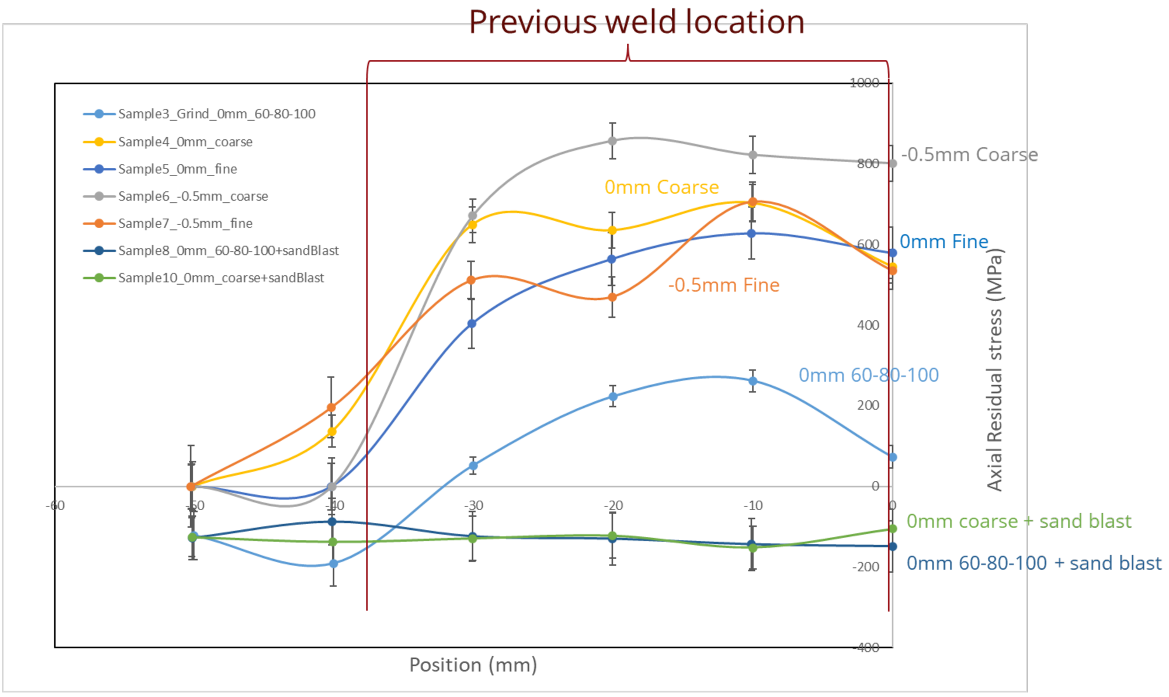


Figure 6: Residual stress along the surface for the different post weld treatments.

Sandblasting the specimens results in the residual stress state being shifted to a compressive state, as is generally the case with this surface treatment. No difference between the milled and ground sample can be observed after sandblasting.

6. Conclusion

The microstructural analysis part of the project revealed no differences in material properties between weld specimens having been geometrically improved using a milling process and those having been improved using a belt grinding process.

Results from the hardness analysis part showed similar hardness profiles for all specimens, indicating that neither the milling process nor the belt grinding processes affects the hardness of the weld.

Both the milling process and the grinding process achieved roughness average (Ra) results below that of 3.2 μm recommended by DNV-RP-C203 fatigue design standard for offshore steel structures.

The grinding process achieved lower Ra values compared to the milling process and in cases where a sub-micron surface finish (<1 μm) would be required, only the grinding process could achieve this.

The residual stress analysis part revealed that milling will increase the residual stress state to a higher tensile level, while the grinding process results in a lower tensile stress state. As residual stress may be added to the real stress amplitude during cyclic loading, tensile stress values are generally considered negative, while compressive stress levels are considered beneficial.

The analysis also found that post-milling sandblasting of the welds results in the residual stress state being shifted to a compressive state, as is generally the case with this type of surface treatment. No difference in residual stress profile between the milled and grinded sample could be measured after sandblasting.

The overall conclusion of this analysis is that the machine milling process performs at a similar level to the conventional belt grinding process, except for som differences in residual stress and surface roughness prior to sandblasting.

7. Perspective

This technical report documents and concludes that machine milling may replace belt grinding as best available technique for improving weld geometry and the fatigue strength of welds in steel structures without adversely affecting the material properties of the weld.

From the point of view of the wind industry, and producers of wind turbine support structures in particular, and with a view to a laser-guided milling robot designed specifically for improving weld geometry and the fatigue strength of inside and outside circumferential welds in such structures, the report's findings supports multiple perspectives on the benefit and value of replacing belt grinding with machine milling:

Improving productivity manyfold

If the force pair between the milling tool and the steel material is stabilised and chatter and resonance vibrations are prevented, then a single-pass level of machining performance may be achieved. At that level of performance the entire weld cap and the weld toe is removed during a single pass of the milling tool and an entire circumferential weld seam may be geometrically improved in the time it takes to rotate the wind turbine support structure once on its supporting roller beds.

If roller beds are operated at a rotational speed of 1.2 metres/min. then a full rotation of a 10 metre diameter monopile section would take ((10 x 3.14)/1.2) = approx. 26 minutes.

In comparison, removal of the entire weld cap and weld to on the same length weld seam using manual belt grinding is known to take upwards of 12 hours.

Operator-independent and repeatable-quality fatigue strength improvement

According to The International Institute of Welding (IIW), weld geometry improvement methods have been widely investigated and have in most cases been found to give substantial increases in fatigue strength.[1]

The IIW points out, however, that there are large variations in the actual improvements achieved. According to the IIW, one explanation for this is "*the **lack of standardization of the optimum method of application**, but variations in the material, type of loading and type of test specimens may also have influenced the results. **The effectiveness of the treatment also depends heavily on the skill of the operator**.*"[2] [emphasises added]

A recent meta study of 445 small- and full-scale fatigue test results of various weld types and steel grades confirmed that weld profiling has a "*a large positive effect on the fatigue strength of*

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[1] P. J. Haagensen and S J. Maddox, *IIW Recommendations on Post Weld Improvement of Steel and Aluminium Structures*, Revised 16 February 2004 p. 1.

[2] Same as [1]

welded joints."[3] but also noted that "*[f]atigue strength can be reduced by introducing a deep artificial notch through grinding…*"[4]

Replacing manual weld grinding with automated machine milling can not only improve productivity manyfold but can also ensure that the quality of the fatigue strength improvement process result is repeatably higher - providing that the automated process may be controlled and precision milling ensured.

Automated machine milling producing consistent-quality weld fatigue strength improvement may also support work to evaluate current fatigue design standards based also on manual weld grinding being standard method.

Reducing cost of fatigue strength improvement

Assuming the following costs, performances and factors:

- Unit cost of manual weld grinding of EUR 14.00/meter weld
- Total hourly cost of automated weld profiling of EUR 170.00/productive machine hour
- Manual weld grinding output rate of 2.60 meters/hour
- Productivity improvement factor of 25 from replacing manual weld grinding with automated weld profiling

The reduction in unit cost from replacing manual weld grinding with automated machine milling may be estimated as:

New production cost/hour:	170 EUR
New number of units produced/hour	2.60 meters/hour x 25 = 65 meters/hour
New unit cost:	170 EUR / 65 meters = 2.61 EUR/meter
Reduction in unit cost:	14.00 - 2.61 = 11.39 EUR/meter
Percentage reduction:	11.39 / 14.00 x 100 = 81.35 %

Achieving a productivity improvement factor of 25 and an unit cost of EUR 2.61 will significantly reduce the time and cost of doing fatigue strength improvement in wind turbine support structures - and may support the decision to include more weld seams in the fatigue strength improvement plan for a particular support structure.

Better HSE

The process of grinding is associated with dust that may be difficult to contain and collect and therefore requires protective gear. Machine milling produces shavings that may be collected as scrap metal and for recycling purposes.

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[3] Braun, Moritz and Wang, Xiru A review of fatigue test data on weld toe grinding and weld profiling in *International Journal of Fatigue* 145 (2021)

[4] Same as [3]

Also, the machine milling process produces less noise than grinding and as such a decision to replace manual weld grinding with automated weld profiling can also benefit the health and safety environment.