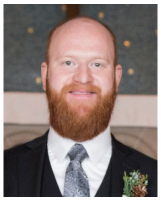
TURBOMACHINERY & PUMP SYMPOSIA | HOUSTON, TX
DECEMBER 14-16, 2021
SHORT COURSES: DECEMBER 13, 2021

LASER WELDING FOR TURBOMACHINERY ROTOR RESTORATION

Dr. Michael W. Kuper
Materials Engineer
Elliott Group
Jeannette, PA, USA

Michael J. Metzmaier
Engineer IV
Elliott Group
Jeannette, PA, USA



Michael Kuper is a materials engineer in the Product and Technology division of Elliott Group. He has a B.A., M.S., and Ph.D. in Materials Science and Engineering from The Ohio State University. His past experiences include analysis of dissimilar metal welds involving 9Cr-1Mo-V steel welded with nickel based filler metals, and high deposition rate additive manufacturing of metallic materials. He currently has 5 publications, has presented research at over a dozen technical conferences, and is an active peer reviewer for the journal Welding In The World.

Michael Metzmaier is a welding engineer within the Materials Engineering department of Elliott Group. He has a B.S in Welding and Fabrication Engineering Technology from The Pennsylvania College of Technology. He has held various positions within Elliott Group including manufacturing engineer, rotor division supervisor, and welding engineer.

ABSTRACT

Laser cladding is gaining acceptance for restoration of turbine and compressor shafts, which has resulted in increased customer demand for laser cladding options. This has increased the number of laser welding suppliers, who are offering a variety of solutions. Therefore, it is important to understand the basic capabilities, limitations, and potential pitfalls of the laser cladding process. For example, it is still unclear how the process should be qualified to ensure that laser weld repairs meet the requirements for the given application. As with any welding process, the desired outcome is a metallurgically sound deposit that meets or exceeds the minimum design criteria for the application. Filler material alloy selection, form, and delivery methods can have a significant impact on the quality and suitability of the weld deposit. For example, all fusion welding processes generate a heat affected zone, and the properties in that region are unlikely to meet base metal requirements without a post weld heat treatment when the base metal is quenched and tempered steel, which is commonly used for turbomachinery shafts. However, it is commonly claimed that a post weld heat treatment is not required with laser welding due to the low heat input of the process, which greatly reduces the size of the heat affected zone. While this may be true in some cases, it is important to recognize that the heat affected zone will still be present and testing must be completed to ensure that the repaired component will be suitable for the application. This paper discusses the most commonly repaired shaft areas, the risks associated with laser welding in these locations, and the types of tests that should be required to qualify a procedure. Additionally, examples of successful repairs are shared including experimental results from the qualification process.

INTRODUCTION

One of the most critical components of turbomachinery equipment is the rotor. These precision assemblies rotate at extremely high speeds and must withstand significant stresses for extensive service times. To achieve this level of reliability, manufacturers must ensure that the components are suitable for the application. Tight controls on composition, mechanical properties, and processing ensure that the parts are acceptable. These inspections, verifications, and safeguards maximize the usable service life while minimizing the risk of catastrophic failure. However, wear and tear from normal operation will eventually cause sufficient damage that replacement or repair is required. Generally, accumulated damage is superficial, and repair offers a cost and time advantage, as compared to replacing the entire rotor while adding minimal risk related to the repair process, since repairs are generally reliable. Once the shaft has been deemed repairable, the repair process must be chosen, and typical processes include spray coating, plating, arc welding, plasma welding, and laser welding. Each of these processes has advantages and disadvantages depending on a variety of factors including the location and extent of damage, operating conditions, service environment, the substrate and desired repair material, and customer acceptance. This paper will focus specifically on laser welding repairs. In particular, a discussion of general laser welding will be provided including how the process relates to and can be beneficial for compressor and turbine shaft repairs, including the considerations that need to be addressed to use this process. Example laser weld overlay and scratch repairs will be provided, and results will be shared from the laser weld repair qualifications used.

REPAIR BY TRADITIONAL ARC WELDING

Before the advent of laser beam welding (LBW), the most common process for shaft repair was submerged arc welding (SAW), mainly because the process is robust and offers a high deposition rate. However, this process involves high heat input, which can cause distortion of the shaft and high residual stress. Because of distortion, SAW repairs tend to require removal of all protruding features from the repair area, rebuilding of those features, and extensive overlaying to ensure sufficient machining stock to restore dimensions. Figure 1 shows an example of a SAW repaired rotor after welding. Also, because of the high residual stress from welding, repairs always require a post weld heat treatment (PWHT) before final machining, which relieves residual stresses that minimizes shaft movement (distortion) during the machining operation.

Figure 1: An example of a SAW repair on a rotor. Note the large surface area requiring overlay, much of which was added to ensure the rotor would have enough machining stock to account for distortion induced by the repair process.

Despite being a high deposition rate process, SAW deposition rate is partially limited by control of flux and maintaining interpass temperatures. Recently, LBW has become a commonly offered alternative process to SAW for superficial rotor restoration.

LASER BEAM WELDING

Access to a focused laser allows for welding (including cladding), cutting, and heat treatment [1], however, this paper will focus mainly on welding. Although LBW has existed since the 1970's, improvements in technology and affordability have expanded its range of industrial applications [2-7], which now include turbomachinery rotor restoration. The main advantage of LBW is that it is a high energy density process, and is therefore capable of welding with very low heat input, which minimizes base metal degradation, the size of the heat affected zone (HAZ), residual stress, and distortion, while also enabling very fast welding speeds [8]. Meanwhile, the smaller HAZ, is also beneficial in that less volume of the shaft has the potential for detrimental properties caused by the heat from the fusion process. This is particularly important in the case of heat treatable alloys such as quenched and tempered steels, which are commonly used for turbomachinery rotors. An example laser welding setup can be seen in Figure 2.

In addition to low heat input, the LBW process produces high quality fusion welds with a metallurgical bond (no delamination, which can occur in coatings based on adhesion), is easily automated for consistency and repeatability, and has high geometric precision. For example, the spot size of the laser used for this study can range from 0.2 mm in diameter for small welds to 2.0 mm in diameter for higher deposition rate overlays. Regardless, in order to capitalize on the advantages of the LBW process, the capability of the process must be matched with the application. The rest of this section will discuss additional considerations that must be explored before implementing LBW for rotor restoration.

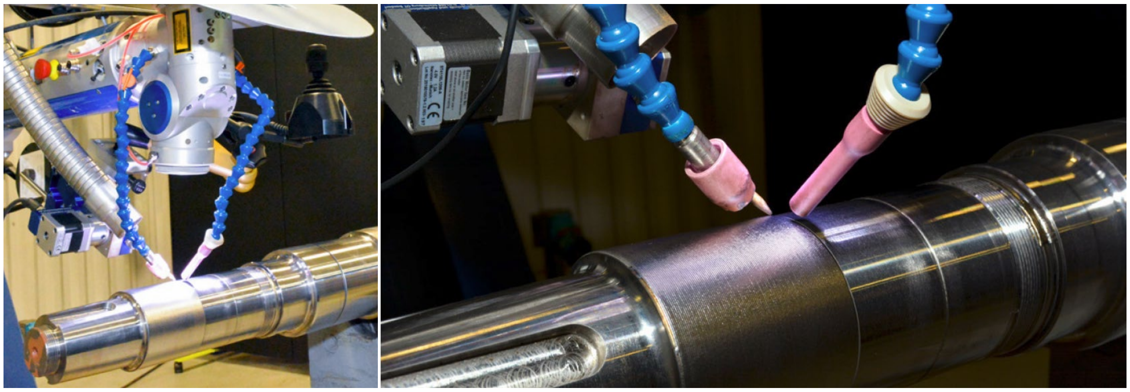


Figure 2: Laser welding system (left) the welding setup (right).

Filler Metal Delivery

There are two distinct laser welding processes, where one uses powder based filler metal (LBW-P) and the other uses wire based filler metal (LBW-W). In LBW-P, powder is delivered from a powder feeder through tubing and one or more nozzles by a jet of inert gas, which delivers the powder into the weld pool. For LBW-W, the filler metal is delivered by feeding the wire into the weld pool, either by hand or by a mechanized wire feeder. These two methods have metallurgical as well as logistical differences that must be considered when determining the most appropriate process for a given repair. This is especially true considering that these differences are not yet accounted for in ASME BPVC.

Variables for welding procedure specifications (WPS) for laser beam welding is covered by ASME BPVC Section IX Table QW-264 and QW-264.1. Among the essential variables are specifics related to the powder filler metals, including powder metal size, density, and feed rate. However, there is no mention of filler wire parameters. This indicates that the current code only considers powder based laser welding applications. It follows that procedure qualification would then also only be relevant for powder based laser welding. This is one reason why additional procedure qualification requirements may be necessary for laser beam welding.

The Laser Source

Type of Source

A variety of laser sources can be used for laser welding, though this article will focus on Nd:YAG and fiber lasers, which are two of the most common laser sources for welding. Nd:YAG lasers consist of a neodymium doped yttrium aluminum garnet crystal that is excited by a xenon flashlamp to produce the laser beam, while fiber lasers consist of an array of diodes that excite an optical fiber doped with rare earth elements to produce the laser beam [9]. While either of these laser sources can be used for rotor restoration, each of them offers tradeoffs including beam quality, beam size, beam frequency, lifespan, cost, and efficiency. With these in mind, choosing the best laser will depend on the application. When ASME BPVC compliance is a concern, however, the fiber laser is the better choice. The reason for this is the difference in the way that the laser beam is generated and its stability over time. Within the Nd:YAG laser, the xenon flashlamp bulb degrades over time and becomes dimmer as it ages. The dimmer bulb results in lesser excitation of the Nd:YAG crystal, which decreases the intensity of the laser beam produced. The effect of this is that the power output for a given laser setting will decrease throughout the lifetime of the flashlamp, though the rate of degradation will likely be unknown. This is problematic for compliance, since according to ASME BPVC Section IX Table QW-264, laser power is a critical variable that may not be changed for a given weld procedure. Maintaining this requirement would be nearly impossible for a Nd:YAG laser, although this fact is not mentioned in the code. In contrast to Nd:YAG sources, fiber laser sources do not have this problem, since excitation is performed by diodes. Therefore, fiber lasers are vastly superior, and arguably necessary, in situations that require code compliance.

Continuous or Pulsed Laser

Some laser systems now have the ability to operate in a pulsed mode in addition to operating continuously. The advantage of using a pulsed laser is that the heat input can be reduced to minimize the size of the HAZ, the amount of residual stress, and the amount of distortion. Aside from the general advantages, pulsing is also useful in specific instances, such as welding on a finish-machined part, where a PWHT is not possible. This is because pulsed power has a lower heat input than continuous power. Pulsed laser operation, however, is mostly limited to LBW-W, as LBW-P systems operate most effectively using continuous power. This is because in powder-based applications, the powder is delivered continuously, which would result in a large amount of wasted powder or lack of fusion caused by insufficient heat between pulses. For wire-based systems, the wire feeder is precisely controlled by the equipment to maintain stable welding conditions. It is worth noting that weld mode as a standalone variable can also have an effect on the deposition rates of the welding process, but this is largely dependent on the type of system as well as the conditions of the repair. Overall, the weld mode should be chosen based on the type of filler metal delivery, but also based on the type of repair and desired weld properties.

Joint Design

The joint design must be suitable for the type of welding system to minimize the potential for defects. Wire based welding systems are typically more tolerant of sharp corners and deep grooves than powder systems. This is due to the fact that wire systems do not require a gas transport system to deliver the filler material to the weld zone. Turbulence in the carrier gas used to deliver powder to the melt pool caused by the substrate geometry, such as a v-groove, can lead to poor powder delivery rates and poor shielding. Poor powder delivery rates results in low welding efficiency and excess heat reaching the substrate, while poor shielding can result in porosity and the formation of oxide inclusions. Additionally, for LBW-P, excess unfused powder can accumulate in the joint as well. Welding over this loose powder can cause significant defects including lack of fusion, porosity, or cracking. As a result, powder based filler metal delivery in a groove requires a wider groove angle, which creates more access to the weld joint, but also increases the volume of the groove. Therefore, the volume of the v-groove necessary for extracting test specimens when using LBW-P is very large compared with the typical size of a laser weld bead, making the manufacture of test specimens for procedure qualification impractical. In the case of wire based filler metal delivery, the angled wall of the groove create geometric challenges for shielding gas and wire delivery, which increases the likelihood of porosity and increases the susceptibility for lack of fusion defects. However, groove welding is possible with LBW. Additionally, for most shaft repairs where LBW is applicable, the repairs tend to be weld overlays, which do not require groove welding. Figure 3 shows common shaft repair types including overlays, buildups, and stub repair. Although stub repair would require groove welding, it would not generally be performed using LBW, since other processes have a higher deposition rate. Regarding filler material type, LBW-P and LBW-W will be acceptable for general shaft repairs, though caution should be taken when welds will be close to steps or features that could cause turbulence with a powder process. However, weld procedure qualification requirements may be impossible or impractical for LBW-P, and LBW-P may also struggle where porosity would be unacceptable.

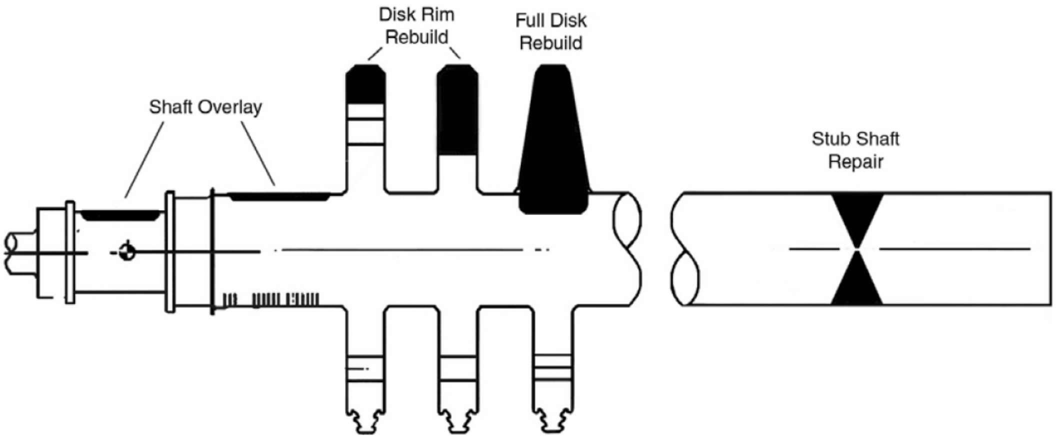


Figure 3: Examples of rotor repairs. The stub shaft repair is an example of a groove weld [10].

Filler Metal Cost and Availability

The ability to choose a filler metal is dependent on the availability of the material in question. Generally, both wire and powder versions are available for a variety of materials. However, wire based materials tend to be limited to commonly welded alloys, while powder materials tend to be more geared toward higher alloy steels and specialty alloys. This is because one of the key drivers for powder production is powder-based additive manufacturing, which has the highest cost-benefit for the more exotic materials. Because of this, it is difficult to find carbon and low-alloy steel in powder form, since these materials are cheap enough that the use of powder form is not cost effective for most industrial applications. Since carbon and low alloy steels are used heavily in the turbomachinery industry, wire-based laser welding systems tend to be a better option due to better availability of these materials. Additionally, filler metal in wire form is also generally cheaper than powder form. For example, Inconel 625 wire is $26/lb while Inconel 625 powder is $48/lb [11].

Defects

From an applications standpoint, one major difference between powder and wire based laser welding is the type of defects and the likelihood of forming defects during welding. LBW-W is capable of producing fully dense, defect-free welds [11], while LBW-P generally has a small amount of porosity at a minimum. Regardless, suboptimal welding parameters, joint geometry, or conditions can generate defect for either process. Typical defects that occur in laser welding, in general, include the following, with examples shown in Figure 4, which shows defects in a LBW-P overlay.

- Porosity
- Lack of fusion
- Unfused particles
- Cracking

Porosity is characterized by voids that occur within the weld deposit, created by escaping gases that become trapped during solidification, which has been witnessed in-situ [12]. For LBW, there are several methods by which gasses can be introduced into the weld pool, but the main theories include trapping shielding gas or metal vapors, cavitation caused by unstable keyhole welding, and gasses that were entrapped in the powder particles during the atomization process and released during welding [13]. In addition, porosity can occur from poor shielding gas coverage during welding, which is usually caused by an improperly aligned gas lens or turbulence near the weld pool. This may occur because of the turbulence created by rapid oxidation of the solidifying weld pool or possibly from gasses created from burning the oxygen found in air. Lastly, lack of base metal and filler material cleanliness can also contribute to porosity. Welding over organic matter (oil, grease, dirt, oxides, etc.) causes outgassing during welding that becomes trapped in the weld pool as it solidifies.

Lack of fusion is characterized by locations where the filler metal did not fuse with the base metal. This occurs when the heat source generates insufficient heat to coalesce the filler and base metals. The typical causes for this include poor welding angle, excessive filler material feed rate, and/or inadequate laser power. Similar to lack of fusion, unfused particles are characterized by remnants of unmelted powder being present in the weld. This type of defect is exclusive to LBW-P because it involves powder while LBW-W does not. The cause unfused particles is similar to lack of fusion, where there is insufficient heat to fully melt and fuse the filler material with the base material. This generally occurs because the laser did not have the time, power, and/or correct positioning to melt all of the filler metal in the weld area.

Cracking is characterized by weld metal fracture because of stress. Cracking can be caused by a multitude of factors, though common examples include highly restrained joint design, rapid cooling rates, filler metal susceptibility, contamination, weld bead profile, and/or incorrect welding parameters.

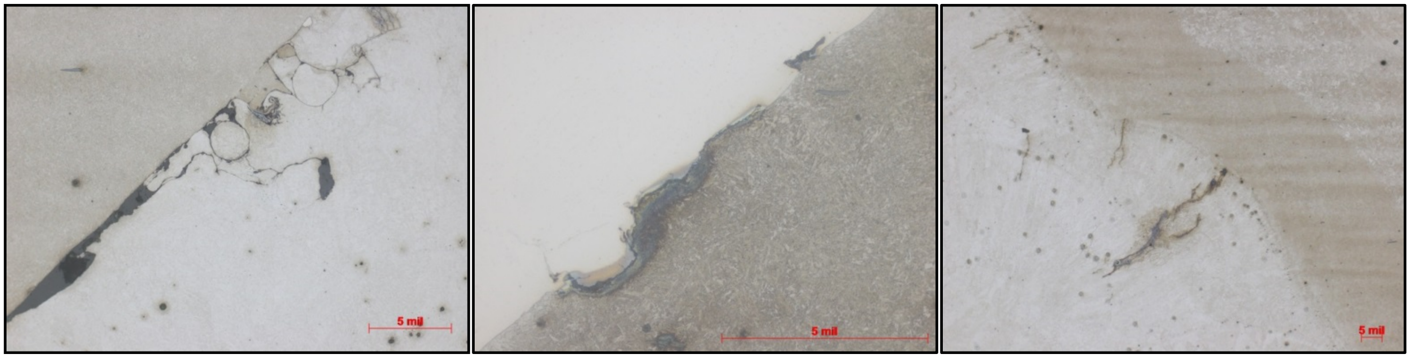


Figure 4: Common defects found in laser welding including unfused particles (left), lack of fusion (middle), and cracking (right). These defects were found in a weld made using powder based filler metal delivery. Porosity can be seen speckling each image.

LASER BEAM WELDING FOR ROTOR RESTORATION

Powder vs Wire Filler Metal Delivery

For shaft repairs, LBW-W is generally more applicable than LBW-P. The first reason for this is that LBW-W has a lower probability of forming defects, namely porosity, which may result in rejectable surface indications after final machining. Second, the ability to use a pulsed laser source in LBW-W reduces heat input, which helps minimize distortion, residual stress, and the size of the HAZ [8]. Third and finally, wire filler metal is cheaper and more readily available than powder in general, and it may be the only option available for carbon and low alloy steels, which are commonly used as turbomachinery shaft materials.

The Post Weld Heat Treatment

For rotor repair using conventional arc welding, a PWHT is generally required. First, residual stress from arc welding is large enough to cause shaft movement after final machining, particularly during the heat stability test that is required for turbine rotors. The PWHT relieves residual stress to minimize shaft movement during machining. Third, because rotors are typically quenched and tempered martensitic steels, welding creates hard and brittle untempered martensite in the weld deposit and HAZ. Untempered martensite reduces impact toughness, potentially below the base material requirements, especially for low temperature service. The PWHT tempers the fresh martensite that formed during welding, which restores the impact toughness of the shaft. Unfortunately, however, the PWHT can also over-temper the base material, which may result in a loss of strength in some cases.

The PWHT is also a costly and time-consuming operation. Figure 5 shows the setup for a PWHT applied to a rotor. For this process, the shaft must be suspended vertically to minimize distortion. In other words, if the rotor were heat treated horizontally, the rotor would bow and sag between supports that would become permanent after the heat treatment. After suspending the shaft vertically, heating blankets and thermocouples are added which must provide intense, yet precise heat (generally over 1000 °F), and this heat must be evenly distributed. If heat is added non-uniformly, then stress will be relieved non-uniformly, which could result in detrimental distortion. Heating/cooling rates and hold times must be controlled and monitored carefully. Overall, the process is relatively complex and time-consuming, meaning it is also costly.

Figure 5: Example setup for a post weld heat treatment [10].

Often, laser weld applicators make the assertion that a PWHT is not required with their process because the weld deposit and HAZ created by laser welding are small enough that their presence has a negligible effect on the overall shaft properties. However, little academic research has been performed on mechanical properties of laser weld repairs in turbomachinery applications. While the weld deposit and HAZ may be small, it is dangerous to assume that they will not affect the shaft's fitness for service, particularly when the shaft material is quenched and tempered steel, which is the most commonly used shaft material. In order to avoid the PWHT, precautions must be made to ensure that the repair will meet the required properties without the PWHT. These precautions include the testing recommended in this document as well as considering compatibility with the erosion and corrosion requirements of the operating environment.

Current Qualification Requirements

As mentioned above, current ASME BPVC does not distinguish between LBW-P and LBW-W, nor does it account for the inevitable change over time in output power discussed above for Nd:YAG lasers. These will need to be remedied in the future to account for the differences in the typical applications for and qualification of these processes. Regarding procedure qualification, groove welds would be qualified to ASME BPVC Section IX Table QW-451.1. However, for rotor restoration, LBW repairs are typically performed on superficial damage, and would therefore be considered weld overlays. The procedure qualification requirements for overlays from ASME BPVC Section IX Table QW-453 can be found in Table 1 below along with the requirements for groove welds.

Table 1: Procedure qualification test requirements for overlays and groove welding per ASME BPVC Section IX [14].

Hard Facing Overlays	Corrosion Resistant Overlays	Groove Welds
• Liquid penetrant testing • 3 hardness readings per specimen • Macro test	• Liquid penetrant testing • Four transverse side bend tests (or two transverse and two longitudinal bend tests)	• 2 tensile tests • 4 transverse side bends

Although hardness readings are required for hard facing overlays, ASME does not list acceptance criteria. Therefore, hardness limits shall be applied based on the application and service environment conditions on a case-by-case basis.

As mentioned before, most rotor repairs will qualify as weld overlays, but in addition to the above requirements, further testing may be necessary for laser beam welding in some instances. In general, the critical design factors for shafts should also be considered, which are dependent on which portion of the shaft requires repair. These critical properties will be discussed in the following section.

Critical Properties Based on Weld Repair Location

The most common damage locations on a shaft undergoing restoration include the coupling fits, journals, probe areas, seal areas, and the main body. Because of the nature of the repair process (fusion of the weld deposit and the formation of the HAZ), it is understood that the properties of the repaired areas will not match the properties of the original shaft material. Additionally, each part of a shaft has its own set of design criteria. Therefore, it is important to ensure that the restored areas meet the minimum design requirements at each repair location. With that in mind, below is a discussion of the critical properties that should be considered for each region of the shaft, and a summary of this information can be found in Table 2.

Shaft Main Body

Main shaft body repairs are generally located in the lowest stress areas where matching the shaft material composition and properties is generally unnecessary. In these locations, the intent of the repair is to restore dimensions without creating distortion elsewhere. However, as the main body of the shaft is in contact with the process gas, weld repairs made on equipment used for hydrogen service (over 100 psig partial pressure of hydrogen) must be constrained to a maximum yield strength of 120 ksi and a hardness of 34 Rockwell C to meet the requirements of API 617 [15]. Because of this, further analysis is required to determine if and how LBW may be applied for rotor repair that will operate in hydrogen service.

Journals, Seals, and Probe Areas

Journals, seals, and probe areas are generally smaller in diameter compared to the main body of the shaft, so stresses in these locations are moderately high and should be accounted for when selecting a repair method. Tensile strength and toughness should be part of repair evaluation in these areas. Journal areas must also be capable of meeting surface roughness requirements after final machining and grinding (typically 32 micro-inch or better), meaning porosity could be a concern in these locations. Repairs located in probe areas must have uniform microstructures to prevent erratic electrical runout readings. Probe areas are typically ground and burnished to maximize probe precision and accuracy. The filler material must also act as a target material for the eddy-current probe and changes to probe calibration may need to be considered. Although hardness is not a major concern for journals and probe areas, seal areas will be in contact with the process gas and must meet the maximum strength and hardness requirements mentioned above if the rotor will operate in hydrogen service.

Couplings

The coupling area is usually one of the smallest diameters on the entire shaft, which means it experiences some of the highest stresses. This area may also contain additional stress concentrators such as keyways, grooves, or compression fits. Unless there are other highly stressed integral features on the rotor such as turbine disks, the strength of the entire shaft is selected based on this feature. This portion of the shaft may also experience high alternating stresses, which can be induced by the equipment that drives the rotor, meaning the endurance limit must be considered [16]. Care should be taken when determining the endurance limit, however, since surface treated material may exhibit reduced endurance limits up to 50% compared to the base material [17]. Therefore, direct testing of the fatigue characteristics is necessary in addition to tensile properties. Because the fatigue considerations of coupling repair is complex and requires additional considerations and testing that goes well beyond ASME BPVC guidelines. Because of the criticality and complexity of coupling repair design and assessment, repairs in this area will not be considered in the present study.

Based on the critical properties identified in this section, the testing required by ASME BPVC Section IX alone is inadequate to assess the suitability of the repair for all common repair locations, except for the main body of the shaft. To remedy this discrepancy, it is recommended to perform supplemental tensile testing and impact testing, at a minimum, for all repair qualifications made in the journal, probe, and seal areas. Hardness measurements shall also be taken for main body and seal repairs in cases where hydrogen service limits the rotor yield strength. In addition, as mentioned before, coupling areas require additional considerations related to fatigue testing that are outside the scope of this document.

Table 2: Critical material properties based on the repair location.

Critical Property	Couplings	Journals	Probe Areas	Seals	Main Body
Tensile Strength	X	X	X	X	
Impact Toughness	X	X	X	X	
Hardness (for Hydrogen Service)				X	X
Capability of Finely Finished Surfaces	X	X	X	X	
Electrical Runout			X		
High Cycle Fatigue	X				

PROCEDURE QUALIFICATION

The following section details example test results from LBW performance qualifications on low alloy steels commonly used for shafts. Each of these base metals were welded using AWS A5.28 Class ER120S-1. The materials used in this study, including the abbreviations used in this paper, the relevant industrial standards, and composition limits for primary alloying elements in each material can be found in Table 3. All weldments were made using a 900 watt pulsed laser welding system with a fiber laser source. The welding parameters used for this study are considered intellectual property and cannot be shared in detail. However, the same welding parameters were used throughout this study, with an average laser power of 522 W. This power is about 58% of the laser system's capabilities, thus representing an intermediate deposition rate (approximately 0.10 lb/hr).

Table 3: The abbreviation, industrial standard, and composition of primary alloying elements for the materials described in this section.

Abbreviation	Industrial Standard	Primary Alloying Elements					
		C	Mn	Ni	Cr	Mo	V
BM1	ASTM A470 Grade B Class 4	0.22 - 0.30	0.20 - 0.60	3.2 - 3.7	0.75 max	0.40 - 0.60	0.04 - 0.12
BM2	ASTM A470 Grade C Class 7	0.28 max	0.20 - 0.60	3.25 - 4.00	1.25 - 2.00	0.25 - 0.60	0.05 - 0.15
BM3	ASTM A470 Grade D Class 8	0.25 - 0.35	1.00 max	0.75 max	1.05 - 1.50	1.00 - 1.50	0.20 - 0.30
BM4	AISI 4330 (Modified)	0.33 - 0.36	0.20 - 0.40	2.75 - 3.50	1.25 - 1.50	0.30 - 0.40	0.07 - 0.10
-	AWS A5.28 Class ER120S-1	0.10 max	1.40 - 1.80	2.00 - 2.80	0.60 max	0.30 - 0.65	0.03 max

For each base material, a v-groove was machined into a 1" (25.4 mm) plate for welding. The groove was machined with a 25° included angle (12.5° per side) to a depth of 0.625" (15.9 mm). The depth was measured to the bottom of the groove, which was machined with a radius of 0.1875" (4.76 mm). After welding, the weldment was liquid penetrant tested for surface defects, then test specimens were extracted for mechanical testing. In addition to the groove weld, tensile specimens consisting entirely of weld metal were created by depositing and stacking layers of weld metal, each consisting of a pad of weld beads (similar to additive manufacturing). The bars were approximately 0.5" wide, 0.5" tall, and 5" long. Two tensile specimens were extracted from each for testing. One test specimen was tested in the as-welded condition, while the other was tested after receiving a PWHT for three hours at 1200 °F. The following list summarizes the mechanical tests performed for the LBW-W procedure qualification of each base metal welded in this study, with all specimens extracted from the v-groove weld except where noted.

- Two transverse tensile tests
- Six Charpy impact tests
    - Three from the weld metal
    - Three from the HAZ
- Hardness scan (Five indents each)
    - Weld deposit
    - HAZ
    - Base metal
- Four side bend tests
- Two longitudinal tensile tests (extracted from the all-weld metal buildup)
    - One in the as-welded condition
    - One after the PWHT

Results

All welds passed liquid penetrant testing and side bend testing. The macro test also passed inspection, meaning it contained no visible cracks at 5X magnification. Figure 6 shows a cross section of a LBW overlay, which highlights the small size of the HAZ in the LBW overlay, averaging 0.00975" thick in this study. Additionally, the LBW weld deposit was clean with no detectable porosity. The dark speckles on the image are from slight surface rust.

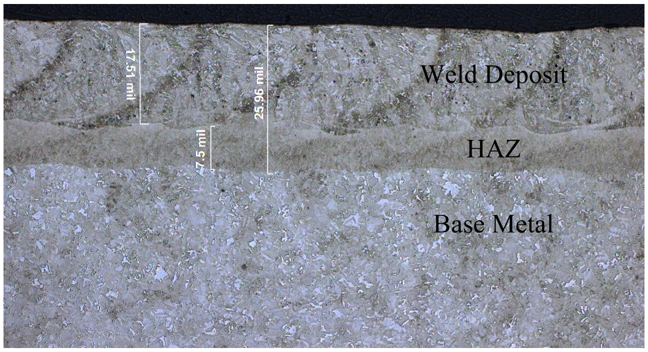


Figure 6: Cross section of a LBW overlay showing thickness measurements of the fusion zone, HAZ, and overall region affected by welding.

Table 4 shows the results of the all-weld tensile tests including yield strength, tensile strength, elongation at failure, and reduction of area at failure. This table lists the experimental values for the as welded and PWHT samples, and includes the property requirements of the filler wire from AWS A5.28 [18].

Table 4: Tensile test results from specimens extracted from all-weld metal (ER120S-1) buildups in the as-welded and PWHT condition.

	As Welded	After PWHT (1200 °F)	AWS A5.28 Requirements (As Welded) [18]
Yield Strength (ksi)	133.6	78.4	105
Tensile Strength (ksi)	137.1	98.3	120
Elongation (%)	17	25	14
Reduction of Area (%)	78	76	-

The results from the groove weld tensile tests can be seen in Table 4 for each of the four base metals used. Test results include yield strength, tensile strength, elongation at failure, reduction of area, and the failure location. The table also includes the mechanical property requirements from the base metal standards [19].

Table 5: Average tensile test results from v-groove welds made using ER120S-1 wire on various base materials and the mechanical property requirements for each base material [19].

Base Material	BM1		BM2		BM3		BM4	
Experimental Data / Standard Requirements	Exp	Standard	Exp	Standard	Exp	Standard	Exp	Standard
Yield Strength (ksi)	105.1	90 min	125.5	95 min	90.5	90 min	135.5	145 - 165
Tensile Strength (ksi)	124.3	105 min	135.5	120 - 135	111.5	105 - 125	142.3	175 min
Elongation (%)	20.0	17	20.0	18 min	18.5	17 min	15.8	13 min
Reduction of Area (%)	63.5	45	75.5	52 min	65.5	43 min	77.0	40 min
Failure Location	Weld	-	Weld	-	Weld	-	Weld	-

The results from the Charpy v-notch impact testing can be seen in Table 6. Test results include the test temperature, the average impact toughness, the average lateral expansion, and the average percent shear. Also included are the mechanical property requirements from the base metal specifications [19], if applicable.

Table 6: Average impact test results for v-groove welds made with ER120S-1 on various base materials and the impact toughness requirements for each base material [19].

Base Material	BM1		BM2		BM3		BM4	
Test Location	Weld	HAZ	Weld	HAZ	Weld	HAZ	Weld	HAZ
Test Temperature °F	-20	70	-20	70	-20	70	-20	-20
Impact Toughness, *Measured* (ft-lbs)	174.0	57.7	168.3	115.0	186.0	79.3	114.3	71.3
Impact Toughness, *Requirement* (ft-lbs)	20 min		40 min		20 min		-	
Lateral Expansion (mils)	83.0	39.3	72.3	61.7	82.3	49.0	66.3	44.3
% Shear	100.0	52.3	100.0	100.0	100.0	65.7	-	-

The hardness survey results for each of the groove welds can be found in Table 7. Table 6 also contains the measured thickness of the weld deposit and HAZ from each weld.

Table 7: Average Vickers hardness (HV_{10}) and thickness of the weld metal, HAZ, and base metal for each material welded with ER120S-1.

	Location	BM1	BM2	BM3	BM4
Hardness (HV_{10})	Weld Deposit	376	369	335	373
	HAZ	388	390	390	475
	Base Metal	258	299	267	377
Thickness (in)	Weld Deposit	0.020	0.015	0.014	0.015
	HAZ	0.010	0.011	0.008	0.010

Example Repairs

In addition to the mechanical testing performed for the procedure qualification, repair welds were performed on two damaged shafts. The first shaft was damaged by extensive pitting corrosion in the seal, probe, and journal areas, shown in Figure 7. The figure also shows the repaired shaft after welding and after final machining. The probe area was also ground and burnished, which can be seen in Figure 8 along with the electrical runout measurements. The difference in color between the repaired area and the rest of the shaft resulted from the difference in hardness of the substrates during burnishing, however, the mechanical and electrical runout readings were within the required tolerances.

The second shaft was damaged by a box cutter while being unpackaged for assembly, shown in Figure 9. The scratch was approximately 0.003” deep and was repaired locally using a single weld bead, which can also be seen in Figure 9. After repair, the shaft was ground back to geometric specifications, inspected, and installed for service.

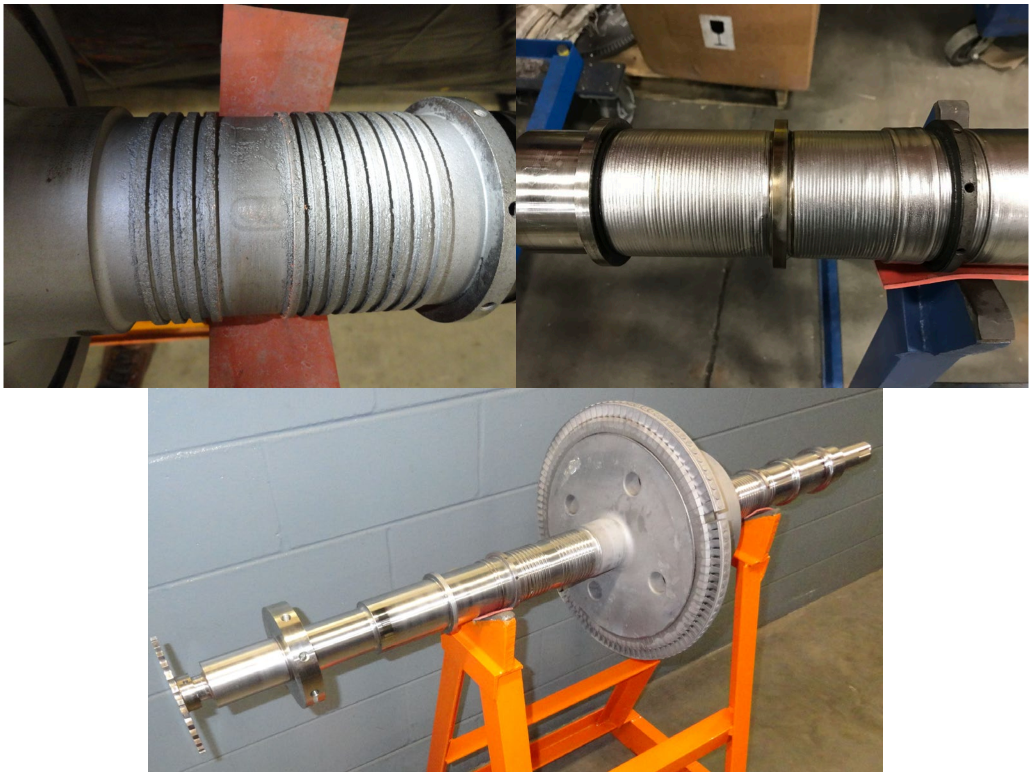


Figure 7: Overlay rotor restoration before repair (top left), after the weld repair (top right) and after final machining (bottom).

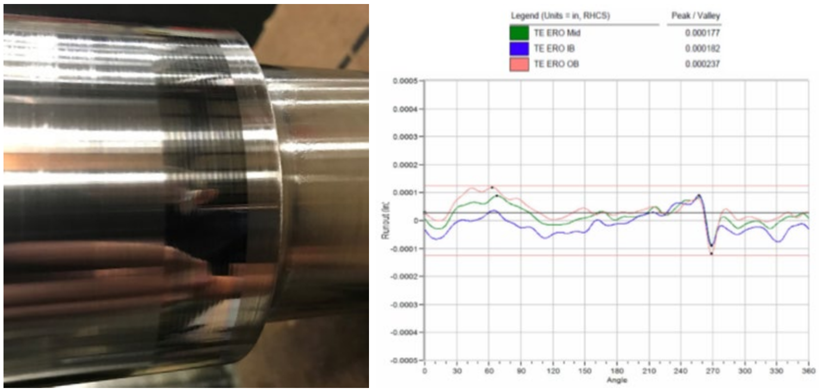


Figure 8: Example of a burnished probe area after repair (left). The repaired region appears dark because of a difference in hardness between the base and weld metal, however, the repair met the geometric tolerances, surface finish, and electrical runout (right) required for a probe area.

Figure 9: The scratch, which has been circled, in a journal area (left), the same scratch after LBW repair (middle), and the repaired area after final machining (right).

DISCUSSION

Mechanical Properties

Tensile Properties and Impact Toughness

The as welded ER120S-1 used in this study exceeded the mechanical property requirements of the AWS wire standard by 26.7%, 14.2%, and 21.4% for the yield strength, tensile strength, and elongation respectively in the all-weld tensile specimens. These excellent values are speculated to originate from grain refinement caused by the rapid solidification inherent to the laser welding process. Regarding the weldments, samples tested from each v-groove indicated that the mechanical properties exceeded the requirements of the relevant base material in all cases except for BM4. Therefore, BM1, BM2, and BM3 can be welded with ER120S-1 with the process used in this study without having to worry about meeting the base metal mechanical properties. The reason that BM4 weldment did not meet the BM4 base metal requirements is that this base material overmatches the weld material. ER120S-1 has a minimum tensile strength of 120 ksi, while BM4 has a minimum tensile strength of 175 ksi. Despite this, the weldment performed admirably, achieving a 142.3 ksi tensile strength when tested. The higher strength exhibited here, as compared to the other welds, was likely caused by base metal dilution.

Despite excellent mechanical properties in the as-welded condition, the test specimen that received a PWHT showed a decrease in tensile and yield strength by 41% and 28% respectively, to levels that would be unacceptable when compared with all base materials used in this study. As a result, this filler wire should not be used in situations that require a PWHT, unless the anticipated drop in strength is acceptable from a design perspective.

In general, the impact toughness results were exceptional. The impact toughness of all welded joints (those that had impact toughness requirements) were well above the required values. Additionally, lateral expansion and percent shear results were also exceptional. It is speculated that these excellent results were due to the fine grain size of the weld metal, which can be seen in Figure 6, though further characterization and testing is required to confirm.

Hardness

As mentioned previously, ASME code requires hardness scans for weld overlay qualification, but does not set acceptance criteria. For rotor restoration, the most applicable restriction that may be applied is the maximum hardness requirement (34 Rockwell C) set by API 617 for compressor shafts operating in hydrogen rich environments. This requirement would be applicable for main body and seal repairs, since these regions of the shaft contact the process gas. According to Table 1 of ASTM E140, which governs hardness conversion, 34 Rockwell C equates to 336 on the Vickers scale [20]. When subject to a maximum of 336 HV, none of the base metals used in this study would be acceptable for hydrogen service after repair welding because the HAZ hardness exceeds the defined limit. Also, the weld metal exceeds the 336 HV hardness limit in all cases except for the BM3 weldment, which was measured at 335 HV and should be considered on the extreme borderline of acceptability. It should also be mentioned that BM4 could not be used for hydrogen service in any case, since the base metal hardness was also too high.

Because of the high hardness of the HAZ and weld deposit, none of the materials used in this study would be acceptable for hydrogen service in the as-welded condition. The hardness of these regions could be reduced using a PWHT, however as mentioned before, the weld metal used in this study loses considerable strength from a heat treatment, which may be unacceptable for shaft applications. Other filler metals may be more appropriate if a PWHT is necessary, but this is outside the scope of the current work. Additionally, the extreme hardness of the HAZ may require a substantial PWHT to meet the requirements of API 617 for hydrogen service, which may over-temper the base metal of the shaft, which could lower the strength beyond the limits set by the application. As a side note, it should be mentioned that a potential solution to this issue would be to perform a localizes PWHT using induction heating, which has a skin effect that may be able to temper the HAZ without significantly over-tempering the bulk of the shaft. This possibility has not yet been explored and warrants further study. Regardless, because of the reasons outlined in this paragraph, LBW may not be the best option for repair in cases involving hydrogen service, particularly when the base material is quenched and tempered steel.

Finish

Since geometric runout was within the allowable limit (0.002”) after welding and finish machining, distortion induced by LBW was insignificant. No surface indications were found after final machining, meaning no porosity was detected during the liquid penetrant test. Additionally, the probe area was successfully burnished using the standard process, resulting in acceptable geometric tolerances. The electrical runout test in the probe area was also acceptable within the tolerance limits, and in this case, the probe did not require recalibration. It is hypothesized that the acceptable electrical runout can be attributed to the high degree of uniformity in the weld deposit, which resulted from the high degree of precision and control inherent to the mechanized LBW process. Further study would be necessary to asses this hypothesis. For the scratch repair, there was some initial concern that the localized weld would not “clean up” after final machining. In other words, it was predicted that cratering at the weld start or stop, or undercutting along the weld toes may lead to negative space (missing material) after final machining. However, final machining to the original dimensions after welding produced a smooth surface without topological defects or low spots.

Advantages of Laser Weld Repairs

Scratch Repair

The scratch which was approximately 0.003" in depth would have rendered the shaft as scrap without a viable repair process. Traditional arc weld was eliminated as an option due to the fact that it would have required welding from the journal area through the coupling end of the shaft. Welding in the coupling area was not feasible in this case due to the strength requirements in that location. Instead, the laser welding process was utilized to perform a localized repair of the scratch, eliminating the need for welding in the coupling area while saving significant processing time. Final grind of the repair area did not require additional stock removal beyond the original drawing tolerance.

Overlay Repair

The turbine rotor shown in Figure 7 sustained extensive pitting corrosion damage in the seal and journal locations. Conventional arc weld overlay of those areas would have required a multi-step process to repair. First, all damage and protruding features (i.e. packing teeth, balance rings, thrust disk, etc.) would be machined off of the shaft with an additional undercut of 0.125" radial stock. The shaft would then be welded, building up material as required to restore the geometry of all features, with extra stock added for machining and to account for distortion from the welding process. The weld repair would then require a stress relief heat treatment to remove residual stress. This is necessary because the residual stress would tend to move the shaft during machining, which would result in a high probability of failing to meet the required geometric tolerances. In the case of turbine shafts, removal of residual stress is critical to passing the heat stability check. After stress relief, the shaft would be final machined and then undergo non-destructive testing. Turbine rotors would then be subject to the aforementioned heat stability check.

By utilization laser welding, the repair process would require fewer steps. First, the damaged areas would be undercut, though undamaged areas, including protruding features, may be left on the shaft. Second, the LBW overlay would be performed to restore shaft dimensions with an additional 0.020" machining stock. Third, the repair would be machined to meet the drawing dimensions, and lastly, the prescribed non-destructive testing would be performed to check for defects. Overall, this process requires significantly less machining before and after the weld repair, and it eliminates the PWHT. Also, in the case that the rotor is being clad with a corrosion resistant material such as nickel based alloys, LBW deposits less material, which may offer costs savings. It should be noted that the time to overlay weld a shaft may be longer for LBW than a conventional arc welding processes, like submerged arc welding, but the faster machining times and elimination of the PWHT when using LBW generally make up for any time lost during welding by a considerable margin. Of course, this depends on a variety of factors including the size of the rotor, the extent of repairs, the complexity of features, etc., so the best weld repair process for a given application can vary and should be selected on a case-by-case basis. Nonetheless, LBW offers clear advantages in many cases for repair of superficial damage, which occurs commonly over time and exposure to service conditions.

CONCLUSIONS

Laser welding, when applied correctly, is an effective method for the restoration of turbomachinery shafts. The process is quick and efficient in performing superficial repairs, and in some cases allows for the repair without the need to perform a PWHT, which saves further time and costs. However, in order to perform LBW repairs outside of the main body of the shaft, it is important to fully qualify the welding procedure with supplemental testing to ensure the integrity of the as-welded repair. This testing includes tensile testing, impact testing, and hardness. While not discussed extensively in this paper, fatigue testing is also critical for coupling repairs. Furthermore, these requirements and recognition of the differences between wire and powder based filler metal delivery in LBW need to be addressed by Section IX of ASME BPVC to ensure compliance to these practices as an industry standard.

NOMENCLATURE

HAZ = Heat Affected Zone
LBW = Laser Beam Welding
LBW-P = Laser Beam Welding (powder filler metal)
LBW-W = Laser Beam Welding (wire filler metal)
PWHT = Post-Weld Heat Treatment
SAW = Submerged Arc Welding
WPS = Welding Procedure Specification

REFERENCES

[1] Shane. "Laser Welding: The Basic Guide." MachineMfg. https://www.machinemfg.com/laser-welding-guide/ (accessed 8/23/2021.

[2] A. Papacharalampopoulos, P. Stavropoulos, and J. Stavridis, "Adaptive control of thermal processes: laser welding and additive manufacturing paradigms," *Procedia CIRP,* vol. 67, pp. 233-237, 2018.

[3] J. De Pelsmaeker *et al.*, "Clear to clear laser welding for joining thermoplastic polymers: A comparative study based on physicochemical characterization," *Journal of Materials Processing Technology,* vol. 255, pp. 808-815, 2018.

[4] A. Perveen, C. Molardi, and C. Fornaini, "Applications of laser welding in dentistry: a state-of-the-art review," *Micromachines,* vol. 9, no. 5, p. 209, 2018.

[5] J. Helm, A. Schulz, A. Olowinsky, A. Dohrn, and R. Poprawe, "Laser welding of laser-structured copper connectors for battery applications and power electronics," *Welding in the World,* pp. 1-12, 2020.

[6] M. Quazi *et al.*, "A comprehensive assessment of laser welding of biomedical devices and implant materials: recent research, development and applications," *Critical Reviews in Solid State and Materials Sciences,* vol. 46, no. 2, pp. 109-151, 2021.

[7] F. Gäbler, "Optimizing Automotive Welding Applications with CleanWeld: A unique approach to fiber laser welding," *PhotonicsViews,* vol. 16, no. 4, pp. 52-55, 2019.

[8] D. H. Phillips, "High Energy Density Welding Processes," in *Welding Engineering: An Introduction*: John Wiley & Sons, 2016.

[9] OTLASER. "Fiber Laser, YAG Laser, CO2 Laser Cutter, What is the Difference." https://www.otlaser.com/fiber-laser-vs-yag-laser-vs-co2-laser (accessed August 30, 2021.

[10] Elliott Group. *Elliott Rotor Weld Restoration Program*. (2021). [Online]. Available: https://www.elliott-turbo.com/Files/Admin/Literature/Literature%20Updates%20June2017/SVS.4104.0518---Elliott-Rotor-Weld-Restoration-Program-%28final%29.pdf

[11] M. Naeem, "High Power Fiber Laser Welding with Filler Material: Very good results for welding aluminium, titanium, and high strength nickel alloys achieved with wire or powder feed setups," *PhotonicsViews,* vol. 16, no. 5, pp. 51-55, 2019.

[12] S. Webster, S. Wolff, J. Bennett, T. Sun, J. Cao, and K. Ehmann, "Porosity formation and meltpool geometry analysis using high-speed, in situ imaging of directed energy deposition," *Microscopy and Microanalysis,* vol. 25, no. S2, pp. 2556-2557, 2019.

[13] T. DebRoy *et al.*, "Additive manufacturing of metallic components–process, structure and properties," *Progress in Materials Science,* vol. 92, pp. 112-224, 2018.

[14] ASME, "Qualification Standard for Welding, Brazing, and Fusing Procedures; Welders; Brazers; and Welding, Brazing, and Fusing Operators," in *Boiler and Pressure Vessel Code*. New York, 2021, sec. IX.

[15] *API Standard 617: Axial and Centrifugal Compressors and Expander-Compressors*, 2014.

[16] *Design and selection of components for enclosed gear drives*, ANSI/AGMA 6001-E08, 1997.

[17] M. Nascimento, R. C. Souza, W. L. Pigatin, and H. Voorwald, "Effects of surface treatments on the fatigue strength of AISI 4340 aeronautical steel," *International Journal of Fatigue,* vol. 23, no. 7, pp. 607-618, 2001.

[18] *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*, AWS A5.28, 2020.

[19] *Standard Specification for Vacuum-Treated Carbon and Alloy Steel Forgings for Turbine Rotors and Shafts*, ASTM A470, 2005.

[20] *ASTM E140 Revision B - Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and Leeb Hardness*, ASTM, West Conshohocken, PA, 2012.