LASER AND MICRO-PLASMA WELDING OF SINGLE CRYSTAL BLADES - ADVANTAGES OF TOTAL PROCESS CONTROL

C. Pilcher, J. Liburdi
Liburdi Engineering Limited
Hamilton, Ontario, Canada

C. Berger, M. Iovene
Textron Lycoming, Turbine Engine Division, Stratford, Connecticut, USA

ABSTRACT

The single crystal superalloys, used in the manufacture of advanced gas turbine blades, are known to suffer from poor weldability and have a tendency to form cracks during and after welding. These cracks are largely related to the amount of heat input and metallurgical reactions that occur in the Heat Affected Zone (HAZ) adjacent to the weld. Experience has shown that cracks can be avoided by minimizing the HAZ through the use of proper heat management or process control.

Automation systems can offer the level of process control necessary to significantly reduce weld cracking. The systems have proven to be more repeatable, reliable, and efficient, compared to conventional techniques or earlier attempts at automation. In order to succeed, welding automation requires a complete integration of the process, consisting of tooling, robotic accuracy, vision measurement system, filler material, and welding parameter control. With the proper process control technology, it is possible to weld the tips of single crystal blades with difficult to weld oxidation resistant alloys as well as repair conventional compressor, high pressure and low pressure turbine blades.

This paper describes the welding of LT101 single crystal gas producer (GP) blade tips with highly alloyed filler metals for greater oxidation resistance. Results are presented for blades welded using a Laser beam with powder feed and compared to those welded using Micro-Plasma with the same filler alloys in wire form. The experience emphasizes the need for proper selection and integration of the welding processes, and confirms the importance of total process control to achieve the desired results in difficult and unique welding applications.

INTRODUCTION

The single crystal materials used by designers to obtain the higher temperature creep strength present unique problems during their manufacture and subsequent repair. With the relatively high cost of these critical rotating components, a need has been created to develop cost effective manufacturing and repair processes able to weld and restore components without adversely affecting the mechanical strength of the parent alloy.

Typical blade weld repairs that are performed during the overhaul of engines include: a) the build-up of tips on High Pressure (HP) turbine blades worn by environmental attack and/or seal rub; b) the hardfacing of Z-notches or abutment faces of Low Pressure (LP) blades worn by fretting of contact surfaces; c) the build-up of compressor blade tips to re-establish radial clearances worn by seal rub, and d) in specialized cases, the build-up of leading and trailing edge surfaces of compressor airfoils eroded by small particles such as sand ingestion.

Welding is also used in the manufacturing of new blades. For example, the hardfacing on LP blades is generally applied by fusion welding and in some designs the tips on HP blades are welded with a more resistant material. Significant benefits in engine performance or Specific Fuel Consumption (SFC) can be realized if blade tips are manufactured with more oxidation and/or rub resistant materials that differ from, yet complement the base alloy.

Successful welding of these highly alloyed components is difficult due to the array of alloy additions, and requires considerable understanding of the metallurgy and the welding process to obtain the high quality deposits demanded by the aerospace specifications. Proper selection and control of key process parameters is essential to minimize heat input and metallurgical problems such as cracking within the Heat Affected Zone (HAZ), and excessive dilution or mixing zone in single crystal alloys. Furthermore, many of the metallurgical problems are dependent on the base metal and can occur regardless of the type of heat source used in the welding process such as laser or plasma (Liburdi, Lowden and Pilcher, 1989 [1]).

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TABLE 1 - NOMINAL CHEMICAL COMPOSITION OF THE SC102 SINGLE CRYSTAL ALLOY
USED FOR THE LT102 GP BLADE (WT. %)

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Co</th>
<th>Cr</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>W</th>
<th>Ta</th>
<th>Zr</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>bal</td>
<td>2.5</td>
<td>10.3</td>
<td>0.95</td>
<td>3.3</td>
<td>4.4</td>
<td>6.7</td>
<td>4.8</td>
<td>0.001</td>
<td>0.005</td>
<td>0.04</td>
<td>0.04</td>
<td>0.015</td>
<td>0.0012</td>
<td></td>
</tr>
</tbody>
</table>

In recent years, equipment manufacturers and the turbine industry have recognized the need for improved welding processes and have introduced varying degrees of equipment automation, as well as novel processes claiming to reduce heat input and produce better welds. Some of the notable events include: a) the introduction of “dabber” welding for seals, using Gas Tungsten Arc Welding (GTAW) (Cooper, US Patent 4,159,410, 1979); b) the development of automated GTA welding equipment for thin seals (Anderson, 1985); c) the introduction of powder fed Plasma Transfer Arc (PTA) weld overlays (Zuchowski and Culbertson, 1962); d) the development of powder fed Laser welding (La Rocca, 1987); e) the first application of an integrated GTA Welding and grinding cell for shrouded turbine blades (Malone, 1989); f) the use of a precision gantry robot and computer controlled plasma power source to weld turbine blades (Liburdi, 1989), and g) the integration of an in-situ vision measurement system for production welding of HP blade tips (Lowden, Pilcher, Liburdi, 1991).

These developments have demonstrated the potential improvements in productivity and quality offered by weld automation; however, as illustrated by the following examples, proper selection of the weld process and optimum control are required to obtain the best results.

Welding of LT101 Single Crystal G.P. Blades

Engine run experience has shown LT101 single crystal GP turbine blades made from SC102 alloy, whose composition is shown in Table 1, exhibit oxidation/corrosion during typical operation, resulting in increased clearances between the blade tips and the seals. Although these blades are aluminide coated as manufactured, once assembled in the rotor they are tip ground to dimensional requirement, thus removing the coating at the tips. The unprotected area on the tip then oxidizes from exposure to the hot combustor gases.

Consequently, a program was conducted to determine the feasibility of using fusion welding to apply a customized environmental blade tip for the single crystal (S.C) airfoils. Two welding processes; Laser Beam Welding (LBW) with powder feed and Micro-Plasma Arc Welding (MPAW) with wire feed were investigated as candidate approaches to restore eroded SC blade tips to their original dimensional requirements using the special alloys developed.

Fusion welding was chosen because of its superior bond strength and large build-up capabilities compared to alternative processing methods such as diffusion bonding and plasma spray. Also, both welding techniques are able to deliver low heat input to the single crystal (SC) base alloy, thus minimizing the metallurgical problems associated with cracks initiating in the Heat Affected Zone (HAZ), and the reduced strength of the dilution or mixing zone of the single crystal parent alloy.

Three oxidation resistant tip alloys were developed for the LT101 SC blade application. The objective was to provide improved environmental resistance of 2 to 3 times compared with the base SC alloy and still have sufficient high temperature creep strength. The tip alloys were designed for thermal stability or compatibility with the SC alloy, while considering weldability, since these properties tend to be conflicting.

The resultant tip alloy compositions are of the MxCrAl type, where M, X are predominate metals such as Ni and Co. The balance includes strengthening elements from the SC alloy such as Cr, Mo, Ti, Al, W, B, plus additional Al, Si, Hf, and Ta for environmental resistance. Also, elemental additions of Re and Nb were included to offer improved strength capability at critical tip temperatures (> 2100°F) (1150°C).

RESULTS

Laser Beam Welding (LBW)

The customized tip alloys were produced in powder form in preparation for LBW which was accomplished using a 400 Watt ND:Yag Laser as a heat source. This laser was believed to be adequate to provide the precision needed for the intricate SC blade tip, even though it produced smaller deposits compared to a higher power CO2 laser.

In LBW, a small beam is formed on a localized area and given sufficient power to produce a molten pool, which is fed by powder particles and allowed to solidify as the laser moves...
Figure 2 - Typical weld profile obtained with the powder fed Laser welds on the LT101 GP single crystal blade. Note the dip (arrow) due to localized overheating and the rounding or insufficient build up at the leading and trailing edges.

quickly across the blade tip. Process parameters, including travel speed, pulse rate, power setting, and powder feed rate, are varied to get the desired result.

A weld schedule was established to accommodate the LT101 blade tip configuration. The S.C. blade is cast with an internal hole from tip to root for weight reduction rather than air cooling, as shown in Figure 1. The objective was to produce a customized blade tip with .050" (1.3 mm) build up and with minimal HAZ using the three compositions as filler materials. No deposit was allowed in the lightening hole. The weld schedule used multiple stringer passes over the blade for each layer to produce the .050" (1.3 mm) build up requirement.

The key features of the LT101 blade tip which made weld build up difficult were the thin wall sections <.020" (0.3" mm) associated with the concave and convex side of the lightening hole and leading and trailing edges. In addition, blade to blade variability of the position of the lightening hole associated with core shift was as high as .015" (0.4 mm). Extremely tight control of the melt pool temperature was essential at these critical locations, in order to achieve an adequate build up without resultant post weld cracking.

The LBW system had limited vision which did not feed back to a controller. Process parameters were selected and modified for each blade to account for blade variability, which slowed processing and produced inconsistent results. In addition, controllers capable of varying all key parameters were not readily available. Powder feed is often varied independently of other parameters which makes control of the melt pool temperature difficult, especially near thin wall sections.

Efforts were made to accommodate blade wall thickness variability by modifying conditions; however, results were inconsistent and produced poor yields. For example, after processing a blade, if modifications were made to the parameters, the next blade did not necessarily benefit due to the blade variability. Local overheating tended to be a problem near thin wall sections. Control of the melt pool was difficult without feedback to the controller. Manually changing the parameters was too slow and resulted in limited success. The resultant laser deposit tended to be non-uniform and rounded at the leading and trailing edge, as shown in Figure 2. The build up around the lightening hole exhibited sizeable dips, where localized overheating occurred in thin sections, and the deposits had reduced the size of the tip cavity. Furthermore, significant cracking was observed in the highly alloyed tip compositions, as shown in Figure 3.

In thicker regions of the tip, the weld build up did not exhibit cracking and was acceptable, as shown in Figure 4. However, multiple passes were required to achieve the .050" (1.3 mm) build up. The dilution zone was acceptable at .015" (0.21 mm).

Another difficulty observed with the Laser system was the tendency for the powder deposit to oxidize in the melt pool. The oxide skin over each pass had to be mechanically removed before the next layer could be deposited. This extra operation increased the total welding time. The problems with oxidation, when using
highly alloyed powders, should be investigated further and could pose a limitation to the use of powder based plasma or laser systems, especially for applications requiring multiple passes.

Several LT101 blade tips were successfully processed using LBW as verified by FPI and radiographic analysis. However, the results obtained tended to be inconsistent and produced less than acceptable yields.

Micro-Plasma Arc Welding (MPAW)

Rather than use the fine powder filler to weld the blades, which might require less heat to melt, the use of wire was selected because of its better control and lower tendency to oxidize. In fact, the technology for precisely controlling the weld pool by using synchronized filler wire and current pulsing, as illustrated in a previous paper, (Lowden, Pilcher, Liburdi, 1991), has been extensively developed and proven reliable, whereas the powder feed technology requires additional development to produce clean, consistent, and controllable flow rates. Experience has also shown that the greater mass of the filler wire can be used advantageously during the fusion process to control the temperature or overheating of the weld pool, and does not result in any significant difference to the amount of dilution or heat affected zone produced in the base metal.

As reported in an earlier development program on high strength welding (Liburdi, Lowden, 1985), the technology is available to manufacture net shape welding rods directly from the metal powders or, alternatively, extrude larger diameter rods into fine welding wire. In this case, the three alloy compositions were economically converted into 0.032" (0.8 mm) diameter welding wire by consolidation and extrusion methods.

The Micro-Plasma Arc Welding (MPAW) process uses a small torch with a recessed tungsten electrode to transfer electrical energy and produce a column of ionized gases or plasma that locally heats the surface to be welded. The strength of the arc or power is easily regulated by adjusting the current level and pulsing frequency, while the filler wire can be synchronized with the current pulses and injected in the molten pool when required. The result is a weld deposit that can be controlled with great precision and varied to produce a thin or heavy build up.

The welding of the LP101 GP blades was performed on a Liburdi Automated Welding System (LAWS™) which uses a high precision gantry robot holding a micro-plasma torch and wirefeed mechanism, as described in a previous paper (Liburdi, 1989). The welding parameters such as current (high/low), voltage (high/low), pulse rate, duty cycle, and wire feedrate (high/low), are controlled and synchronized by the welding power supply. All welding parameters are fully programmable with sloping for smooth transition through each positional site. Motion control is equipped with curve fitting in order to minimize the number of sites required to trace the welding path. In addition, the motion control system fully coordinates all motion parameters with the welding power supply for repeatable control of the programmed welding path. The system is also equipped with the Liburdi Vision System (LVS™) which is used to image the component to be welded, digitize the critical areas, and relay this information to the welding system immediately before welding. The motion controller then compensates its welding path and welding parameters based on the vision information and, thus, customizes the weld to the particular blade being welded.

Initially, twenty-four blades used in the development were tip ground to give a consistent surface for welding and dimensionally inspected to study the part to part variations. The analysis revealed: a) trailing to leading edge chord length variation of ±.020" (±0.5mm); b) trailing edge thickness variation of ±.015" (±0.4mm); c) concave/convex lightening hole wall
accomplished using a single pass and without any interruption at the leading edge.

The path used to weld the LT101 GP blades is illustrated in Figure 5. The sites were strategically located to pick up critical features around the lightening hole and airfoil contour, and allow the welding parameters to be adjusted according to the local requirements. The vision system provides a positional accuracy of \( \pm 0.001\) " (\( \pm 0.02 \) mm) for all sites and allows precise tracing and customizing of the weld path for each blade.

For the LT101 blade tip configuration, the weld was started at site 1 and progressed in a single continuous pass through the different sites, ending with site 13 at the trailing edge. Using the vision data, the weld parameters were adjusted for varying thickness around the lightening hole and avoid any weld drop through in the cavity. Also, a continuous weld was sustained around the leading edge of the blade by using the smooth rotation of the gantry robot to maintain the optimum entrance angle of the filler wire while articulating around the tight radius.

Accurate control over the filler wire was very important in controlling the weld pool and avoiding overheating. This was accomplished by quickly introducing additional mass to quench the weld pool as required. This welding technique was especially useful in eliminating all trailing edge variability and establishing a consistent ball at the end of the weld.

Using the program developed for the first filler wire composition, parameters were soon adjusted to a maximum of 20% off nominal for the other two welding wire compositions. Similar welds and microstructures were produced with all filler wire compositions. Successful welds were achieved on every blade in a full hands-off production mode in less than 90 seconds per blade.

The resultant welds on the LP101 blades, shown in Figure 6, illustrate the uniform build up achieved with sufficient material to finish the leading and trailing edges and with no drop through or blockage of the tip cavity. Metallographic sections through the cavity (Figure 7) and sections taken all along the tip of the blade.
blade (Figures 8 and 9) revealed no evidence of either heat affected zone or weld metal cracking with any of the three compositions. The micrographs show a well bonded, clean deposit of approximately 0.070" (1.7 mm) in height produced in a single pass with minimum base metal dilution.

To complete the selection program, the candidate alloys will be tested for strength and oxidation resistance and the welded blades will be service tested in an engine to determine the best alloy for future production.

CONCLUSIONS
Although both the Laser and Micro-Plasma based systems demonstrated ability to weld the single crystal blade tips, better results were obtained using the LAW System because of its accurate vision based control and interactive wire feed. VISION is critical in providing the artificial intelligence; however, for optimum results, it must be tightly integrated into the motion and welding parameter generation. In addition, the systems must be capable of precisely metering and altering the rate of powder or wire feed, in order to maintain control over the weld pool.

The comparison also implies that the power supply used to weld single crystal blades is of secondary importance. Instead, the complete Automation System must be engineered to provide the required degree of control, accuracy, tooling, and artificial intelligence for the particular application.

The result of proper automation will be more reliable welds and repairs for single crystal or conventional superalloys which will allow turbine users to benefit from the improved reliability, lower costs, and greater yields from repairs.

REFERENCES


