A History of Additive Manufacturing Using Conventional Welding Processes

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Executive Summary

Electric arc welding has been around since the 1880s. While arc welding has been mostly used for joining metals together, it has also been used to add material to parts to increase the part's thickness, length, diameter, and to add reinforcement. Arc welding has also been used to enhance the performance of parts by adding layers of weld metal that have improved strength, creep resistance, wear resistance or corrosion resistance over that of the original material. While building up weld metal layer on layer using an electric arc and wire to create parts is now referred to as additive manufacturing, weld metal buildup using an arc and wire is proven technology that has been around for a century. What is new is that the weld metal is deposited by a computer-controlled robotic arm instead of by a welder. As a result, the process is highly automated, repeatable, and can be monitored continuously while the weld metal is being deposited. Using this technology, large industrial parts are already being made today using arc welding and wire.

1.0 Introduction

Additive manufacturing using conventional welding processes has been part of the welding industry for a long time – except that it was called "weld metal buildup." While the first all-welded steel ship hull was built in 1918, the birth of additive manufacturing using welding occurred in 1920 when P. O. Nobel of the General Electric Company developed automatic arc welding equipment that used direct current and wire to build up to worn motor shafts and crane wheels[1] and Ralph Baker of the Westinghouse Company patented using layers of weld metal to make decorative articles, e.g. vases. Advances in computing and robotics has made it easy to build entire components out of weld metal, far exceeding the traditional use of weld metal buildup.

This White Paper documents:

- The origins and history of weld metal buildup.
- Case histories where weld metal has been used for decades to create buildups and stand-alone parts in both nuclear and non-nuclear construction.
- How material manufactured using wire and an arc compares to plate, forgings and castings.
- How ASME Code has dealt with weld metal in the design of components.
- How Directed Energy Deposition-Wire Additive Manufacturing (DED-WAM) differs from Laser Powder Bed Fusion Additive Manufacturing.

2.0 Shape Welding

While building up material using arc welding was first patented in 1920, it did not become a widely used method for producing industrial parts until the 1960s. The Russians were one of the first to produce industrial parts using electroslag welding[2] to create valve bodies. Valves as shown in Figure 1 were used in nuclear facilities in the USSR.

Figure 1. Electroslag castings of stop valve bodies [2]

In 1967, Mitsubishi patented methods for constructing both cylindrical and spherical cross-section pressure vessel components entirely out of weld metal. The patents[3] described a table that could both rotate and tilt in synchronization with a moveable welding head that deposited weld metal as the table rotated beneath it.

Karl Million and H. Zimmermann in a paper presented at a DVS conference in 1986[4] examining the concept of manufacturing of heavy nuclear components by “shape-welding” parts using a multi-layer welding and equipment similar to the drawings shown in Figure 2.

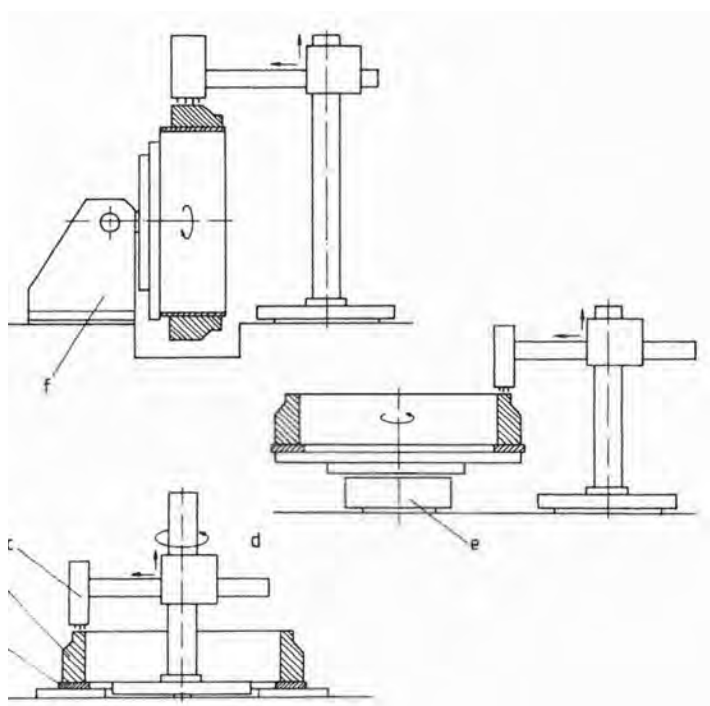


Figure 2. Shape welding and equipment used for multi-layer builds. (4)

They noted that shape welding had been discussed in the literature in the early 1960s, and that a 20-ton steel ring had been made from weld metal in 1978.

An article by Kussmaul, Schooch and Luckow in the September 1983 *Welding Journal* described a 64-ton pressure vessel 216 inches long, 71 inches in diameter and 8 inches thick that had been manufactured in 1976 using the submerged arc welding process and low alloy filler metal[5]. The vessel was tested extensively, and the properties easily exceeded those of SA-533 Grade B, Class 1, an alloy commonly used to build nuclear reactor pressure vessels. Babcock and Wilcox subsequently a developed computer-controlled welding cell for making components using GMAW and SAW similar to the robotic welding cells in use today. They demonstrated that large components could be manufactured completely out of weld metal and equal or exceed the properties of conventionally-made components, but welding was perceived as only for joining, so the concept was not accepted by industry.

3.0 Technical Aspects of Direct Energy Deposition Using Wire

Direct Energy Deposition Wire Additive Manufacturing (DED-WAM) using a heat source such as an arc to melt wire and deposit weld metal to create components is a continuation of yesterday's "Shape Welding." A welding head is attached to a robotic arm. The robot moves the welding head to deposit weld metal along a defined path, layer upon layer, to create near-net shape parts. Parts are usually mounted on a positioning device that synchronizes its motion with that of the robot to keep the weld in the flat position; the flat position is the easiest position to work in when it comes to making sound welds. Once a shape has been created, it can be nondestructively examined and machined to its final shape.

DED-WAM may use any welding process that melts the wire directly with an arc, such as Gas Metal Arc (GMAW) or Submerged Arc welding (SAW). It may also use processes where the energy that melts the wire is separate from the wire, such as Gas Tungsten Arc Welding (GTAW), Laser (LBW) or Electron Beam welding (EBW)[6]. These processes have been in use for decades, but mostly to join materials. DED-WAM, on the other hand, goes beyond joining parts. The process can be used to build entire components from a shape drawn on a computer. For large components, the benefits of DED-WAM are reduced production costs, reduced lead times, and an improvement in uniformity of the material, especially when compared to large castings and forgings.

4.0 Large Weld Metal Buildup Case Histories -- Non-nuclear Applications

The following case histories illustrate where weld metal has been used to build up components that were used in critical services and to manufacture new components entirely from weld metal. The weld metal is referred to simply as weld metal buildup in early projects and as DED-WAM buildups in later projects.

Case 1: Steam turbines

In the 1980s, the Elliott Company[7] developed a process for repairing high-pressure steam turbine shafts and disks damaged by fatigue or stress-corrosion. Elliott machined away damaged material and completely rebuilt many rotor disks entirely using weld metal. The rebuilt disks were then machined, and the blades reinstalled. Elliott reported that they had repaired some 300 rotors using weld metal before 1994 when the cited article was published.

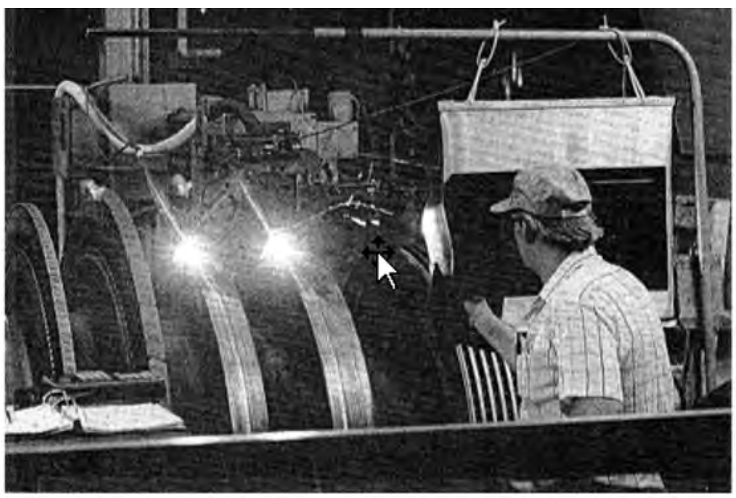
The repaired machines operated from 1200 to 6730 RPM, from 600°F to 950°F and at pressures from 290 psi to 1250 psi. Weld metal was deposited using the submerged arc welding process. The weld metal was typically a Ni-Cr-Mo-V low alloy steel that exhibited 110,000 psi tensile strength and 83,000 psi yield strength. Elliott reported that over 700 lbs. of weld metal was deposited on one of the rotors.

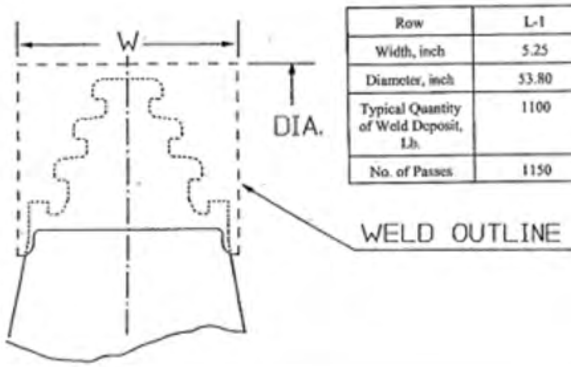
Case 2: Steam turbine coupling flange

Elliott Company also reported using weld metal to completely rebuild a fatigue-damaged coupling flange that was integral to a turbine shaft. The new flange was a medium carbon steel 25 inches outside diameter and 3-1/2 inches wide. Over 600 lbs. of weld metal were deposited to recreate the flange.

Case 3: Steam Turbines

An internal EPRI paper noted that beginning in 1984, Westinghouse Electric Company replaced with weld metal rotor steeples on the low-pressure disks of over 218 steam turbines[8]. The typical rotor material was ASTM A-470, a high-strength low alloy steel. The existing steeples were removed from the entire circumference of the disks by machining. After nondestructively verifying that the remaining material was sound, weld metal was added to restore the required dimensions(Figure 3). After volumetric examination, the weld metal was machined to restore the dove-tail mounting configuration, after which the blades were reinstalled.





Row	L-1	L-2
Width, inch	5.25	4.38
Diameter, inch	53.80	53.80
Typical Quantity of Weld Deposit, Lb.	1100	750
No. of Passes	1150	790

Figure 3. Turbine Rotor Reconstruction. The photo shows weld metal being added to the surface of a turbine rotor disk. The sketch shows a typical weld metal buildup and outline of the machined dovetail configuration that holds the turbine blades in place [(7).]

The paper noted that there were <u>3600 weld restorations</u> of 14 rows on 5 rotors for Public Service Company of Oklahoma (PSO), Northeastern 2, Houston Lighting and Power (HL&P), Cedar Bayou 2 and Cedar Bayou 3. Rotors and discs ranged from 50 to 100 inches in diameter. The weight of weld metal deposited ranged from 200 to 3800 pounds per disk. Most repair welds were made using machine Gas Tungsten Arc welding and a NiCrMoV type filler metal. This process produced rotors with mechanical properties that were better than the original rotor forgings properties, particularly with respect to fatigue. TVA successfully used a very high-performance filler metal, ER90S-B9,[9] to repair of several of their turbine disks.

Case 4: Insurance Company perspective on weld-repaired steam turbines rotors and disks

Starting in 1982, Hartford Steam Boiler Inspection and Insurance Company began a study on the insurability[10] of steam turbine rotors that had been repaired by welding. Prior to that, Hartford considered weld repaired turbine disks and rotors to be uninsurable. A Hartford team evaluated proposed repairs on a case-by-case basis. While the most common weld repair to a turbine rotor was bearing/journal buildup, the second-most common was disk rim steeple restoration similar to the repairs by Westinghouse in Case 3.

According to the Hartford report, between 1982 and 1993, approximately 450 steam turbine and 235 utility rotors were rebuilt using welding. Hartford has not reported a single failure of a rotor attributable to weld repair since the beginning of the program. The report also noted that welding was not only being used for repair work, but also to optimize the design and extend plant life. Hartford also reported using the same approach to both the hot and cold sections of land-based gas turbines. Finally, Hartford continues to insure turbines that have been repaired by welding.

Case 5: Offshore Oil Extraction Component

A high-strength steel water bushing (Figure 4) designed for 6000 psi pressure weighing 485 pounds and nearly 4 feet tall was manufactured by Vallourec, S.A. using DED wire additive manufacturing. It was installed on a rig in the North Sea in early 2021[11]. A water bushing is a safety device used to counter hydrocarbon overpressure pulses from wells while they are under construction.

This was a safety-critical component in the energy industry that was completely produced using DED wire arc additive manufacturing. Nondestructive examinations, metallurgical evaluation and heat treating were conducted to comply with stringent O&G specification. DED wire additive manufacturing of the bushing allowed Vallourec to optimize the design and cut the bushing’s weight by roughly one-half compared to conventional manufacturing technology.

In the 1980s, Hydrill had over 2000 castings and forgings that were rated for 15,000 psi, but to drill down to 20,000 feet, they needed to increase the pressure rating to 20,000 psi. This was done[12] by building up the thickness of using SAW and an 2-1/4 Cr 1Mo wire to build up as much as 2 inches in thickness on some tools. Others, including Cameron, Vetco and FMC, also used this approach to increase pressure ratings of their components. Over 500 tons of wire and 1,000 tons of flux were used, per year, for a three to four year period.

Figure 4. Water Bushing. A high-strength steel water bushing weighting 485 lbs. and nearly 4ft tall was manufactured using DED-WAM (wire). [10]

Case 6: Offshore Oil Extraction Component

In early 2021, Vallourec created two 385 lb. lifting plugs[13] using DED wire additive manufacturing for use on an offshore oil rig in the Timor Sea. The lifting plug is designed to lift a full drill string weighing over 100 tons (Figure 5). Lifting plugs are safety-critical components that form the junction between the rig elevator and the well pipes. They allow operators to handle and move long tubes in a safe and secure manner. Lifting plugs are traditionally made from forged thick-wall bar. By using wire additive manufacturing, Vallourec was able to increase the safety margin by increasing the diameter of the plug by 15% over what would have been possible using standard bar sizes.

Figure 5. A 385lb lifting plug that is designed to lift a full drill string of over 100-tons at an off-shore oil rig in the Timor Sea. The lifting plug was manufactured using DED-WAM (wire). [11]

Case 7: Shipboard fitting

The world's largest wire additive manufactured shipboard fitting, a 3,200 lb. Panama Chock[14], was produced to meet Keppel Technology & Innovation project-specific requirements. It was the first to receive a DNV verification certificate (Figure 6).

Traditionally manufactured as a casting, Panama Chock's are welded to the ship's deck and used for towing and mooring.

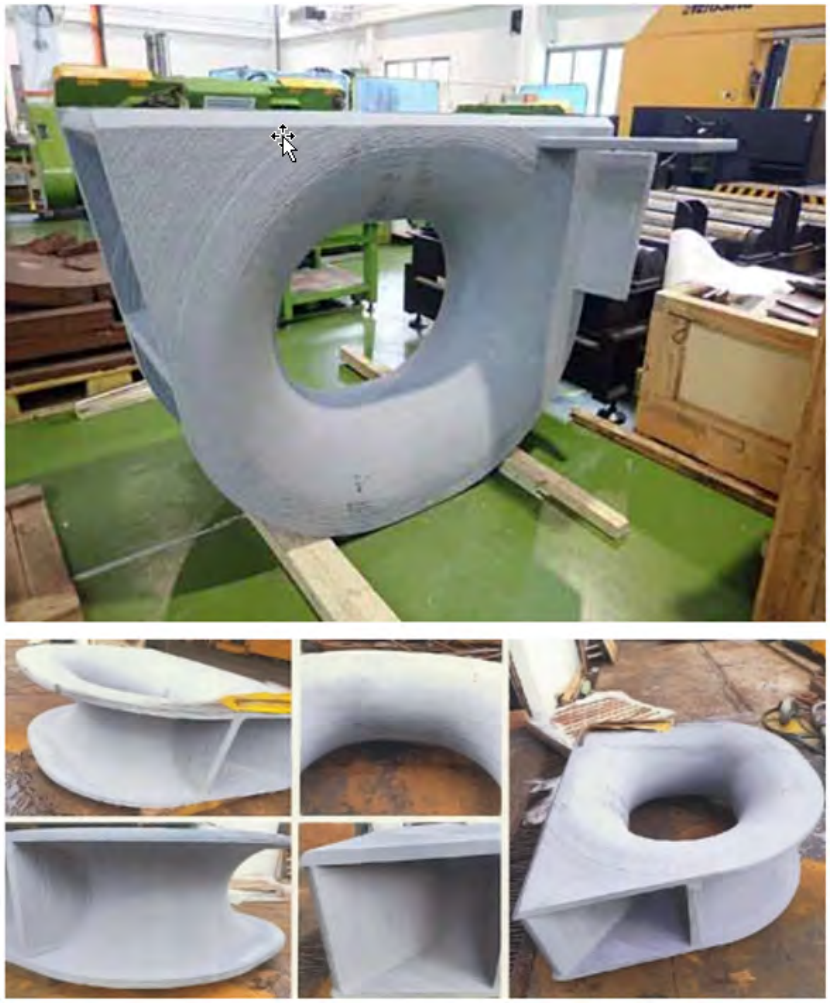


Figure 6. A 3200 lb. Panama Chock was manufactured using DED-WAM (wire). This part replaces a casting.[12]

Case 8: Lifting hooks

Global heavy equipment manufacturer Huisman produced four large-format crane hooks using DED-WAM[15]. They are designed to lift 350 metric tons. The hooks measure about 3 feet by 4 feet and weigh 3,800 lbs. (Figure 7). The hooks have been certified by Lloyd's Register and delivered to a client in the maritime industry.

Using DED wire additive manufacturing to produce the large-format parts allowed Huisman to manufacture the hooks with a consistent level of internal quality which is difficult to achieve when hooks are made by casting of forging.

Figure 7. A crane hook capable of lifting of 350 metric tons was manufactured entirely using DED-WAM. The hook measures 3ft by 4ft and weighs 3,800lbs. [13]

5.0 Large Weld Metal Buildup Case Histories -- Nuclear Applications

The above case histories described applications of weld metal buildups of rotors and disks in the power industry and also provided case histories from the oil extraction and shipping industries. This section provides several additional case histories of weld metal buildup where the technology has been used in nuclear industry applications.

Case 9: Acceptance of "Shape welding" by the German nuclear industry regulators.

In 1998, the German Nuclear Safety Standards Commission (KTA) allowed use of products and components manufactured using "shape welding"[16]. While "shape welding" was removed from the regulations in 2006, the use of weld metal buildup for repair welding is still allowed.

Case 10: Buildup of nozzle openings and flange surfaces by Siemens

While no components in operating nuclear plants were completely produced by "shape welding," shape welding was used by Siemens to build up of nozzle openings and flange surfaces in the Atucha 2 reactor vessel in Argentina[17] and likely in other reactors and steam generators that were built by Siemens. (Figure 8).

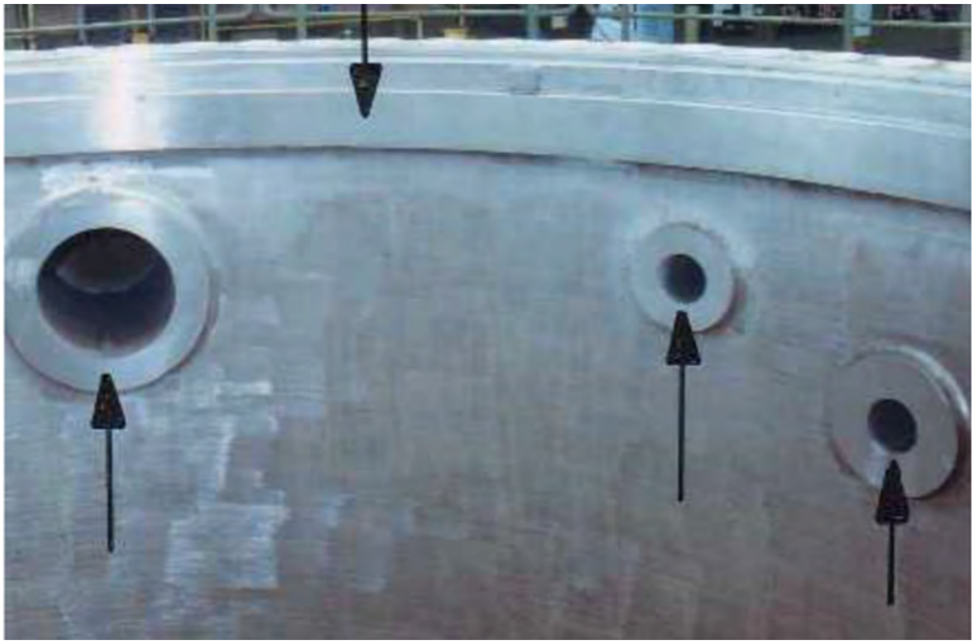


Figure 8. This photograph shows nozzle opening reinforcement and flange surfaces in the Atucha 2 reactor vessel in Argentina[17]. The circular features were created in place by Siemens using DED-WAM.

Case 11: Buildup of bottom heads of nuclear vessels to facilitate attachment of skirts.

Weld metal buildup was used extensively at Chicago Bridge and Iron (CB&I) in Memphis, TN when they were building GE BWR reactor vessels in the 1970s. To avoid having to buy a forged ring with an integrally forged skirt extension, CB&I[18] deposited weld build-up on the bottom head of each reactor vessel they built. They used the submerged arc welding process to produce a contoured cylindrical section; it took around 5 days running 2 shifts per day to complete the buildup on each vessel.

The weld buildup was machined to make a long-radius configuration at the intersection with the vessel to minimize thermal stresses which could be very high when ambient temperature water would be injected into the reactor during a SCRAM shutdown. The weld buildup transition is shown in Figure 9 at the red circle near the bottom of the vessel where the skirt is attached. The forged skirt was butt welded to that transition buildup near time of final assembly of the vessel.

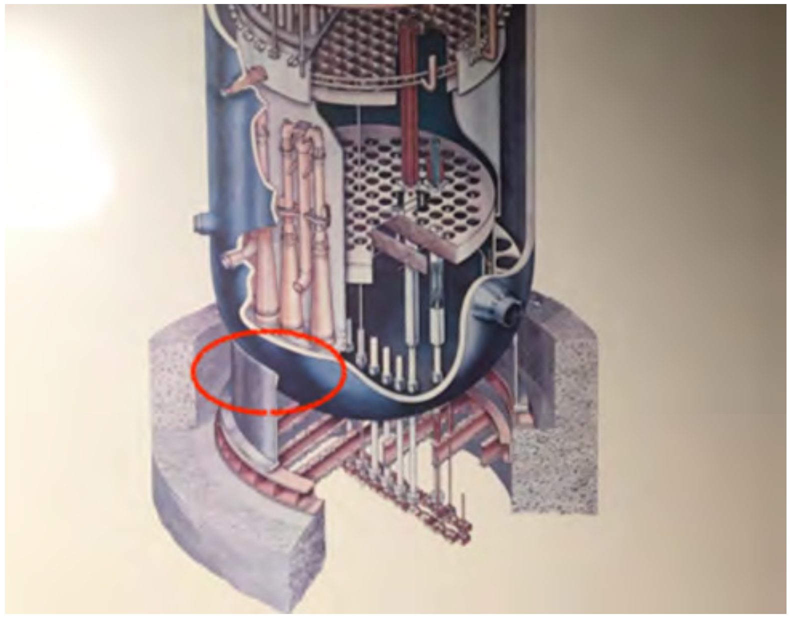


Figure 9. Lower one-half of a Boiling Water Reactor (BWR) Vessel[19]. DED-WAM was used to buildup a weld metal transition on the bottom head of the vessel where the skirt attaches to the head (depicted in the red oval). The buildup provided a smooth transition from the head to the skirt.[15]

Case 12: Buildup of anti-rotation lugs on reactor vessels and steam generators

Westinghouse Electric Company[20] has reported that they commonly attached anti-rotation key lugs to the interior shell wall of reactor vessels and steam generators. These lugs engage lugs on the wrapper to prevent wrapper from rotating. Previously lugs were manufactured from strips of thick plate that was welded to the internal shell wall. Today they are formed by depositing about 110 lbs. of weld metal approximately 18 inches long, 10 inches wide and 3 inches thick using submerged arc welding. The buildup is then machined to form the key. The use of weld metal buildup eliminated material availability issues and allowed more precise location of the keys since they were built in place. Also, the buildup can be more easily ultrasonically examined compared to a partial penetration groove weld.

Case 13: Installation of the steam generator partition plate

To install the steam generator partition plates, a 3-inch square bar 9-1/2 feet long made from Inconel was welded to the tubesheet face. After the weld was ultrasonically examined, the partition plate itself was welded to that bar. Grain orientation in the bar often made ultrasonic examination of that weld difficult. Today, approximately 200 lbs. of Inconel weld metal measuring 9-1/2 feet long, 3-1/2 inches wide and 1-5/8 -inches thick is deposited on the tubesheet. After the weld has been ultrasonically examined, it is machined to form the weld bevel and then welded to the partition plate.

Case 14: Buildup of handholes, inspection ports and flange surfaces on vessels

While the primary and secondary manways are integrally reinforced nozzles welded into the channel head and the upper shell, all handholes and inspection ports in Westinghouse vessels are formed by applying large weld buildups to the exterior surface of the shell followed by final machining to form the reinforced opening and bolted joint closure joints.

Case 15: Handholes and nozzle projections using weld metal

Babcock and Wilcox[21] routinely deposited large weld metal buildups using the submerged arc welding process to reinforce manways and nozzles on Section III vessels. A pilot hole was drilled into a vessel shell to center the rotating welding head. The equipment created a large doughnut-shaped weld buildup that was then machined to the required configuration. This approach was used to build carbon and low alloy steel handholes and reactor nozzle projections on commercial nuclear pressurizers, steam generators and heater bundles.

Case 16: Creation of an Inconel 600 elbow using weld metal

Because of the long lead times for forged high alloy elbows and safe ends, Babcock and Wilcox created at least one Inconel 600 elbow entirely out of weld metal[22]using GMAW. That elbow was NPS 12 or 14, 18 to 24 inches long and over 1 inch thick. Babcock and Wilcox followed up on the work done earlier in Germany and developed mainframe computer-controlled welding equipment that coordinated the motion of the workpiece with the motion of the welding torch in the mid-1980s[23]. They used SAW and synergic GMAW to create cylinders, cones, flanges elbows and dished heads and described the process as "Shape Melting." They also used real-time monitoring of the welding process parameters, vision systems to track bead alignment, interpass temperature monitoring and water spray to control interpass temperature. They built parts from many alloys but use a lot of Inconel 625 and showed that 625 parts made by "Shape Melting" had more uniform properties and exhibited more desirable properties than the same parts made by conventional processes. Unfortunately, as with the work by Kussmaul, Schooch and Luckow in Germany, the effort was never commercialized due to the assumption that welding was a joining process and had no application in the production of finished components.

Case 17: The US Navy permits weld metal buildup in ship construction.

The US Navy in NAVSEA Technical Publication T9074-AD-GIB-010/1688, Requirements for Fabrication, Welding, and Inspection of Submarine Structure dated 1 MAY 1997 permits weld metal buildup on ships. Section 13.9.3 says that correction of joint fit-up and surface or edge preparation to correct excessive root openings, the buildup on the two joint edges shall not exceed 2 inches in thickness. The entire weld buildup to correct oversized root openings may be applied to one joint edge.

NAVSEA Technical Publication S9074 -AR-GIB-O10/278, Requirements for Fabrication, Welding, and Inspection and Casting Inspection and Repair for Machinery, Piping and Pressure Vessels dated 1 August 1995, section 10.3.5.3 says that when buildup by welding to correct oversize root openings or errors in joint preparation is used, it shall not exceed the lesser of 1/2 inch or 1/2T where T is the thickness of the part being welded.

Case 18: Weld Metal Overlays in the US and Abroad

A compelling case showing the ubiquity of weld metal buildup in the nuclear industry is that over 800 weld metal overlays[24] have been installed on piping worldwide in the BWR fleet since the early 1980s. They have provided excellent service, effectively elimination stress-corrosion cracking issues in stainless steel piping. Over 300 weld overlays have been used in the PWR fleet since the early 2000s. Most of the overlays were in the US and associated with preventing or mitigating stress-corrosion cracking in stainless steel piping and pressurizer nozzles.

Weld metal overlays outside the US were used to repair pressurizer nozzles at Switzerland- Kernkraftwerk Leibstadt (KKL) nuclear plant (2012), Taiwan- Maanshan (2011), Brazil- Angra Unit 1

(2010) and South Korea- Kori Unit 1 (2009). More recently this technology has been extended to dozens nozzle-to-safe end welds where Alloy 52 weld metal has been applied as the overlay filler metal. The welding practices used include temper bead welding over the nozzle region as shown in Figure 10.

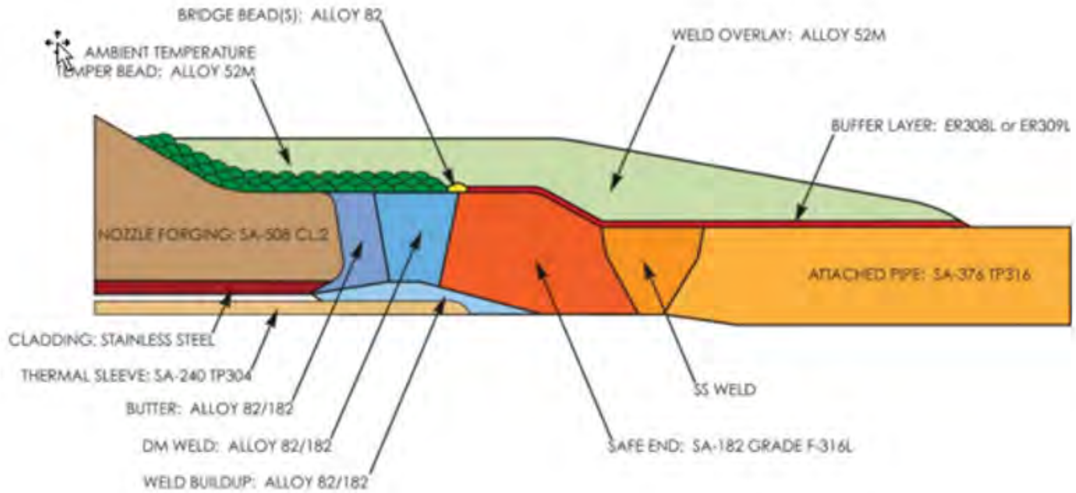


Figure 10. A weld overlay was applied to a nozzle-to-safe end weld to mitigate stress corrosion cracking[24].

Case 19: ASME Code Cases Permitting Weld Metal Buildup

The following ASME Section XI code cases that allow the use of weld metal buildup have been accepted by the NRC in Regulatory Guide 1.147 with no added restrictions.

- N-853 PWR Class 1 Primary Piping Alloy 600 Full Penetration Branch Connection Weld Metal Buildup for Material Susceptible to Primary Water Stress Corrosion Cracking
- N-740, Full Structural Dissimilar Metal Weld Overlay for Repair or Mitigation of Class 1, 2, and 3 Items.
- N-653, Full Structural Overlaid Wrought Austenitic Piping Welds
- N-661, Wall Thickness Restoration of Class 2 and 3 Carbon Steel Piping for Raw Water Service
- N-766, Nickel Alloy Reactor Coolant Inlay and Overlay for Mitigation of PWR Full Penetration Circumferential Nickel Alloy Dissimilar Metal Welds in Class 1 Items.

6.0 Comparison of Flaws in DED Wire Additive Manufactured Products to those in Plates, Forgings and Castings

Plates, forgings and castings are used in both structural and pressure retaining applications with little hesitation. Industry recognizes that these products can have flaws. To address their presence, materials specifications and construction standards impose requirements to identify and limit the size of those flaws so that these materials can be used safely and reliably. This section will look at flaws commonly found in plate, forgings and castings, and it will compare them to potential flaws that one would expect to find in DED-WAM components.

7.1 Comparison to Plate and Forgings

Plate and forged materials are anisotropic[25]. That is, if you orient tension or impact test specimens in different directions in a plate or forging, the results will be different. Metals develop fiber-like grain structure analogous to that of wood as they are deformed during rolling and forging operations. Grains get stretched in the same direction that the metal is stretched as it is formed. After forming is complete, the grains align with each other in one direction. As a result, the mechanical properties (strength, ductility, fatigue resistance and creep strength) are the best when loads are applied parallel to grain flow, i.e., parallel to the rolling or forging direction. While still adequate, the properties transverse to the direction of grain flow are always slightly lower, with the biggest differences occur in ductility and toughness.

Rolled and forged materials over 6 inches thick can exhibit large grains and segregation of elements at mid-wall if the reduction of thickness during forging or rolling is insufficient. Both conditions result in reduced strength and toughness midwall.

Rolled and forged product can have laps. Laps are surface irregularities that appear as linear defects and are caused by folding over of the hot metal at the surface during forming operations. While these folds are forced into the surface during subsequent operations so that the surface appears smooth and uniform, they can be peeled off the metal surface in a manner similar to a scab.

Rolled and forged products can have large inclusions caused by refractory materials breaking loose during pouring. These break up into small pieces during forging, but they do not go away.

Rolled and forged product can have hydrogen flakes. Flakes (or "fish-eyes") are internal fissures usually found in large forgings as cracks. They manifest themselves after an incubation period, and they are usually found middle third of the thickness. Hydrogen has some solubility in steel and is present during all steelmaking operations unless the steel was made under vacuum. While most of the hydrogen diffuses out of the steel on solidification, some is retained in the austenitic phase as the steel cools. This hydrogen will segregate to internal voids and inclusions resulting in pressure buildup leading to crack development. Since flakes appear after an incubation period, it is difficult to find them immediately after steel has been forged. Flakes can decrease the toughness and ductility of steel.

Bursts can occur in thick section forgings. With thick parts, high triaxial stresses can occur deep within a section as it is forged. If these stresses exceed the tensile strength of the material, they will tear it apart internally. This usually happens when the forging temperature is too high. Bursts are usually embedded deep in the material, making them difficult to detect. In contrast, grain flow in forgings can lead to false indications of flaws when doing ultrasonic examination of forgings.

Forgings can be overheated. The proper forging temperature will vary depending on the grade of steel involved and the extent of hot working that is to be performed. Hot working is carried out above the recrystallization temperature for the steel, and it is best to finish forging close to this temperature. Excessively high temperatures increase scale formation, and grain size. Large grains degrade the mechanical properties. Extreme overheating will cause incipient melting causing lower melting constituents to migrate to the grain boundaries. This condition severely impairs the mechanical properties. It is known as "burning" and is irreversible.

When designing pressure vessels, the stress a designer uses to calculate the minimum wall thickness is based on a fraction of the tensile or yield strength properties found in the Materials Specifications in ASME Section II, Parts A and B. Those specifications dictate not only the required properties, but they also specify that the tension, hardness and impact specimens be removed from a corner of the plate.

In 1968, the American Iron and Steel Institute (AISI) started a study of the variations of chemical compositions and tensile properties in steel plates. Over the next 6 years some 4500 samples were removed from plates made by multiple US and Canadian steelmakers. The data were analyzed statistically, and probability curves were created showing confidence level versus difference from the strength reported as the official test results taken at a plate corner. For a 70,000 psi tensile strength material, Figure 11 shows that probability that a tension test specimen taken at a location other than from a corner would be within 4,000 psi of a test taken from a corner is 99%. The probability of that test being within 2,000 psi of the corner value is only 73%. Conventional wisdom is that the properties of plate are uniform everywhere in the plate, but they are not, and industry accepts that without requiring additional testing. Materials made using DED with wire will have a similar distribution of properties.

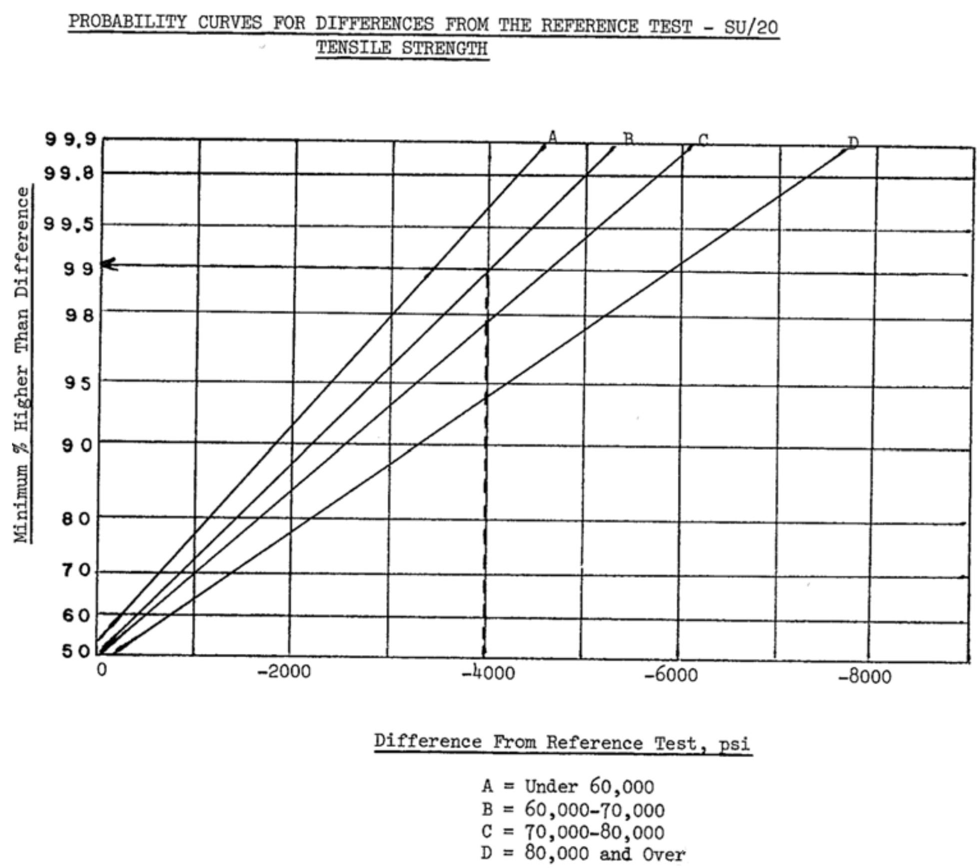


Figure 11. This chart[26] shows the confidence level that a tension test specimen removed from some location on a plate other than from the corner will have the same value found from one taken from the corner of the plate.

Material manufactured using wire melted with direct energy can be made into any of the shapes that can be produced using plate and forgings. The resulting material will be less isotropic than rolled or forged material. Thick sections made using wire melted with direct energy will more uniform in composition through their thickness and have more uniform grain size than plate or forgings, especially when compared to thick sections. This will make the material easier to ultrasonically examine and to easier to join to other materials.

While weld metal may have small slag inclusions and porosity, there is no concern for surface laps, hydrogen bursts, excessive grain growth or burning that can be present in forgings. While the mechanical properties of components manufactured using DED with wire are affected by cooling rate, the properties of a component created using DED and wire will have been demonstrated to meet specification requirements over a range of cooling rates during Section IX, QW-600 qualification of the welding procedure specification.

7.2 Comparison to Castings

Castings are made by filling a mold cavity with liquid metal. This develops a smooth skin through intimate contact with the mold surface. While simple in concept, flaws can be introduced into a casting.

If some of the liquid metal solidifies prematurely, other liquid will flow over it and create a cold lap. Where the molten metal fills a mold from several directions, advancing fronts can form a skin that gets entrapped as the fronts flow together. This will form a plane of weakness known as a "cold shut."

Inclusions in castings are intermetallic particles such as sulfides, oxides and silicates that are formed by chemical reactions between the atmosphere and the various alloying elements in the steel. Inclusions are usually small and do not cause a problem except when they segregate to one place such as the centerline of a casting.

Exogenous inclusions result from accidental entrapment of foreign matter during pouring. These vary widely in size and type and include dross, slag and flux residues, formed and separated in the melting furnace but carried over with the metal stream during pouring.

Molten metal has a much higher solubility of gas than the solid metal. Gas dissolved in liquid metal is ejected from the liquid as the liquid cools; however, it can get trapped, forming pores. Turbulence within the liquid metal stream as it is poured into the mold can aspirate air that may not have time to rise to the surface and escape prior to solidification. Porosity is easily detected by radiography and ultrasonic examination.

When molten metal is poured into a mold, it solidifies, and contracts. The outer surfaces solidify first and become rigid while the center of a section may remain molten. As the liquid in the center solidifies and cools, it contracts, and more liquid has to be supplied to the casting centerline, otherwise a centerline shrinkage crack will be formed. Gates and risers are used to supply that liquid; sizing them and locating them effectively is an art. Since pouring temperature influences the effectiveness of gates and risers, they are not always fully effective in eliminating shrinkage cracks.

Hot tears are created when sufficient liquid is provided to prevent shrink cracks, but uniform contraction during cooling elsewhere in the casting is prevented by the geometry of the product. This happens where thin and thick sections intersect. Hot tearing is also driven by segregation of certain elements and impurities during solidification.

During solidification some elements will segregate creating gradients of composition within grains. Impurities will collect at the solid/liquid interface as the metal solidifies. This will cause properties to be non-uniform and lead to local differences in composition that may cause corrosion problems and embrittlement.

Castings will have large grains. While castings with large grains can be radiographed effectively, ultrasonic examination is not reliable since large grains absorb and deflect echoes from flaws before they can get back to the transducer; this will leave flaws undetected. This is a big problem with high alloy materials like stainless steel and nickel alloys, especially for inservice inspections where radiography cannot be used.

Casting properties on production parts are measured based on testing of keel blocks that are cast simultaneously with the casting. While the properties measured using keel blocks are accepted as representative of the casting itself, a keel block does not have the same cooling rates as the castings themselves. Thermal mass affects the cooling rate, and the cooling rate of a keel block will be different from some areas of a casting; this can lead to the properties in the casting being different from the properties of the steel in the keel block, especially with alloyed steels.

Finally, many cast valves used in high-temperature and nuclear applications are examined by radiography. The acceptance criteria for those radiographs typically allow flaws that are much larger than the flaws that are permitted for the welds joining the valve to the piping. Valves used in today's nuclear plants were repaired by welding extensively. In my personal experience, it was not uncommon for 25% of the volume of a valve casting to be weld metal.

Like castings, components of any shape can be manufactured using wire melted with direct energy. DED wire added weld metal will be much more uniform in composition than the same composition metal poured into a casting mold. It will have small grains, making effective ultrasonic examination possible, even for stainless steel made by DED wire. The mechanical properties of components manufactured using DED with wire are affected by cooling rate, the properties of a part created using DED using wire will have been demonstrated to meet specification requirements over a range of cooling rates during Section IX QW-600 qualification of the welding procedure specification. While the range of cooling rates (and resulting properties) in a casting can be very large, the range of cooling rates with DED wire are comparatively narrow, resulting in more uniform properties in the part.

8.0 ASME Code and Weld Metal

Since it was first published in 1914, the *ASME Boiler and Pressure Vessel Code* has depended on ASTM standards to specify the properties of materials used in Code construction. The ASTM standards for materials that ASME Section II committee has approved have defined chemical composition, defined mechanical properties, defined heat treatment and defined testing of heats and lots of material by the steelmaker. Based on those properties that have confirmed by heat and lot testing, ASME assigned allowable stresses to those materials. When design temperatures increased to where creep was a concern, researchers ran 100,000-hour creep-rupture tests to establish allowable stresses for use where creep was a factor. Weld metal was similarly tested to verify that its performance was comparable to wrought product, but data for weld metal was never formally submitted to ASME for the purpose of assigning allowable stresses.

Weld metal has always been assumed to have the same properties as the base metals it held together. What about joint efficiency factors? They affect the allowable stress a designer can use and depended on the extent of examination of welds, not on the properties of the weld metal What about "weld strength reduction factors (WSRFs)" for creep strength-enhanced ferritic steels? Those factors compensate for the loss of creep strength in the heat-affected zone (HAZ) of the castings, forgings, plate or pipe that were being joined; they have nothing to do with weld metal properties.

What do ASME Codes specify when it comes to weld metal? ASME Section I says:

> PW-5.4 Welding electrodes and filler metal shall be selected to provide deposited weld metal of chemical composition and mechanical properties compatible with the materials to be joined and the service conditions anticipated.

Subsequent paragraphs specify restrictions on carbon content and Ni+Mn when welding Grade 91, but nothing else.

Section III, NX-2400, requires the room temperature mechanical properties of the weld metal to be equal to that of the base metals to be welded. Section III requires testing of each heat and lot of welding consumables to verify those properties. It specifies nothing regarding the composition of weld metal.

Section VIII provide nonmandatory guidance in UW-6 for the selection of welding filler metals. It makes the manufacturer of the vessel responsible for selecting appropriate filler metals but requires the user to require using a specific filler metal when necessary to achieve satisfactory vessel performance for the intended service conditions. UW-6 goes on to provide general guidelines that the strength and composition of the weld metal should match that of the base metals to be welded.

The B31 Code sections specify default filler metal requirements by requiring that the weld metal strength and nominal chemical composition match that of the base metals to be welded, but also allow the designer to specify other filler metals.

In short, the expectation of the ASME BPV Code and B31 Code is that weld metal room temperature mechanical properties and its nominal composition match that of the base metals to be welded. Except for low-temperature service, the only testing required is two tension and four bend tests conducted at room temperature. That is all that is required for weld metal to be used *not only at ambient temperature, but also in the creep regime*. There are millions of butt and socket welds that have been made as described above that are providing safe and reliable service -- and have been doing so for decades. Essentially all “weld failures” reported in high temperature service are *failures in the heat affected zone* (Type IV failures). Parts made from weld metal are not susceptible to Type IV failure.

Weld metal buildup has been used in ASME code construction extensively for the last 60 years. While those who were responsible for products that used weld metal buildup were careful to be sure that the properties of those buildups were suitable for the service, a test coupon 1-1/2 inches thick that has had two tension tests and four bend tests performed on it is all that is required by ASME Code to deposit weld metal buildup up to 8 inches (200 mm) thick of unlimited length and width. I note that this is all that is required for pump and valve casting repairs; some castings are over 25% weld metal. I also note that there are thousands of welds out there made using the same processes that will be used for DED-WAM that are operating successfully in both the time-independent and time dependent (creep) regime.

Now that industry wants to manufacture entire components from weld metal without the presence of base metals of known properties, designers need to know the properties of weld metal. The properties of a given composition weld metal depends not only on its chemical composition but also on how it is deposited – Heat input, base metal thickness, preheat and interpass temperature, transfer mode, bead size and shape –all affect the properties of the weld metal.

8.0 Section IX Requirements for Qualification of DED-WAM Material Manufacturing

Weld metal can be stacked up one bead on top of another to form a thin wall. It can also be deposited with many beads next to each other as well as on top of each other to form a thick wall. The properties of thick walls will be different from those of thin walls due to cooling rates and interbead tempering. The welding procedure qualification process specified by ASME Section IX uses the number of weld beads across a layer in test pieces to determine the number of beads across a layer qualified, and the width of the test piece determines the maximum width qualified.

Cooling rate is also controlled by the base metal temperature and the heat input as measured by volts, amps and travel speed. The Section IX qualification process requires testing weld metal that was deposited at a high cooling rate (lowest welding interpass temperature with lowest the heat input) and at a low cooling rate (highest welding interpass temperature with the highest heat input). By doing bracketed qualification testing for each thickness range, the properties of the weld metal deposited at extreme conditions will be demonstrated as being adequate, allowing the welding procedure to specify volts, amps, travel speed and interpass temperature that will produce weld metal of proven properties.

DED-WAM parts are commonly created by adding weld metal to a “sacrificial backing plate” that is removed after the part is built. Weld metal can also be deposited directly on wrought, cast or forged components and left in place. For example, an outlet nozzle could be built directly on a vessel shell the same way that reinforcing material is currently being deposited. The qualification process requires testing of the DED-WAM weld metal itself and it also requires testing at the weld metal/base metal interface when DED-WAM material will be deposited directly on production parts.

By testing thin and thick sections at both high and low cooling rates, the properties of the weld metal become predictable and can be used for design purposes. By doing the same testing at the DED/Base metal interface, the properties at the interface are tested more extensively than welds joining parts have been qualified for decades under Section IX rules.

After establishing the mechanical properties of the DED-WAM build, the designer can compare those properties to wrought, cast or forged specifications such as SA-516 70 or SA-452 TP316H and use the allowable stress and other properties of those specifications as a basis for design.

9.0 Directed Energy Deposition-Wire Additive Manufacturing (DED-WAM) differs from Laser and Electron Beam Powder Bed Fusion (PBF) Additive Manufacturing Processes.

When using DED-WAM, the wire is fully melted to create a shape. The properties of weld metal made using traditional materials conforming to industry accepted filler metal specifications are well known. Typical layers of weld metal are about 3 mm thick. While there may be flaws in the weld metal, those flaws are readily detected by traditional ultrasonic or radiographic examination methods and evaluated using established acceptance criteria.

ASME has published criteria for Laser and Electron Beam Powder Bed Fusion (PBF) additive manufacturing process in ASME PTB-13-2021: *Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing*. In BPF metal powder is fused using either a laser or electron beam energy source and deposited in layers that are 50 to 100 μm thick. The PBF process takes place in a sealed build chamber that is filled with an inert gas such as argon when using a laser or under is under a vacuum when using an electron-beam. The energy source selectively melts specified areas of the powder in a prescribed geometry conforming to the component being manufactured. Additional layers are deposited and fused until the part is completed. The size of a part that can be made is limited to the size of the chamber, whereas the size of what can be built using DED WAM is unlimited.

With PBF, powders can be partially melted and still create a shape. Because layers are thin compared to DED-WAM deposits, flaws in PBF metal are characteristically very small and widely scattered, making detecting them challenging with traditional ultrasonic or radiographic examination methods. The acceptance criteria for such flaws have to be specified by the product designer.

Control of material properties for PBF is the same as with any welding process. Understanding the effect of the cooling rates in the build chamber is required to produce acceptable material. The control on heat input and cooling rate is somewhat more complex because the build chamber can contain multiple energy sources that overlap to produce a single part.

10.0 Summary and Conclusions

Tons of weld metal have been deposited over the past 100 years using “weld metal buildup” in critical structural and pressure-retaining applications. More recently, the term “weld metal buildup” has taken on a new name—additive manufacturing -- where weld metal is added directly to a component or a component can be built entirely from weld metal.

The following summarize the key takeaways from this White Paper discussion on DED-WAM or weld metal buildup whichever you choose to refer to it as:

Weld metal deposited by conventional welding processes using wire for filler metal has a long history of successful performance in industry both in joining metal components together and as weld metal buildups.

- Replacing welders with “computer controlled” robotic welding provides the manufacturer greater control and reliability versus depending on a person making welds manually or running a machine that does the welding.
- There are hundreds of applications where weld metal buildup has been used successfully to change the dimensions of a part and to rework components using weld metal of modified composition to extend component life.
- The properties of weld metal are predictable with high confidence. The new ASME Section IX QW-600 rules for qualification of DED-WAM requires the manufacturer to show that properties required by the designer will be achieved for all welding parameters that the manufacturer will use in production.
- DED-WAM has been used successfully for decades to repair and build up nozzles, lugs, reinforcement pads, transition pieces between members and for rotating equipment where the stresses are high and there is cyclic loading.
- Components built with DED-WAM have more uniform composition, mechanical properties and soundness than when made using castings, forgings, plate or assemblies. This is especially true when there are thick sections
- Parts made by DED-WAM using wire can be examined by radiographic and ultrasonic methods in a similar manner as forgings and castings, and in some cases, more reliably.
- Industry worldwide is moving forward with replacing many forgings and castings with components built entirely out of weld metal.

Creating components and adding material to components using DED-WAM with wire has been used in both heavy industry and the nuclear industry for decades. While this process has a flashy new name -- Additive Manufacturing -- the process uses weld metal buildup similar to that we have been using for the last 100 years.

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Walter J. Sperko

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