In situ post-weld heat treatment on martensitic stainless steel turbine runners using a robotic induction heating process to control temperature distribution

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Abstract.

A new robotic heat treatment process is developed. Using this solution it is now possible to perform local heat treatment on large steel components. Crack, cavitation and erosion repairs on turbine blades and Pelton buckets are among the applications of this technique. The proof of concept is made on a 13Cr-4Ni stainless steel designated “CA6NM”. This alloy is widely used in the power industry for modern system components. Given the very tight temperature tolerance (600 to 630 °C) for post-weld heat treatment on this alloy, 13Cr-4Ni stainless steel is very well suited for demonstrating the possibilities of this process. To achieve heat treatment requirements, an induction heating system is mounted on a compact manipulator named “Scompi”. This robot moves a pancake coil in order to control the temperature distribution. A simulator using thermal finite element analysis is first used for path planning. A feedback loop adjusts parameters in function of environmental conditions.

1. Introduction

Runners have a great impact on overall turbine efficiency and service life. Hydraulic flow and centrifugal forces generate high structural stresses. To stay in step with market transactions for electricity output (typically in increments of 5, 15 and 60 minutes), turbines are stopped and started frequently, increasing fatigue stresses. Combined with aging, this new pattern of increased stress accelerates crack propagation and other damage.

Cracks, cavitation, erosion and other such damage to steel (Figure 1) are primarily repaired by welding. Welding generates high internal stresses and affects the microstructure of steels, including 13Cr-4Ni, a martensitic stainless steel (MSS) widely used to cast modern turbine runner blades [1]. Lacking a solution to perform in situ heat treatment (HT), quality repairs are impossible without dismantling the runner and shipping it to a suitable heat treatment facility. To restore microstructure and reduce internal stresses, post-weld heat treatment (PWHT) is needed. Without PWHT, power plant operators must patch damaged areas with austenitic filler. This significantly degrades mechanical properties and cavitation resistance, while introducing high tensile internal stresses.
A new robotic process is developed to perform local short-duration PWHT on site. The temperature distribution is controlled using thermal finite element (FE) analysis simulation, a compact robot and an induction heating system. This system makes it feasible to perform quality repairs in situ.

The Scompi robot [2], [3] used for PWHT is designed specifically for in situ welding, gouging, grinding, polishing and hammer peening in the confined space between turbine runner blades. The induction heating system is designed small enough to be mounted on the compact robot. The robot controls the temperature distribution by moving an induction pancake coil attached to its end effector along a cyclic path. A simulator using FE analysis computes the temperature distribution generated by the displacement of the induction heating system. A nonlinear optimization algorithm uses the FE simulator to compute the parameters of the best cyclic path to generate a uniform temperature distribution. Since the turbine runner cannot be inspected beforehand to know the area to be repaired, it is important that path planning can be performed on site. To achieve faster-than-real-time simulation, computational efficiency is enhanced through a GPGPU and multicore architecture. Temperature sensors and a feedback loop are used to compensate for changing environmental conditions. The temperature distribution is verified on a sample and a full-size Francis turbine runner blade. The effect of the PWHT on mechanical properties is tested on sample welds.

2. Welding repairs on MSS turbine runners

2.1. Applications

According to [4], welding is the only reliable process for repairing cavitation, erosion and cracks on runners. The Scompi technology presented in [2], [3] is developed to perform high-quality repairs on site. This portable robot was first developed to remedy on-site cavitation damage on hydraulic components. Hazel et al. present in [3] the robotic operations needed to repair cavitation on site. A crack is conventionally repaired by gouging, welding, grinding and polishing. Figure 2 illustrates those operations.

As discussed below in Section 2.2, heat treatment must be performed on MSS after welding. The heat treatment process presented in [5]–[7] and illustrated at Figure 2f is a new application for Scompi technology. It opens opportunities to perform local PWHT on site and hence increase the quality of repairs. Robotic heat treatment is a great asset in many situations to extend service life.

This technology can also be applied in large-scale steel component manufacturing. Defects are often found or arise once a large component is assembled and the entire assembly is heat treated. A widely used means to manoeuvre large, complex steel parts is to weld a shackle to the surface. Before delivering the part, the manufacturer must remove the shackle. This operation generates a large number of defects. Such defects can be minimized by heat treatment of critical zones after touch-up welding.
2.2. Mechanical properties of welded metal and the heat-affected zone
Chemical composition and microstructure have a tremendous effect on MSS runner lifetime. If homogeneous welds were made to repair a CA6NM blade without PWHT, loads generated from turbine operation would result in immediate failure. PWHT tempers martensite and forms reversed austenite. Microstructure modifications resulting from such heat treatment reduce hardness and strength but increase impact toughness and ductility [8]. MSS runner lifetime is also influenced by carbon content. Indeed, Sabourin et al. [9] observe that the higher the carbon content of the martensitic alloy, the lower the lifetime of a runner, though this effect is poorly understood.

Bilmes et al. [10] present the impact of different heat treatments on microstructure. The authors use a flux cored arc welding (FCAW) process with an E410NiMoT-2 welding wire. Charpy notch impact tests are performed before and after four different heat treatments. The resilience at room temperature obtained after welding is 30 J (18 J at -77 °C). This value is improved to 84 J (64 J at -77 °C) with double stage heat treatment. Zappa et al. [11], [12] and Bilmes et al. [13] present similar analyses for gas metal arc welding (GMAW).

Bilmes et al. [10], [13] clearly show that mechanical properties also depend on the runner base metal, filler metal and welding parameters.

2.3. Residual stresses
A turbine runner is a welded assembly of complex parts. Thermal cycles and mechanical operations resulting from the fabrication process and repairs generate high internal stresses, which can amplify crack propagation and lead to an unstable fracture. Stresses thus have a major impact on runner lifetime. The Paris equation (1), discussed in detailed in [14], is used to predict crack propagation.

\[
\frac{da}{dN} = C(\Delta K)^n, \quad \Delta K_{ih} < \Delta K < \Delta K_{IC}
\]  

(1)

where \(a\) is the crack length, \(N\) the number of cycles, \(C\) and \(n\) are material constants, and \(\Delta K\) is the range of the stress intensity factor. \(K\) is computed using eq. (2).

\[
K = \sigma Y \sqrt{a}
\]  

(2)
where \( \sigma \) is a uniform tensile stress perpendicular to the crack plane and \( Y \) is a dimensionless parameter that is a function of the geometry. \( \Delta K_{th} \) is a fatigue threshold needed for a crack to grow. Below \( \Delta K_{th} \), the crack length remains constant. \( \Delta K_{IC} \) is the limit of the stable fracture.

3. Local heat treatment system

A new robotic process developed to perform on-site local heat treatment was first presented in [5]. The process uses an induction heating pancake coil mounted on a compact manipulator. The Scompi robot moves the coil along a cyclic path over the area or the volume to heat (see Figure 8). Temperature measurement systems and a feedback loop are used to compensate for non-simulated conditions. The solution is illustrated in Figure 3, which shows Scompi heating a repaired crack on a Francis runner.

![Figure 3: Induction heating system mounted on a Francis runner](image)

4. Induction heating

Widely used in industry, induction heating is a safe, efficient and easy-to-control technology. Melting, heat treatment processes and metal forming are typical applications [15]. Systems built for such applications are generally large, permanent and dedicated to a specific operation. The electrical system is stationary and the part is moved through the inductor. The new robotic induction heating technology is different and of sufficiently compact design to be transported in order to treat turbine runners on site. The confined space between Francis runner blades is illustrated in Figure 3.

The high-frequency current passing through the coil generates eddy currents in the metal to a very shallow depth. The electrical resistance of the metal leads to Joule heating. Magnetic hysteresis losses are also generated in materials that have significant relative permeability. Figure 4 shows Scompi heating a curved metal plate.

To move the coil rapidly with a compact robot, a portable electronic device is developed. The power source, capacitor bank and pancake coil are linked in a parallel resonant circuit. In the low-current section, an RF cable connects the inverter system to the capacitor bank. In the high-current section, two flexible braided leads run from the capacitor bank to the pancake coil. The components are illustrated in Figure 3 and Figure 4.
5. Thermal finite element modelling

The geometry is meshed and locally refined for thermal finite element analysis using linear hexahedral and prismatic elements. The power flux is evenly distributed inside the elements under the coil. The power flux distribution (W/m²) is assumed constant, without significantly affecting the precision of calculations. A graphic representation is shown at Figure 6a. Details are presented in [5].

The thermal finite element formulation is adapted from Cook et al. [16]. To make the simulation faster, the formulation is linearized on one time step as follows:

\[
\frac{1}{\Delta t}[c(T_n) + \beta [k(T_n) + [H(T_n)]]_n]_n = \left( \frac{1}{\Delta t} [c(T_{n-1}) + (1 - \beta) [k(T_{n-1}) + [H(T_{n-1})]]_n]_n + (1 - \beta) [R_h(T_n) + \{R_h(T_n)\}]_n + \beta [R_h(T_{n-1})]_n + \{R_h(T_{n-1})\}_n \right)
\]

(3)

where \(\Delta t\) is the time step, \(n\) the time step number, \(\{T\}\) the temperature vector, \(\{R_h\}\) the heat input vector, \([H]\) the heat transfer vector, \([K]\) the conductivity matrix and \([C]\) the specific heat matrix. For stability, the \(\beta\) factor of the Newmark-Beta scheme is set to 0.5.

To perform such an optimization and achieve faster-than-real-time simulation, computational efficiency is enhanced through a GPGPU and multicore architecture. Real-time simulation is a great asset for path planning on site. The on-site simulation must be flexible in order to adjust heat treatment parameters to unexpected situations.

6. Path planning

To simplify coil path generation for complex shapes, a curvilinear coordinates system is attached to the FE mesh of the part. The parametric-curvilinear space is defined as a generalized coordinate function \(r(u,v,w)\) as given below:

\[
r(u,v,w) = [x(u,v,w) \quad y(u,v,w) \quad z(u,v,w)]
\]

(3)

where \(u\), \(v\) and \(w\) are the parametric dimensions and where \(x\), \(y\) and \(z\) are position coordinates in Cartesian space. The \(r(u,v,w)\) function is expressed as a third-order composite object defined by a set of control nodes, allowing curvature continuity in all directions. The details of the representation are given in [2]. The \(u\) and \(v\) parametric coordinates are tangent to the surface while the \(w\) coordinate is normal to it. The surface at \(w = 0\) corresponds to the top of the part to be treated. The coil orientation is maintained normal to the surface.

For further simplification, the coil path is defined by a set of parametric surface curves \(c(s)\) in the \(r(u,v,w)\) curvilinear coordinates as expressed by eq. (4).
where \( s \) is the arc length along the path. The cyclic coil path is composed of two surface curves, \( c_1 \) and \( c_2 \), connected by turnaround arcs at their extremities as shown in Figure 5. Distance \( w(s) \) between the coil and the surface is used to modulate the power distribution along the path.

\[
c(s) = [u(s), v(s), w(s)]
\]  \hspace{1cm} (4)

7. Computing average cyclic heat input

The pancake coil is moved along a cyclic path. The back-and-forth movement generates local temperature variations. To minimize temperature variations, the robot must travel along the path as fast as possible. The greater the lag between successive passes of the source over a specific coordinate, the greater the temperature variation. The simulator must estimate the effective temperature from those variations. Heat treatments are generally performed in furnaces where the temperature is stabilized and kept constant. The effective temperature is the constant temperature that produces the same effect on steel properties as the varying temperature inherent to robotic heat treatment.

As presented in [5], the solution developed consists in computing an average temperature. For a complete path, an average source power flux \( (W/m^2) \) is created from the real source power flux as shown in Figure 6a. The power flux distribution is proportional to the time the inductor spends over a coordinate. This effective heating source is illustrated in Figure 6b and computed with eq. (5). The first term is the flux that the source actually outputs. The second term expresses the fraction of the total time to travel the complete cyclic path during which the \((x, y, z)\) coordinate is actually heated.

\[
f_j(x, y, z) = \frac{Q}{A} \frac{I(x, y, z)}{t_{tot}}
\]  \hspace{1cm} (5)

where \( Q \) is the output power, \( A \) is the area under the pancake coil, \( t \) is the time the coordinate is being heated during one cycle and \( t_{tot} \) is the time needed to complete one cycle.
This way of computing heat input results in an average temperature distribution that is assumed to be the effective temperature. This solution reduces by some orders of magnitude the time needed to simulate and plan a heat treatment. One cycle can be computed in one simple step. Obtaining the real temperature distribution would require more than 100 steps for one cycle.

8. Nonlinear optimization of the heating source parameters

The system described in Section 3 is used to control the temperature distribution on a steel part. To achieve high-quality heat treatment, a uniform temperature distribution must be precisely maintained within a significant volume. The system presented here is developed specifically for local heat treatment, which requires generating a zone of uniform temperature on and around the area repaired (Figure 7a) and keeping the temperature as constant as possible for the duration of the treatment (Figure 7b).

The flat pancake coil must be an order of magnitude smaller than the smallest radius of curvature of the surface to treat. Coil size entails a tradeoff between flexibility and size of the heat-treated zone. A larger diameter results in a wider heat-treated zone but limits the complexity of the geometry that the system is able to heat.

Path planning is performed with an in-house simulator using thermal finite element analysis. A nonlinear optimization algorithm improves the parameters in four steps. Figure 8 presents the four optimization steps. First, path and power distribution parameters are estimated in order to achieve the best temperature distribution. Acquired experience on similar geometries is used to choose the best values. Second, the algorithm modifies the distance between the back and forth paths to improve the lateral temperature distribution and make the heat treatment wider and more uniform. Third, the algorithm modulates the power distribution in function of the longitudinal position to achieve a smoother longitudinal temperature distribution. Lastly, the algorithm fine-tunes parameters in order to keep the temperature within a specific range throughout the heat treatment. To better understand the
process, Figure 8 shows a simulation made to improve the temperature distribution in the steady state, i.e., over an infinite period of time.

![Figure 8: Simulator planning a heat treatment](image)

9. Experimental validation

9.1. Temperature distribution

The precision of the model was first validated on a simple plate [5]. Results showed a good match between the simulated temperature with the effective heat input and the average temperature measured by means of thermocouples, an infrared camera and a pyrometer.

9.2. Mechanical properties

The effect of this new heat treatment process is validated on the UNS S41500 stainless steel coupon shown in Figure 9. The chemical composition of UNS S41500 and CA6NM stainless steels are comparable. The plate is first treated to bring the microstructure to the level of the runner base metal. To simulate a real crack repair in the lab, a groove is machined in a 292 x 149 x 57 mm plate (Figure 2b). Four layers of weld metal are deposited by FCAW to fill the groove (Figure 2c). The top layer is machined flush to the plate surface (Figure 2d). Lastly, PWHT is performed using the robotic heat treatment process to restore the microstructure and reduce internal stresses (Figure 2f).

![Figure 9: UNS S41500 stainless steel coupon for robotic heat treatment](image)

One objective is to compare the microstructure after robotic heat treatment to that after conventional furnace heat treatment. To ascertain the mechanical properties reflecting microstructure, Charpy impact tests and Vickers hardness tests are run on the as-welded fusion zone after robotic HT and after furnace HT. Greatly improved properties are obtained when treating 13Cr-4Ni between 600 and 630 °C for one hour. The results are presented in Figure 10. The properties measured after such heat treatments are similar for both the robotic and furnace techniques. These results are also consistent with those of Bilmes et al. [10].
The second objective is to reduce internal stresses significantly. Internal stresses are measured with the contour method and depicted in Figure 11. For this specific application, robotic heat treatment reduced internal stresses by a factor of 3. This is consistent with results achieved by manufacturers through conventional heat treatment in a furnace. Sabourin et al. [9] report that, under optimal conditions, in-shop heat treatment performed by the manufacturer after runner assembly decreases internal stresses from 410 to 130 MPa. Yield strength of CA6NM is above 550 MPa. Details regarding validation are presented by Godin et al. [6].

10. Conclusion

A new, innovative robotic heat treatment process is proposed to perform short-duration local PWHT on large MSS parts such as turbine blades. The new process paves the way to many applications in the hydropower industry, where weld repairs must be performed but PWHT of the entire assembly is not an option. On-site cavitation and crack repairs on turbine runners could most certainly benefit from the new process, thereby avoiding the need to dismantle the unit for shipment to a HT facility.

Robotic PWHT is achieved with a compact induction heating system mounted on a portable manipulator named “Scompi”. Thermal finite element analysis is used to simulate the temperature distribution resulting from the displacement of the heating coil. Nonlinear optimization is used to make the temperature distribution as uniform as possible over a significant volume.

Tests are performed on UNS S41500 stainless steel samples to validate the effectiveness of robotic PWHT. Measurements are made on the as-welded fusion zone after robotic HT and conventional HT in a furnace. Impact energy and hardness results after robotic HT are comparable to those after conventional HT. Temperature can be controlled to stay within a narrow range (600 to 630 °C).
Although the new robotic HT process already shows promising results, ongoing R&D work is being carried out to broaden the range of applications. For example, electromagnetic FE simulations of the coil power distribution could improve temperature prediction accuracy on highly curved surfaces. Mechanical FE simulation could help optimize HT to minimize residual stresses.

11. Acknowledgments
The authors want to acknowledge especially the contribution of Jacques Lanteigne, who developed the thermal finite element formulation used in the simulator. He also helped the authors achieve a closer match between simulations and measurements. The authors also wish to thank Jean-Benoît Lévesque for performing stress measurements using the contour method on UNS S41500 stainless steel coupons.

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