Field Welding Repair of Heavy Equipment

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Welding repairs of heavy equipment in the field can vary in levels of success. This can be due to the high strength steels used in the manufacture of heavy equipment implements that require special metallurgical considerations. Repair difficulties can be further compounded by the limitations of tooling typically found on a construction site and schedule commitments. Overloading or excessive impacts can cause damage to the bucket teeth of an excavator or bulldozer rippers. A shop could perform a proper repair but that increases cost and takes precious time. A successful repair of these items done out in the field can reduce downtime and improve productivity. This project will attempt to develop a welding procedure that can be done in the field to successfully repair such damage. Considerations will be given for tooling that can typically be found on the construction site and skills familiar to a contractor or operating engineer. Using the structural steel welding code as a guide, different welding procedures will be compared for their ability to successfully weld high strength steels like that found on heavy equipment. Equipped with this welding recipe, anyone who can weld would be able to make a successful repair.

Keywords: Heavy Equipment repair, welding repair, ASTM A514, AISI 4140, weld procedure

Introduction

Catastrophic structural damage to a heavy equipment's implements can happen due to excessive loading or unnecessary impacts and subsequently remove equipment from service. A hasty repair in the field can have questionable results with many suggesting that such repairs are futile. The manufacture of this equipment most likely involves detailed welding procedures, induction heat treatment or other forms of heat treatment best done in a shop environment. However, removing equipment from service for shop repairs can be costly and detrimental to schedules. It is therefore understandable that a capable contractor or operating engineer would want to attempt a welding repair in the field to get the equipment back in service. This project will experiment with different weld procedures, on similar steels used in the equipment's manufacture, that could be implemented in the field to improve the success of such a welding repair. Considering heat treating equipment is limited in the field, this project will examine techniques that could be done in the field with readily available construction tools. This project will examine the performance of weld samples prepared with no heat treatment considerations, a weld preheated that could be done on site with something like an oxy-fuel torch, and a weld that has an altered weld bead progression.

High strength steels are a necessity in the construction of heavy equipment and their implements. The demand placed on their components must be able to withstand high impact and abrasion. A typical low carbon steel, such as A36 structural steel, would most likely not be sufficient to deliver the needed performance expected of today's equipment. Hensley Industries, who manufactures ground engaging tools for industries such as excavation and mining, suggest that the possible steels used in the manufacture of equipment buckets include: ASTM 514 (T1), Bisalloy 80, Weldox 100, or 400 BHN Abrasion Resistant Steel-Hardox 400 (Hensley Industries, Inc., 2019). They are, however, silent on the steel composition of their teeth adapters. Bucket teeth and other earth cutting edges are most likely made from a high manganese steel due to their excellent hardness and wear properties. It has been suggested that AISI 4140 can also perform well as a bucket tooth material (Herbirowo, S, Syahrum, M, Hasbi, M Y, Chandra, S A, Ridlo, F M, & Adjiantoro, B, 2019; Suryo, S. Hadi, Bayuseno, A.P., Jamari, J., Ramadhan ,Muhammad Arief Rahmat, 2018). For this project, ASTM A514 will be used to represent the bucket walls and AISI 4140 will be used to represent the teeth. Both of these steels are readily available on the commercial market in plate form compared to that of high manganese steels. 4140 will exhibit many of the same problems that welding similar hardenable high carbon steels would create. The project will also infer that the bucket construction is such that the hard tooth is welded directly to the bucket so that two different types of steel will be welded to each other.

Literature Review

The welding of some carbon steels can be a precarious proposition due to the formation of specific microstructures within the steel. In low carbon steels, after solidification of a weld and the base metal, the microstructures of pearlite, cementite and ferrite will exist. In higher carbon steels the formation of the brittle microstructure of martensite can be of concern (Callister,2000, p. 357). Martensite formation is typically a concern in steels with over a .4% carbon equivalency content (Bhadeshia, Honeycombe, 2017, p. 387) Another concern in higher carbon steel with alloy elements of manganese, chromium and molybdenum is Widmanstatten structure. Overheating can cause grain growth and subsequently brittle fracture along grain boundaries vice a ductile failure through the grain boundaries (Neely, 1979, p. 224).

Martensite is a microstructure of great concern in carbon steels. This microstructure is very brittle and has little to no ductility (Callister, 2000). It is possible to create tempered martensite thorough the tempering of steels containing martensite. Tempered martensite consists of ferrite matrix with uniformly dispersed cementite particles. (Callister,2000, p. 318). This increases the ductility of the steel while maintain its strength (Bhadeshia and Honeycombe, 2017, p. 237). Raising the steel with martensite to 480-1200° F can allow a diffusion process to form tempered martensite (Callister,2000, p. 318).

Preheat, interpass control and post-weld heat treatment (PWHT) are all tools commonly employed to successfully weld carbon steels. Preheat is the application of heat to the base metals prior to the initiation of welding. The most important use of preheat is to reduce the cooling rate of the metal (The James F. Lincoln Arc Welding Foundation, 2000, p. 3.3-1). The temperature differential between the metal and the weld deposit will be lower and therefore heat will be drawn out of the weld area slower with a lower differential temperature. A slower cooling can reduce the formation of martensite in the heat affected zone (HAZ) of the weld. In the same way, a minimum interpass temperature could be delineated in a weld procedure. On thicker or larger materials, the temperature of the material could fall below the minimum preheat temperature in between consecutive weld passes and might require reheating. Implementing interpass control ensures the part is reheated as needed by external means in-between weld passes. A maximum interpass temperature could also be specified between weld passes as to help limit grain growth within the base metals. This prevents the part from overheating due to the rapid heat input consecutive weld beads can create. If grain growth is excessive, a PWHT of normalizing can be used to refine the grains (Neely, 1979, p. 247). PWHT can also be used to relieve residual stresses in the weld.

Destructive testing of materials and weldments can provide valuable information for the mechanical performance of selected samples. One test is a tensile test in which the sample is stressed in tension until failure. This can provide an Ultimate Tensile Strength (UTS). Along with UTS tensile tests can also give us a measure of ductility by determining percent elongation and percent reduction in area (Callister, 2000, p. 128). Reduction in area is a measure of the sample's cross-sectional area prior to testing and after failure. Elongation is a change in the samples length from before testing to after failure of the sample. A Charpy V-notch (CVN) is an impact test to measure the amount of energy a sample can absorb. A notch is intentionally machined in the sample to induce a stress point and then struck with a hammer with intentions to fracture the sample. This test is a rapid loading situation compared to that of the slower tensile test. Results from Charpy V-notch testing are qualitive and are used more for comparison purposes (Callister, 2000, p. 205).

AISI 4140 is a common low-alloy steel used in applications like crankshafts, connecting rods, axle shafts and gears. The AISI 41XX designation of this steel indicates a chromium content of .8-1.15% and Molybdenum content of .15-.25% (Callister, 2000, p. 360). 4140 is commonly referred to as a "Chromoly" steel due to this content. The addition of both chromium and molybdenum contribute to the hardenability of steel (Bhadeshia and Honeycombe, 2017, p. 227). Among other alloying elements, 4140 also has a typical manganese content of .75-1% (The James F. Lincoln Arc Welding Foundation, 2000, p. 16.1-63). In its annealed state, 4140 has a typical UTS of 95 ksi with 25.7% elongation and 250 ksi with 11.5% elongation in its quenched and tempered state (Callister, 2000, p.797). 4140 is not recommended for production welding due to its hardenability. Typical preheat and interpass for 4140 when it is welded is 400-500°F (The James F. Lincoln Arc Welding Foundation, 2000, 6.1-29).

ASTM A514 is a High Strength Low Alloy (HSLA) steel. It is used as a structural steel in its plate form (American Institute of Steel Construction, 2005, p. 16.1-6) and is also used in cranes and other heavy equipment. Depending on grade, A514's ultimate tensile strength ranges from 100 to 130 ksi with yield strength from 90-100 ksi (The James F. Lincoln Arc Welding Foundation, 2000, p. 6.1-17). The use of low hydrogen electrodes is recommended for the welding of A514 with E11018-M electrodes being recommend to achieve similar mechanical properties of A514. E12018-M electrodes are recommended for thin sections used in guided bend test (ArcelorMittal USA, 2006, p. 3). Unlike many other steels, A514 does not benefit from a slow cooling and the HAZ becomes harder but maintains ductility (ArcelorMittal USA, 2006, p. 6). Excessive preheat, interpass and heat input from welding can cause undesirable metallurgical changes in A514 and is therefore important to limit these. According to ArcelorMittal, minimum preheat for plate up to and including .5" is only 50°F to achieve published tensile properties and 100°F minimum for minimum Brinell hardness. They also suggest a maximum preheat and interpass temperature of 400°F of plates up to 1.5" and 450°F for plates over 1.5" thick. (ArcelorMittal USA, 2006, p. 6). Furthermore, it is suggested that A514 not undergo any PWHT due to a possible reduction in toughness and increase in stress-rupture cracking (ArcelorMittal USA, 2006, p. 11).

One strategy to weld high strength steels is the use of tempering or annealing beads. This technique is recommended by Hensley Industries for fillet welds at the toes of the weld (Hensley Industries, Inc., 2019). These beads are intended to temper the HAZ, but they are not part of the actual weldment and must be ground back off at the end. Silva, de Albuquerque, Moura, Aguiar, and Farias (2009) have discussed field repairs of 4140 and suggest two possibilities exist called half bead and two layer techniques. The half bead technique involves grinding back each progressive layer as to help retemper the previous HAZ due to heat input from the next weld layer. The two layer technique is similar in that the second layer is intended to reheat the HAZ of the first layer. They also note that the half bead technique can be problematic in that how much is ground off from each layer could be hard to determine and the amount of time this process takes (Silva et al., 2009). Similar to 4140, the lower carbon content AISI 4130 Chromoly has been discussed for its weldability to A514. According to Penton's Welding Magazine, a preheat temperature of 400° F is to be used in order to comprise for the minimum preheat of 450-500°F for 4130 and the maximum preheat temperature of 400° F for A514 (Welding 4130 steel to T1, 2008).

Methodology

Hypothesis

In order to improve the performance of 4140 welded to A514, the concern of martensite formation in the HAZ must be addressed. 4140 would create the most concern of these two metals due to its high carbon content and deep hardening characteristics induced by the presence of chromium and molybdenum. A "buttering technique", similar to that of the before mentioned two layer technique, that changes weld bead progression will help retemper the heat affected zone. Each base metal will have the grove face beaded with welds prior to full weld out of the joint. This retempering will improve mechanical performance of the weld over similar welds that used no preheat, interpass or PWHT.

Prediction

It is predicted that the "buttering technique" will result in a weld sample with similar mechanical properties to that of 4140 in the annealed state. Instead of a conventional weld bead layering, the change in weld bead progression will reheat the HAZ of the "butter" welds and have a tempering effect. A weld sample prepared with no preheat, interpass or PWHT will exhibit very brittle characteristics due to the relatively rapid cooling of the HAZ. A sample prepared with some preheat will slow the cooling rate and improve the mechanical properties. Therefore the "buttered" samples will produce the best results and stand in sharp contrast to a sample that has no preheat, interpass control or PWHT. The sample with only preheat will perform somewhere in between the two previously mentioned procedures. It is also predicted that the failures will produce themselves most notably in the 4140 side of the weld samples.

Testing

Three different welding procedures will be compared for their mechanical properties. The Structural Welding Code AWS D1.1-96 will be used as a guideline of evaluating these different procedures. It should be noted that the 1996 welding code is not the newest revision but was newest version of the code available within the CSU+ system. Due to budget and time constraints, there were deviations made from qualifying a welding procedure specification (WPS) per the code. These include: no radiographic (RT) or ultrasonic (UT) testing, smaller than required test plates and welder's qualification out of periodicity.

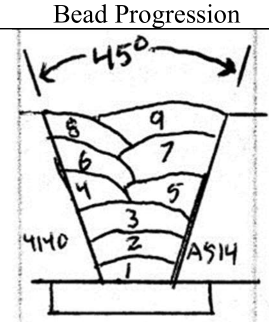
As stated above, the materials of concern will be AISI 4140 and ASTM A514. The 4140 was sourced as .375"x4" annealed cold drawn flat bar. The A514 was sourced from a .375" thick plate. 4140 was chosen as the backing bar due to cost and availability. The backing bar was .25"x1" annealed cold drawn flat bar. The electrode that was chosen is E11018M H4R in 1/8" diameter. This low hydrogen shielded metal arc welding (SMAW) electrode is recommended by ArcelorMittal as well D1.1 for the welding of A514 (ArcelorMittal USA, 2006, p. 3; American Welding Society. Committee on Structural Welding (AWS), 1996*,* p. 340). Lincoln Electric also specifies their Excalibur 11018M MR electrode for use with steels such as A514, A517 and A709. The as welded result performance for 11018M H4R of 111-117 ksi will also overmatch the performance of 4140 in the annealed state (The Lincoln Electric Company, n.d.). Lincoln Electric's Excalibur 11018M MR in 1/8" diameter was also easily sourced in a 10 pound. can at a local welding supply shop.

The test plates for each weld procedure were constructed of two .375"x4"X14" plates, one plate being of 4140 and the other being of A514. A 16" long piece of .25"x1" 4140 was used as a backing bar to provide 1" run off tabs on both ends of the weld joint. The joint is a complete joint penetration single V-groove butt weld with a 45° groove angle. Similar to the Joint Designation B-U2a called out in D1.1(AWS, 1996, p. 78). The 4" wide plates were chosen to give a minimum of 8" long test specimens for guided bend tests and tensile specimens. The 14" length will allow for 4 guided bend test samples, 2 tensile pull samples, a center section for Charpy V-notch samples and enough material for discard sections on each end of the test plate. After welding the plates were processed for sample preparation. It was chosen to use a bandsaw with spray coolant to minimize the effect of heat from something like an oxy-fuel torch or abrasive cutoff wheel. The resulting guided bend samples were ~8" long by 1.5" wide. Two were used for "face" bends and two for "root" bends. Each test plate also produced two tensile test samples. These dog bone shaped samples were 1.25" at the widest sections with the reduced section being .75" wide. The reduced section was 2.25" long with .5" radii from the wide section to the reduced section. Finally, a total of eight Charpy V-notch samples were taken from two separate test plates to compare the different welding procedures. The samples were of substandard size due to the plate only being .375" thick. The resulting size bars were 7.5mmX10mmX55mm. The bars were polished and etched with "Naval Jelly" to revel the weld deposit, base metal and HAZ. From each plate, two samples had the notch placed in the HAZ of the 4140 side and the other two samples had the notch placed in the HAZ of the A514 side for a total of 4 samples from each plate.

Test plate labeled “XA” was welded from an ambient temperature state. No preheat, interpass control or PWHT was used for the assembly of this plate. After all welds were in place the plate was allowed to air cool. The ambient temperature of the steel prior to welding was measured at 60°F and a root opening of .25” was used. Only nine passes were needed to produce satisfactory weld reinforcement as can be seen in Table 1.

Table 1

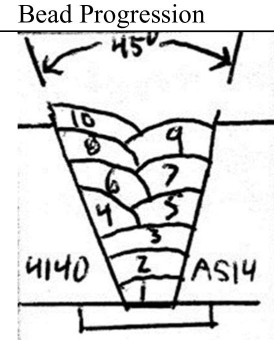
Procedure XA

		Filler Metals		Current		
Pass	Process	Class	Diam	Polarity	Amps	Bead Progression
1-3	SMAW	E11018M H4R	1/8"	DECP	118	
4-9	SMAW	E11018M H4R	1/8"	DCEP	116	

Test plate “XB” was preheated to 180°F as measured by an infrared thermometer just prior to the initiation of welding. No interpass minimum or maximums were maintained during assembly. A .25” root opening was used and the plate was allowed to air cool to ambient. Ten passes were need for satisfactory assembly as noted in Table 2.

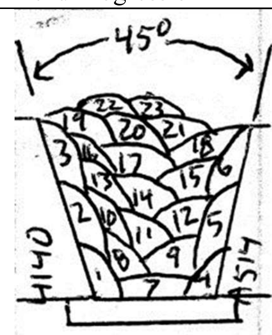
Table 2

Procedure XB

		Filler Metals		Current		
Pass	Process	Class	Diam	Polarity	Amps	Bead Progression
1	SMAW	E11018M H4R	1/8"	DECP	118	
2-4	SMAW	E11018M H4R	1/8"	DCEP	116	
5-10	SMAW	E11018M H4R	1/8"	DCEP	114	

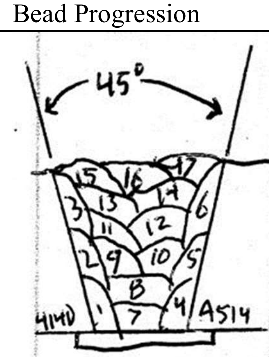
“XC” was assembled using the “buttering” technique. After the assembly was tacked together three consecutive weld beads were placed on the groove face of the 4140 side, followed by three more consecutive weld beads on the A514. These account for the “butter” welds. From there a conventional weld bead progression was used. To allow for the thickness of the “butter” welds a rather large .75” root opening was used. This large root opening resulted in the need for a total of 23 passes as noted in Table 3. This resulted in a large weld area.

Table 3
Procedure XC

Pass	Process	Filler Metals Class	Diam	Current Polarity	Amps	Bead Progression
1-4	SMAW	E11018M H4R	1/8"	DECP	116	
5-23	SMAW	E11018M H4R	1/8"	DCEP	114	

"XD" was prepared similar to that of "XC" only with a smaller .625" root opening being used. This resulted in the need for only 17 weld passes and a smaller weld area compared to that of "XC" as seen in Table 4. This "buttering" procedure was repeated twice due to the availability of extra material.

Table 4
Procedure XD

Pass	Process	Filler Metals Class	Diam	Current Polarity	Amps	Bead Progression
1-8	SMAW	E11018M H4R	1/8"	DECP	116	
9-17	SMAW	E11018M H4R	1/8"	DCEP	114	

Results

Guided Bend Tests

Guided bend tests were done with a roller-equipped bend test jig using 2.5" rollers to match the >90 ksi steels and filler metal per AWS D1.1. XA failed with brittle fracture directly adjacent to the weld on the 4140 side in 3 of the samples. These three samples also show very little deformation in the base metals. All ductility seems to have taken place within the weld area and the sample simply hinged in the weld prior to fracture. One root bend shows some deformation in the base metal but then fractured ~2” away from the weld in the 4140 before making fully though the bender as can be seen in Figure 1. The weld area of these samples would have passed as discontinues are <.375”.

Figure 1. Profile view of procedure “XA” guided bend tests

“XB” showed similar failures to that seen in “XA.” The two face bend specimens have a fracture adjacent to the weld in the 4140 side with little to no deformation in the base metals. The root bends show more deformation in the base metals but still fractured in the 4140 side ~2” from the weld before making it fully through the bender as can be seen in Figure 2. The weld areas in these two root bends would have passed as discontinues are <.375”.

Figure 2. Profile view of procedure “XB” guided bend tests

“XC” seems to have performed the best. One root bend sample passed, third sample down in Figure 3. There was no fracture and discontinuities are <3/8”. Both face bends had a fracture adjacent the weld in the 4140 side. The other root bend fractured ~2” away from the weld in the 4140 side.

Figure 3. Profile view of procedure “XC” guided bend tests

In the “XD” samples, both face bends fractured adjacent to the weld on the 4140 side as noted in Figure 4. The root bends fractured ~2” away from the weld in the 4140 base metal and the weld area of these samples showed total discontinuities <.375”.

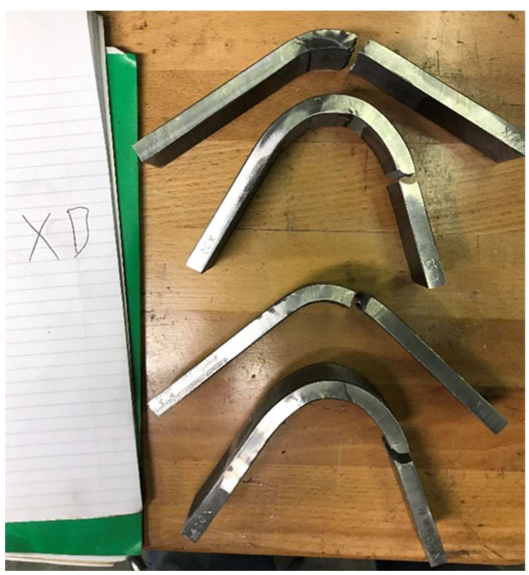


Figure 4. Profile view of procedure “XD” guided bend tests

Tensile Tests

The results of the tensile testing show little variation in UTS between the different weld procedures. The average UTS of the worse performing weld procedure was only 3.43% lower than that of the highest performing weld procedure. All samples performed better than the specification for 4140 in the annealed state and the requirements for the E11018M H4R electrode. All samples showed lower than typical percent elongation for 4140 in the annealed state. Samples that failed within the weld area also showed lower than minimum percent elongation for E11018M H4R.

Table 5

Tensile test results

	Sample	**UTS (psi)**	**% elongation**	**% reduction in area**	**Failure observation**
XA	XA1	121606.55	8.18%	21.82%	~.5" from weld area, 4140 side
	XA6	119038.68	11.64%	39.63%	along weld boundary of A514
	average	120322.62	9.91%	30.72%	
XB	XB1	121606.55	6.58%	20.75%	~.5" from weld area, 4140 side
	XB6	116201.12	4.84%	6.20%	adjacent weld boundary of 4140
	average	118903.84	5.71%	13.48%	
XC	XC1	121481.48	6.89%	19.15%	~.5" from weld area, 4140 side
	XC6	110903.66	4.67%	22.61%	within weld area
	average	116192.57	5.78%	20.88%	
XD	XD1	117388.11	10.80%	26.66%	within weld area
	XD6	118034.06	16.62%	41.88%	within weld area
	average	117711.085	13.71%	34.27%	

Charpy V-notch Testing

Due to budget and time constraints, only two weld procedures were chosen for CVN testing. Procedures XA and XC were chosen at the time due to their performance in the guided bend test. As mentioned before, the notches were placed in the HAZ in both the 4140 side and A514 side. In both procedures the 4140 notches performed drastically lower that of the notches in the A514. Furthermore, XC saw a 57% increase in energy absorbed over XA in the 4140 HAZ, and a 23% increase for energy absorbed in A514 HAZ.

Table 6
Charpy V-notch test results

	Sample	Notch location	Results (Ft-lbs)	Average
XA	XA7	4140	7	7
	XA8	4140	7	
	XA9	A514	70	65
	XA10	A514	60	
XC	XC7	4140	10	11
	XC8	4140	12	
	XC9	A514	90	80
	XC10	A514	70	

Analysis

The guided bend test is perhaps not the best way to verify this type of welding with dissimilar metals. Ultimately, we want a hard tooth welded to a bucket with a ductile weld able to take an impact. A hard material in a guided bend test that requires deformation of the metal might not be ideal in evaluating this special application's weld even if the structural welding code calls out such testing. However, there are some observations that can be made. The first being the 4140 side seems to the side of concern with all the fractures taking place adjacent to the weld or farther along in the sample. Secondly, the samples that did the worse were all face bends in all the procedures. The root bends performed far better. This is counter intuitive of typical guided bend test results. The root bends typically display concern. In this instance, this could be due to the amount of heat the root area of the plates experience. In all the procedures more heat was concentrated at the bottom and then moved up. This could suggest that a "tempering bead" on the surface near the cover passes is all that would be needed to introduce ductility into the base metal. The "butter" of XC and XD might have not had enough effect around the face of the base metals. Thirdly, many of the root bend samples fracture 2" away from the weld. This could possibly be explained simply due to geometry as the sample goes through the bender. Or some grain growth is happening in all the procedures in that region. The temperature gradient through the sample test plates is producing temperatures in that region that are just right to make detrimental metallurgical changes in the base metal such as the Widmanstatten structure mentioned above. The performance in XC and XD might also be explained due to the large size of the weld metal in these samples. The ductile filler metal was able to deform over a larger area compared to that of the small welds of XA and XB.

The tensile testing shows very little variation over the different procedures. It can be seen that the E11018M H4R rod is a good choice for matching the tensile strength of 4140. "XA" shows a surprising amount of ductility based off percent elongation and percent reduction in area. It was predicted that this procedure would have the most brittle failure of all the procedures, but the tensile test evidence is counter to this. XD shows the most ductility of the samples. This is consistent seeing that the sample failed in the ductile weld metal vice the base metals. It interestingly failed at a lower UTS than when the other samples failed in the base metal. Three of the samples also failed ~.5" away from the weld in the 4140 side. This could be consistent with the failures seen in the guided bend test. Some sort of temperature gradient outside of the weld area and HAZ could be causing detrimental changes in the 4140. The reduction in performance seen in XC and XD could simple be due to geometry. Both of these procedures developed excessive distortion during fabrication due to the large amount of weld passes used. This resulted in a noticeable bowing of the samples. The straighten that these samples experienced while under tension could explain this noted reduction in UTS. This could also explain why these samples saw failures in the weld. The weld area would have distorted during the “straightening” and consequently would have had more stresses built up inside.

The CVN testing showed the most noticeable change in the procedures. Possible variabilities with regards to weld size or bowing of the plates mentioned in the previous test are also eliminated in this testing due to the tight machining tolerances and intentional notch placement. It can be seen that the 4140’s energy absorption stands in stark contrast to that of the A514. Failures or issues in the 4140 are seen consistently throughout all three of the separate tests used in this research. An increase in performance can be seen in both the 4140 and A514 HAZs between XA and XC. This can be evidence that the “buttering” technique does affect the HAZ in a positive way for both 4140 and in the A514. This CVN testing is also most representative of the type of service conditions that heavy equipment is exposed to and perhaps gives the most relevant data for this research. The tensile testing showed there is little difference between the procedures but this CVN testing shows there is a difference in these procedures when it comes to quickly loading impact conditions.

Conclusion

This testing had its limitations that must be acknowledged and discussed. The amount of samples used is very small. It would be better to have more repeatability with more data collection points. The .375” plates used for test are also on the small side. Larger plates closer to 1” would have been better at exaggerating the effects of rapid cooling in the HAZ. Bigger plates would have also been more representative of the thickness of which actual heavy equipment is made from. Material selection of a high manganese steel might have also been more appropriate compared to that of the 4140. The “buttering” technique in general also has its limitations. The weld bead profile of the “butter” welds could inhibit good access to properly finish out the weld. It was also seen that procedures XC and XD required a large amount of weld metal. This would require a large amount of metal to be removed from the pieces to be welded, requiring more filler metal, and overall depositing more heat energy into the base materials.

Other testing could have also been done within this project to gather more information. A metallography could have been taken of the samples. This would have given more detailed information of the microstructure of the metals such as grain size and condition of the carbon. Hardness test could have also been taken across the cross section of the samples. This would help in verifying if a tempering action were taking place in the HAZ of the “butter” welds.

Joint design and mechanical connection of the tooth to the bucket is perhaps more important than that of the soundness of the weld. Considerations should be taken into account for repairs on the physical arrangement of a repair. If possible, a repair weld should not be used solely in place of a situation in which pieces can be “keyed” together and only held in place with a weld. In that instance forces are shared through the keyed surfaces and the weld versus the weld taking all the loading. Furthermore, cleanliness and surface preparation are paramount for any welding operation to be successful and perhaps this aspect is the most challenging for any field repair. At the very least this project shows that E11018M is the correct electrode choice for something of this nature. The more common and ubiquitous E7018 that can be found anywhere from a local auto parts store to the quiver of an ironworker would have produced much poorer results. The added cost of sourcing dry E11018M rods could be what determines if a field repair is successful or not. The "buttering" technique does show promise in improving the mechanical properties of a weld repair on these types of steel especially in impact loading. Further testing and refinement of the procedure would be needed to further prove the benefits of this over other procedures.

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