Development of improved weld repair procedures for carbon steel castings

Master’s thesis in Production Engineering

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Gothenburg, Sweden 2020
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Abstract

Wear parts for mining equipment are sometimes in need of repair of cracks found in production. This experimental parameter study addresses the quality of repair welds made with process 111, Manual metal arc welding. The base material is a cast steel, the unalloyed electrodes have a basic coating. Parameters varied in the experiment include preheating, electrode diameter and weld current. Weld speed is adapted by the welder to generate a sound weld. Typically, five weld beads were needed to fill up the groove made with abrasive grinding, simulating removal of cracks. After the visual examination, cross sections were prepared for microscopy and hardness testing.

The top layer welds were free from cracks and larger pores based on visual examination of the surface. Microstructural cross sections show heat affected zones with thickness from 0.8 to ca 3 mm, depending on weld parameters. Larger electrode diameters and higher currents lead to thicker heat affected zones. The weld metal exhibits a columnar dendritic microstructure. In overlapping welds, the columnar microstructure is recrystallized to a fine-grained heat affected zone. The hardness of the weld metal is slightly higher than the base metal hardness. Only a few pores, below 1 mm in diameter were found in the cross sections, but the sampling volume is too small to quantify pore distributions.

Keywords: Repair welding, Manual Metal Arc MMA, Cast steels, microstructure, hardness

Contents

Acknowledgements

I strongly believe that no research work can be completed without the sharing of ideas and help of the society or the people associated with it. I am really very humbled that I have so many people who could support me for my master thesis. I am thankful to both the company and Chalmers who gave me this opportunity to find and complete my master thesis. I am thankful to Johan Ahlström (examiner at Chalmers), Johan E and Thomas B who were my industrial supervisors. A special thanks to Jörgen P, Mikael, Henrik and Spend F who helped me with performing the experiments.

Background and motivation

Two welding processes entitled 111 and 141 are often used during assembly and repair of mining equipment. After machining of parts there might appear a need for repair welding. Process 111, Manual Metal Arc welding (MMA) is used for general repairs while process welding work concerning assembly welding.

Scope of study

This thesis comprises a parameter study on Manual Metal Arc welding (MMA, process 111) for repair operations in cast steels. Experiments are done varying the input parameters weld current and electrode diameter. Three different current settings were selected (low, medium and high as recommended by the electrode producer). Three different electrode diameters were used (2.0 mm, 3.2 mm, 5.0 mm). Tests were done with and without preheating.

The aim is to establish the resulting weld quality after repair welding with process 111, MMA, as evaluated by:

1. Visual examination of welds, searching for surface cracks and pores.
2. Microstructural examination of cross sections, analysing grain structure in the weld metal as well as the Heat Affected Zone (HAZ) appearance and thickness.
3. Hardness measurements in selected samples, both in the weld metal and in the base metal.

Because of certain circumstances, the results section became less conclusive than expected. To partly compensate for that, a more thorough introduction to process 141, Tungsten Inert Gas (TIG) welding including the effect of different polarity settings was added.

Limitations

1. Since the location and the dimensions of the cracks or imperfections (requiring the need for the repair) is not known, the process leaves little room for high levels of automation. Hence this process relies mainly on the specifications defined in the process and the experience of the operator. A certain variability in welding parameters is inevitable in manual welding.
2. The material in the mining equipment cannot be changed to provide a better weldability as the quality of the parts delivered to the customers would be affected. Therefore, the experiments were conducted only on material from worn-out, scrapped wear plates made from cast steels.
3. For time and cost reasons, only samples with the lowest and intermediate current were analysed metallographically. The highest current level was thus mainly analysed by visual examination of the top surface. Three exceptions exist for comparison.
4. Only one experiment was done for each parameter combination, and only one metallographic cross section from each experiment (low and intermediate current, see 3 above) was studied in microscope for time and cost reasons. This means very low sampling volume meaning no statistical certainty could be achieved regarding possible porosity and crack distribution.
5. Only steady state welding was analysed, start and stop effects were only analysed by visual inspection of the surface.
6. Only one type of electrode was used, the un-alloyed basic electrode from ESAB called FILARC 35.
7. Since interpretation of the results required knowledge of physical metallurgy of welding, the author who is in Production Engineering was assisted by the examiner in this work. Also writing the experimental part and doing the microscopy required additional support. Writing of the thesis except for the sections Discussion and Conclusions was done in collaboration.

Theory

Arc welding - a brief introduction

Welding is a joining process used to join metallic or thermoplastic parts or materials. The fusion of the materials occurs when the parts are melted by the application of heat and is often followed by the addition of filler material. The filler is sometimes needed to fill out the gap and achieve a smooth joint, and in some types of joints needed to transfer forces. Welding in metals, which is what we will refer to from now on, is different from soldering or brazing based on the process temperatures related to their melting temperature. In welding the workpieces are melted at the joint interface but in soldering or brazing, a material that has a lower melting point is chosen as a filler to bond the workpieces together. [1][2][3]

Based on the application and the need, the type of metal welding process is selected. In general, a typical arc welding setup consists of a power source, shielding gas supply, a welding gun with an electrode. Based on the need a filler material can be used. The energy input from the power source provides enough energy (a certain current at a given voltage) to the welding gun. The electric circuit is closed by an electric arc between the electrode and the workpiece, and the heat generated melts the workpiece. Based on the need, the type of electrode is selected. In some welding processes like the MMA welding the electrode is melting and helps fill the weld gap, but in other processes the electrode is only providing the electric arc. One such type of welding is TIG welding which uses a non-melting tungsten electrode.

Many different welding processes exist, and details of each cannot be given in this thesis. However, since both TIG welding and MMA welding is used for repair and assembly of mining equipment these methods are explained in more detail below.

Tungsten Inert Gas (TIG)

Tungsten Inert Gas welding (TIG, in North America often called Gas tungsten arc welding (GTAW)) is a form of arc welding that is used to combine/join metals by heating them with an arc generated with the help of the tungsten electrode which is non-melting. The arc is generated in between the tungsten electrode and the workpiece. Inert shielding gas is supplied in order to protect the weld pool. The shielding gas is mainly argon, helium or a mixture of both however nitrogen or hydrogen can also find its application depending on the need and the purpose. The process might use or might not use filler material or pressure depending on the application.

A typical TIG setup is shown in Figure 1 below along with a sketch of its arc formation. The setup comprises the welding power source, welding torch, electrode, shielding gas supply. The control equipment in the power source often encompasses a high frequency generator. The filler material (not always needed) is typically added by immersing a rod of metal in the weld pool from the side. [7][8]

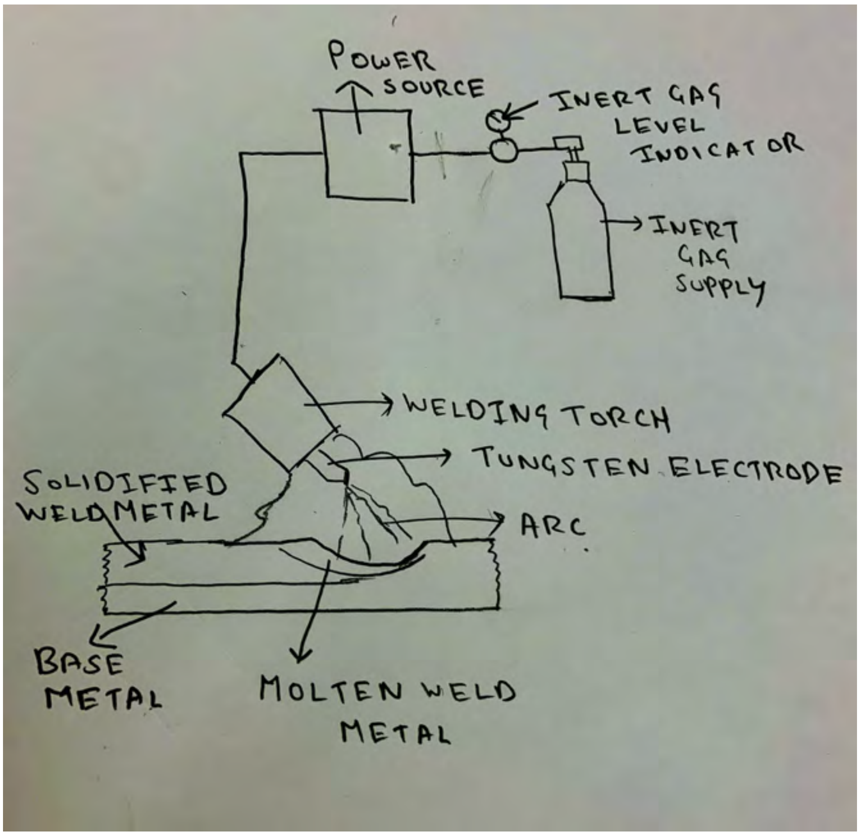


Figure 1. A typical TIG setup along with arc formation. [7]

The TIG process is most often manual, that is the welder is holding the torch in one hand while feeding the filler rod (if there exists a requirement for a filler) with the help of the other hand. Since the filler materials and the torch both need to be simultaneously controlled in order to meet the need of the process, manual TIG requires the welder to possess high welding skills. However, in the case of the mechanised and automatic TIG welding the feed of the filler materials is done through a wire feeder incorporated in the welding torch and this equipment requires less skills to operate from the welder's side.

The use of shielding gas and a non-melting electrode in TIG makes the process advantageous regarding quality as compared to many other arc welding processes. The arc, and the arc pressure is better controlled since the pointy electrode tip gives a very stable starting point of the electric field. This helps producing spatter free surfaces, reduced post weld cleaning, and gives the ability to produce quality welds in most welding positions. Due to these advantages TIG is suitable for a wide range of applications where weld quality is crucial. Thanks to the possibilities to adjust the process, TIG can be done in many common commercial metals like aluminium, steel, magnesium, copper, titanium and can be used for almost all weldable materials excluding lead and zinc. However due to relatively low deposition rates TIG is best suited for welding thin workpieces ranging from thickness of 0.5 mm to 3 mm. [8]

Depending on the material, purpose and the type of the weld to be made the power source is chosen which can be DC (direct current) or AC (alternating current). In addition, DC can be further divided into two types: DC- called straight polarity and DC+ called reverse polarity.

Straight polarity (DC-) setup is the most common type of TIG as it provides the maximum penetration depth. As shown in figure 2, the electrode is connected to the negative terminal and grounded to the positive terminal hence the electrode is negative while the work (workpiece or workpieces to be welded) is positively charged. In between the electrode and the workpiece exists the shielding gas which in general comprise of a mixture of helium and argon. A gas column is ionised in the process (plasma) of TIG as the electrons from the electrode begin to flow towards the workpiece - the arc is established. As electrons travel to the workpiece and on collision liberate heat, a pressure is exerted on the surface of the weld pool. Hence this method offers the best penetration and the tungsten electrode can carry a higher current and operate at lower temperatures as compared to the other polarity arrangements. [8]

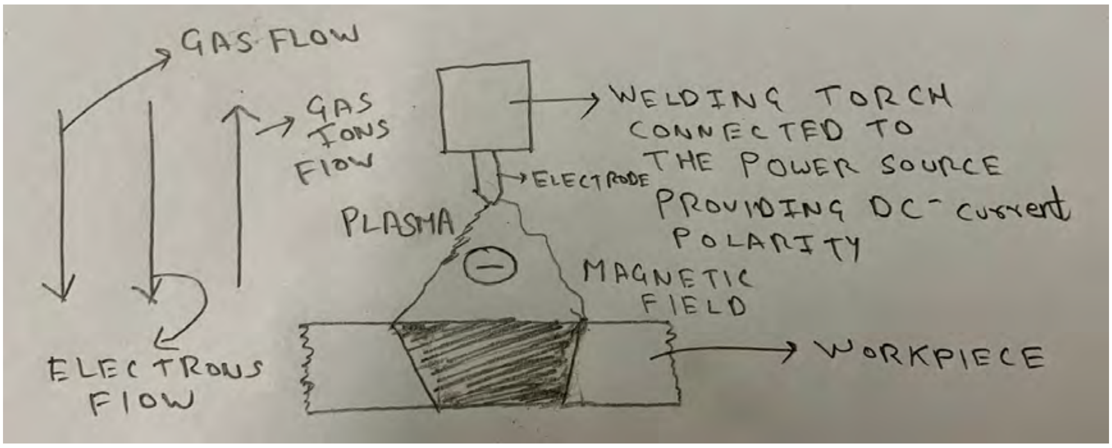


Figure 2- TIG **mechanism with DC - power source. [8]**

In reverse polarity (DC+), the electrode is connected to the positive terminal while the workpiece is connected to the negative terminal, figure 3. Hence the flow of electrons is from the workpiece to the electrode tip making the electrode hot with almost two thirds of the heat generation at the electrode tip. Due to this, the maximum penetration depth is much less compared to the straight polarity DC-. However, the surface oxides formed in the welding of metals such as aluminium and magnesium are broken up as the negatively charged workpiece attracts the positively charged gas ions bombarding the surface. [8]

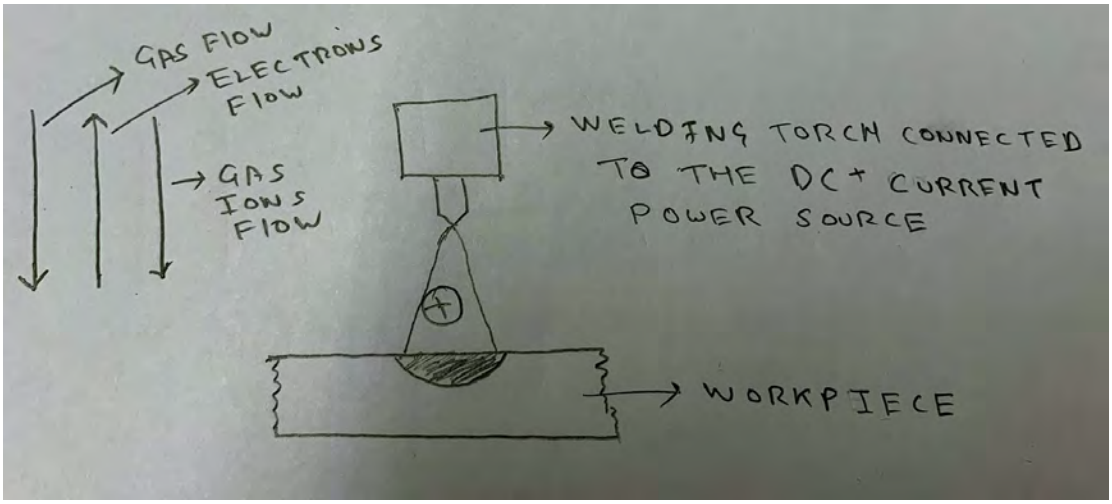


Figure 3- TIG **mechanism with DC$^+$ power source. [8]**

Alternating current offers the advantage to break up the oxides formed on the metals like aluminium and magnesium with less heating of the electrode. Alternating current can be understood as the mix of straight polarity and reverse polarity that means a compromise is possible, where enough breakup of oxides is achieved, with an acceptable heating of the electrode.

The main purpose of the electrode is to establish and maintain the electric arc during the welding process. The shape and the type of the electrode should be chosen to suit the need, for example a thin electrode requires higher current input to provide the same energy as compared to the larger diameter electrode, and this can cause the thin diameter electrode to deteriorate faster due to the higher resulting temperature of operation. Typical recommendations are shown in Table 1. An electrode usually is made from tungsten because of its high melting point. However, a tungsten electrode may contain an addition of thorium or zirconium, see Table 2. This addition is done to increase the current carrying capacity of the electrode and help the emittance of electrons from the electrode by decreasing the work function. [7][8]

Table 1. Electrode and current recommendation. [8]

Material thickness (mm)	**Electrode Diameter (mm)**	**Filler Rod diameter**	**Current Range (A) DCEN EWTh**
1.6	1.6	1.6	60-100
3.2	2.4	2.4	150-170
4.8	2.4	3.2	180-220
6.4	3.2	7.2	260-300

Table 2. Selection of TIG Electrodes with respect to the base metal [8]

Electrode	**Base metal**
Thoriated	Carbon, low alloy, stainless and nickel steel, titanium, copper and its alloys
Zirconium or pure metal/Thoriated zirconium	Aluminium
Zirconium	Magnesium

The electrode can be damaged due to excessive use and overheating and needs to be replaced occasionally. The damage of the electrode can also arise from improper welding operations with the welder touching the workpiece with the electrode. [8]

Manual Metal Arc Welding (MMA)

Manual metal arc welding (MMA, also known as shielded metal arc welding (SMAW) in North America) is a type of arc welding which uses a flux coated consumable electrode. It is one of the simplest arc welding techniques that is easy to learn. It requires less investment as compared to TIG welding which requires a more advanced power source and additional supply of shielding gas. MMA can be performed suiting a wide range of welding applications in carbon steels, cast iron, low alloy and stainless steels along with cast steels. Since this welding technique requires manual skills, the quality of the weld relies on the skills of the welder. [16]

Setup and the principles of operation

The typical MMA setup as shown in figure 4 consists of the power supply whose two terminals are connected to the workpiece and the electrode holder. The consumable electrode has a flux coating to generate gas and slag to protect the arc and the weld pool respectively. The current starts flowing between the electrode and the workpiece as soon as the power supply is switched on and the electrode touches the workpiece creating a short circuit. This ignites the electric arc which melts the workpiece and the electrode. The weld thus consists of material from both the electrode and the workpiece. It is to be noted that here there is no need for an additional supply for the shielding gas as the flux coating serves this function. [15][16]

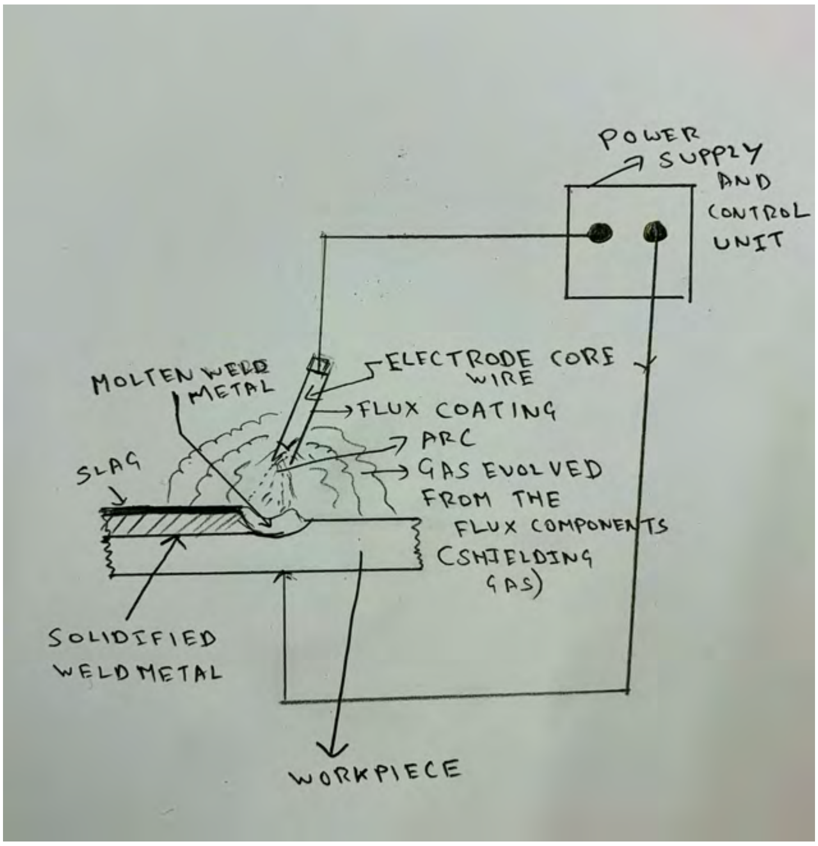


Figure 4- MMA setup and arc formation. [16]

To maintain and control the current it is necessary to have a power source that can supply a direct current or alternating current (depending on the use and availability). However, in the alternating current setting only certain types of electrodes give a stable operation. The two terminals of the power supply are connected to the workpiece and the electrode. Like in TIG welding, the two options of straight polarity or reverse polarity can be chosen to suit the purpose of the application keeping in mind that all electrodes do not support both polarities. [15]

A consumable electrode with a flux coating is chosen for the MMA process. The diameter can vary but the most common electrode sizes are 3.25, 4.0, 5.0 mm. Low hydrogen electrodes are preferred in high strength materials as this can reduce the risk for hydrogen induced cracking. To improve the deposition rate and provide a better arc stability, iron powder may be added to the coating. According to the addition of flux the electrodes are mainly classified as cellulosic (contains cellulose), rutile (contains titanium oxide) and basic (contains calcium carbonate and calcium fluoride). The coating of flux in the consumable electrodes has an integral part in part in protecting the arc and the weld pool. The arc dissociates the flux components into carbon dioxide and carbon monoxide that protects the molten pool from oxidation by displacing the surrounding air. The flux components also break down to form a slag on the weld bead that protects the weld bead as it cools. It is to be noted that the weld metal composition is influenced by the flux and that in turn can affect the mechanical properties of the weld. It is thus important to choose an electrode with a flux to suit the desired purpose and application of the weld. [16]

Though MMA welding is relatively simple to learn it requires skills of the welder for the arc to be stable. The welder needs to change the electrodes (recommended when length of the electrodes is less than 50 mm), clean and prepare the surface to be welded for the next weld bead, so typically the active welding accounts for 30% of the total time. [17]

Industrial application and environmental aspects

Typical repair welding

It is important to note that the electrode, the filler material and the base metal are clean to avoid any impurity that can affect the quality of weld. All the parts having any imperfections or cracks and needs to be repaired are sent to the inhouse weld repair workshop. The parts are then inspected by the operator and a grove is made by abrasive grinding to remove the crack and get a suitable cavity for the welding process. If necessary, preheating can be done before the repair welding process. It is to be noted that filling the grove can require many weld layers/passes depending on the depth of the crack or imperfection. As mentioned, in MMA welding the coated electrodes provide formation of slag that in turns acts as a shield for the weld and can prevent oxidation of the weld bead. However, this slag must be removed with the help of the steel brush especially in between consecutive weld runs. The welding work is subsequently followed by cleaning and a reinspection.

Safety concerns

The welding process releases gases and light emissions that can be unhealthy for the operators. It must be made sure that the welder wears welding glasses and breathes clean air (either with the supply of oxygen or with the help of equipment filtering the air). It is strongly recommended to have the first aid box in the vicinity of the operator if in case any accident takes place. Safety is ensured with the company having a separate health and safety ward in the factory. After the power supply is switched on with the decided parameters, the suction pump automatically starts to evacuate the weld gases. The operator brings the weld gun near the workpieces which initiates the flow of electrons leading to the heat formation in the weld metal. After the welding process it is important to clean the surface of the workpiece with the help of steel brush in order to remove the oxides. Then the suction pump and the power source is switched off and a sign with the message “do not touch as the metal is hot” is placed to prevent an accidental touch by the welder that can otherwise get burnt as the workpiece after the welding is hot.

Welding Metallography and Solidification of the weld pool

As explained in the previous sections of the report during the welding process the joining of the base metals, sheet or plates takes place. The welding is carried out by melting the base metal as well as the filler material as shown in figure 5 below.

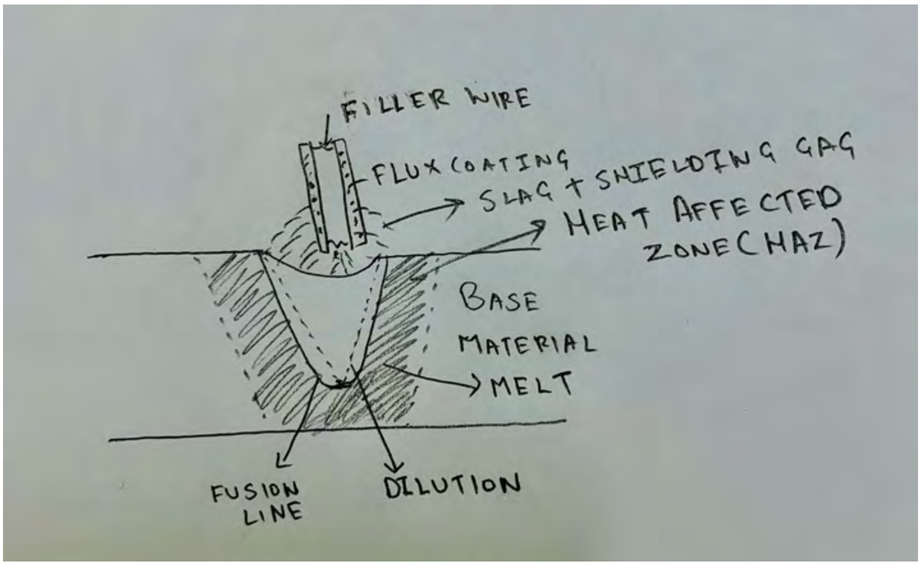


Figure 5- Figure showing the arc and the weld pool along with HAZ

This melted section which consists of molten base metal and molten filler material is called the weld pool as long as it is in the molten form. This weld pool starts to solidify as it cools down which leads to the formation of new grains. The grains that are formed depend on the composition of the weld metal and the shape of the weld pool which results from the different welding speeds and the cooling rate. Usually there is a higher concentration of the alloy and solute elements in the centre of the weld pool which may lead to hot cracking during cooling. [9]

Grains of different structures are formed as the weld pool begins to solidify by the formation of nuclei and their growth. The figure 6 below shows the different solidification modes seen in weld metal, with the arrow indicating the preferred growth direction. [10]

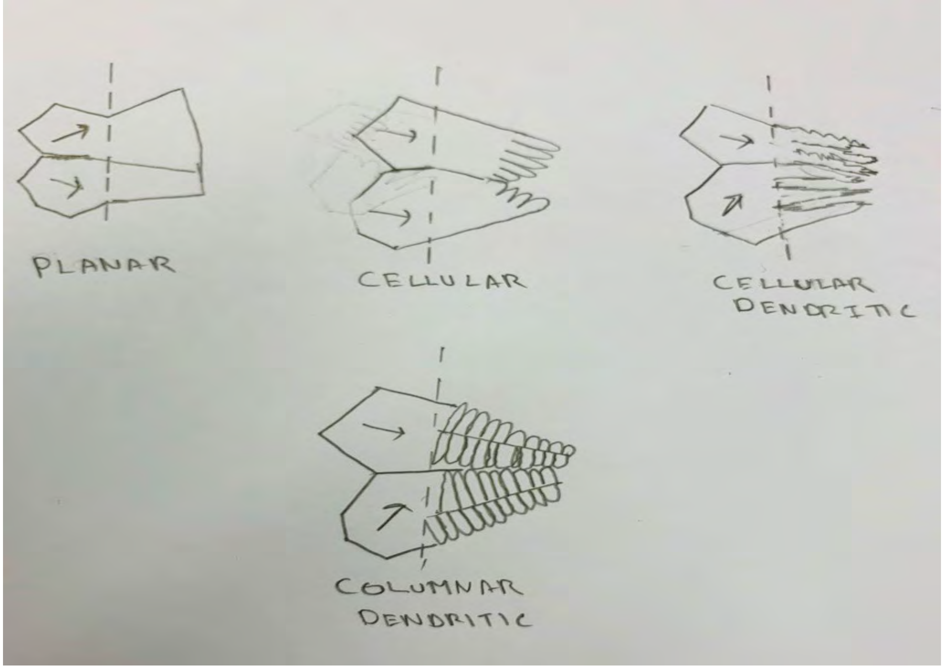


Figure 6- Different solidification modes, redrawn from [10].

The grain starts to form at the boundary of the base metal and the weld pool because at this boundary the temperature difference in the liquid state of the weld pool and the base metal is high. Weld solidification requires no supercooling since grains can form epitaxially on the boundaries of the weld pool. Thus, grains tend to grow from the boundary towards the centre of the weld pool where the temperature difference is low. The growth is planar near the boundary of the base metal and the weld pool and are cellular perpendicular to the boundary of the weld pool and the base metal in the direction away from the dissipation of the heat. In slow cooled welds in high alloyed materials, central regions of the weld metal may contain dendritic structures. The weld speed also affects the structure as shown in figure 7 below. [9, 10]

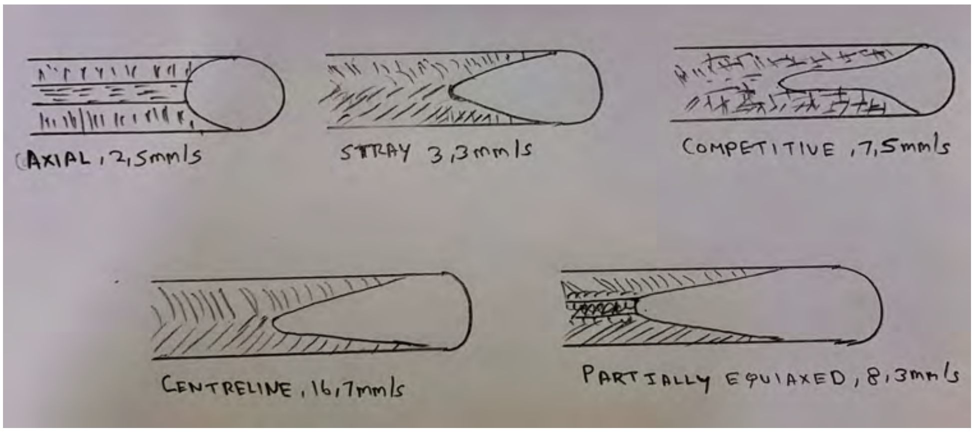


Figure 7- Welding microstructure in relation to the weld speed, redrawn from [10].

The weld pool is nearly circular when the weld speeds are low and it begins to expand into the oval with higher welding speeds subsequently affecting the grain structure.

The grains in the heat affected zone (HAZ) that is just near to the grains formed at the boundary of the weld pool and the base metal tend to become a little coarser due to grain growth enabled by the elevated temperature.

Cast Steels

Cast steels as the name suggests are produced by the process of casting. Many metals like zinc, lead, tin, and copper can be casted for achieving complex geometries. Cast steels fall under the subcategory of the ferrous alloys and is used as an attractive engineering material owing to its mechanical properties such as hardness, toughness, ductility, strength, wear resistance, weldability and price. The mechanical properties of cast steels can be altered based on the chemical composition in the production process and heat treatment. However, in general cast steel is a ferrous alloy which consists of iron as a dominating component with 0.02 to 1.7% carbon by weight. The carbon content strongly affects the weldability property. As compared to wrought materials, the cast materials can be more isotropic (showing identical properties in all directions). [5]

Producing cast steels requires skills and experience as the pouring temperatures of the lower carbon and low alloy steels is between 1565°C to 1700°C and at elevated temperatures the molten steel has the tendency to oxidize quickly. Depending on the chemical composition to suit the application and requirement the molten steel is poured into the mould and is cooled. Depending on the size, dimension, intricacy, cost and accuracy the mould material is chosen usually amongst the materials such as chromite sand, graphite, olivine sand, silica, ceramic, metal or zircon. [5][6]

Advantages of cast steels

1) Isotropy- As the cast steels have the isotropic property it means that the products manufactured by using the cast steels would be “uniform” and would show identical set of properties in all directions.

2) Weldability- Due to the lower carbon content steels can be welded with relatively less difficulty and thus finds its application in the range of the products that requires the process of welding.

3) Complex geometries- Since the cast steels involves manufacturing by casting, it means that complex geometries in the cast steel products can be achieved based mainly on the type, design and geometry of the mould.

4) Wear and corrosion resistance- The parts produced by cast steels have properties such as wear and corrosion resistance and thus the products can find their application in the areas that require moving parts and are prone to wear and tear due to forces such as frictional and compressive forces amongst others. [5]

Disadvantages of cast steels

1) Skills and experience- Since the pouring temperatures for the cast iron steels can be up to 1700°C along with choosing the right composition (for the steel), design and material (for mould) means that the manufacturing process requires both skills and experience of the workers along with proper safety equipment in case of any accident.

2) Cost and time consumption- To melt the steel, pour into the mould and then wait for it to solidify it can be said that the process is expensive and time consuming. Also, the solidified block of the cast steel may require extra machining and heat treatment to suit the desired surface finish.

3) Comparison with cast iron- Cast iron products which have more than 2% carbon content offer better compressive strength and vibration damping than the cast steel products. [5][6]

Hardness Testing

Resistance to permanent indentation or abrasion is called as hardness that means by knowing the hardness value of a material analyses of the strength, resistance to plastic deformation and wear of the material can be made. Various hardness tests exist to calculate the hardness of the material and give the hardness value like Brinell, Rockwell and Vickers. [11][12]

Vickers Hardness test

Developed in 1920th, a square base pyramid shaped diamond inclined at an angle of 136° is used to make an indent on the material/specimen. To measure the hardness the specimen is placed on the anvil of the Vickers hardness meter (example equipment, in fact the one used in our experiment shown in Figure 8). A load from 1 to 120 kgf is selected and by releasing a lever arm, the diamond indenter is loaded onto the specimen for 10 to 15 seconds. The plastic deformation of the material causes an imprint, see figure 9, whose diagonals are measured and then the Vickers hardness value can be directly read from a book of tables, based on the following equation. [11][12]

$HV = \frac{2000P\ sin(\text{a}/2)}{d^2}$, from [12]

Since the face angleα is 136°, P is the applied load in kgf, and d is the mean diagonal value the equation becomes-

$$HV = \frac{1854{,}4P}{d^2}$$

The Vickers test is easy and robust, little surface preparation is required, and a relatively low-cost test offering for most purposes a sufficiently accurate reading. [12]

Figure 8- Vickers hardness test meter

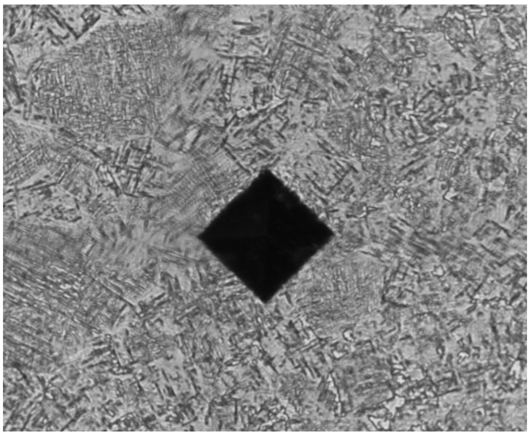


Figure 9- Typical Vickers indent

Experiment

The aim of the work was to study the effects on quality of welds after the repair welding with process 111, Manual Metal Arc welding on the cast G28Mn6+N steel, which is a typical base material. The parameters current and electrode diameter were varied. Voltage was kept constant (at 45 V) and welding speed was adapted according to the experience of the welder. Since preheating is considered an integral parameter affecting the quality of weld, tests were done with and without preheating.

Electrodes and current

For this type of repairs, the most commonly used electrodes are of diameter 2.5 - 4 mm. For the experiment, the effect on the quality of weld while using electrodes diameters 2.0 mm, 3.2 mm and 5.0 mm were chosen. The diameter 3.2 mm was specially chosen to compare to available data from a previous qualification test (Dekra 4505). [18]

The current values are in accordance with the recommendations given by the electrode supplier (ESAB). This is given as a range, see Table 3, the columns for the “low current” and “high current” respectively. For the experiment, an average of these values was calculated and set as a “medium current”. The highest current setting is not frequently used for repair works of mining equipment, as it can lead to excessively high energy input which causes a risk for change in the microstructure of the material.

Table 3 Parameters at which welding was performed-

Electrode diameter (mm)	**Low current (A)**	**Medium current (A)**	**High current (A)**
2.0	45	60	75
3.2	100	117	135
5.0	180	215	250

Note- All the welding runs were performed at a constant voltage of 45 V

Sample overview

All the experiments analysed with microscope are summarized in Table 4 below.

Table 4: Overview of samples analysed with microscope

Sample Name	Current (A)	Preheating temperature (℃)	Electrode Diameter (mm)
2L	45	150	2
2M	60	150	2
2H	75	150	2
3.2L	100	150	3.2
3.2M	117	150	3.2
5L	180	150	5
5M	215	150	5
2LK	45	30	2
2MK	60	30	2
3.2LK	100	30	3.2
3.2MK	117	30	3.2
3.2HK	135	30	3.2
5LK	180	30	5
5MK	215	30	5
5HK	250	30	5

Notes to Table 4:

1. The structure of the sample names- The number means the diameter of the electrode, L (low), M (medium) or H (high) refers to the current setting while the letter K means without preheating (“Cold” translates to “Kallt” in Swedish). So, for example the sample named 5LK means 5 is the electrode diameter in mm, L means the low current settings (as compared to the recommendation for this specific electrode) and K means without preheating.
2. The samples were taken from the middle part of the 30 cm long weld run. This was done as it is assumed that the weld is most uniform near the centre since during the start of the welding process the arc is initiated with a higher current and at the end there is a diminishing energy from the power source that can lead to irregular deposition of the layers affecting the weld quality.

3. Approximate welding speed was estimated based on the total time and the length of the weld beads:

   Welding speed (for 5 mm electrode) = 300 mm / 120 s = 2.5 mm/s

   Welding speed (for 3.2 mm electrode) = 300 mm / 150 s = 2 mm/s

   Welding speed (for 2 mm electrode) = 300 mm / 170 s = 1.67 mm/s

   The heat input which is the multiplication of current and voltage divided by the welding speed was thus varied as a result of adjusted current and welding speed.

Material, method and sample preparation

Scrapped wear plates made from the cast G28Mn6+N steel were chosen for the experiment. The nominal chemical composition is shown in table 5 below:

Table 5 Chemical composition of the G28Mn6+N steels (wt %). [18]

C	Si	Mn	P max	S max
0.25-0.32	0.30-0.60	0.60-1.20	0.035	0.030

From these parts, three metal plates were cut and cleaned as explained in the weld process section of the report, groves were made to prepare the plates for the repair welding with the help of the manual abrasive cutting machine (“angle grinder”).

Repair welding may require multiple weld runs to fill the cavity after removing the crack or imperfection. Hence for the experiment, five runs or layers of weld beads were made consecutively to fill in the groves in the plates. As mentioned, three different sized filler materials that are having the diameter 2 mm, 3.2 mm and 5 mm were used. The experiments without preheating were completed first, before the ones with preheating.

After the completion of each layer the steel brush was used to remove the slag layer and prepare the surface for the deposition of the next weld layer.

After welding and visual examination of the weld surface, the plates had to be cut to take out samples for metallographic examination. Two different cutting machines were required to cut them. The two relatively smaller plates were cut with the help of an automatic abrasive cutting machine with the regular supply of the coolant while the larger plate was cut with the help of an automatic water jet cutting machine.

After the cutting process, the samples were further divided and the middle portion from the weld length, approximately 25 mm long, was taken for the sample preparation.

The samples were further cleaned using acetone and marked. To analyse the samples under the microscope the samples were cast in plastic mould to facilitate handling of the samples along with protecting the samples from the wear and tear. The sample to be moulded was placed in the moulding machine followed by the addition of the plastic powder as shown in Figure 10 below.

Figure 10- Struers Labopress 3 casting machine along with sample placing and addition of the plastic powder

The moulded samples are then ground and polished under the polishing machine. This is done to create a flat, undeformed surface and make the microscopy possible after chemical etching. The polishing of the samples was done in the polishing machine as shown in Figure 11 below.

Y

Figure 11- Struers TegraPol-15 machine (lid closed to keep the machine clean) along with polishing blade container and the polishing machine with open lid.

Results and observations:

Visual examination of plates after welding

Figure 12 shows a photograph of the plates after welding is completed. The visual examination of the weld surface after completion of the top layer could not identify any cracks or severe defects. However, in the outer parts of the weld bead (due to start and stop of the process) pores as well as irregularities in the weld geometry were sometimes found. As mentioned, further sectioning of these plates was done and a cross section extracted from the centre of each selected weld was further examined.

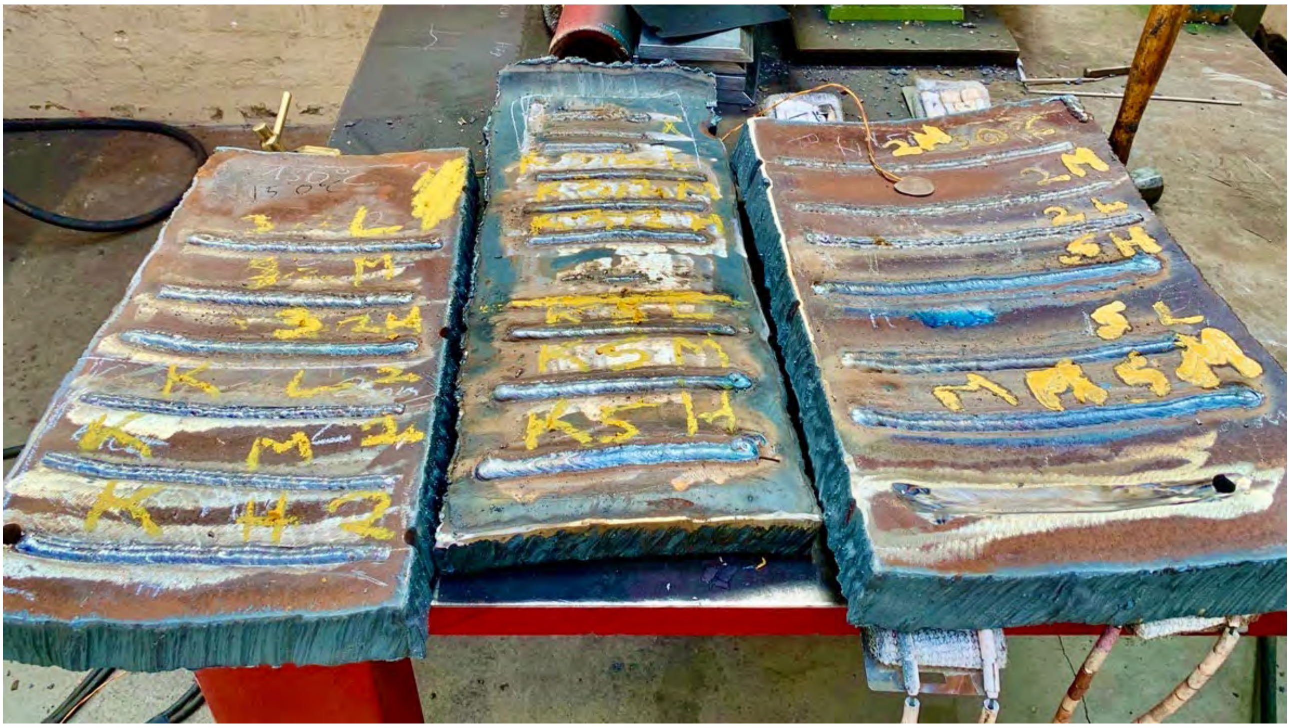


Figure 12-Plates after the welding process, marked and numbered. Plate 1 is the one to the right, plate 2 is the middle one, and plate 3 the leftmost plate.

In Table 5, the plate numbering is inserted to accompany Figure 12, and will be referred to below.

Table 5:-Obtained samples corresponding with its plate number

Plate 1	Plate 2	Plate 3
2H	3.2LK	3.2L
2M	3.2MK	3.2M
2L	3.2HK	3.2H
5H	5LK	2LK
5L	5MK	2MK
5M	5HK	2HK

Metallographic examinations

The typical microstructure of a multi-pass weld was seen in all cases. Detail rich micrographs were obtained using an optical microscope with illumination via the objective lens, see example in Figure 13. The picture shows the dendritic cast microstructure of the base material (top, right corner), the gradual transition to the heat affected zone (HAZ) where the cast microstructure becomes more blurred. Further closer to the weld follows the true HAZ (which is the material that has re-austenitized) with its recrystallized microstructure. In the lower half of the image there is a sharp transition between the base material and the weld metal, with the columnar grains in the weld metal growing perpendicular to the melt line. In between the brown-etched columnar grains, there is a brighter micro constituent, probably ferrite. In the top part of the image, a deeper weld bead has been re-austenitized and the fine grains are showing. This type of transition zone and weld metal microstructure is recurring in all samples. However, due to over-etching some micrographs are not as clear as this one.

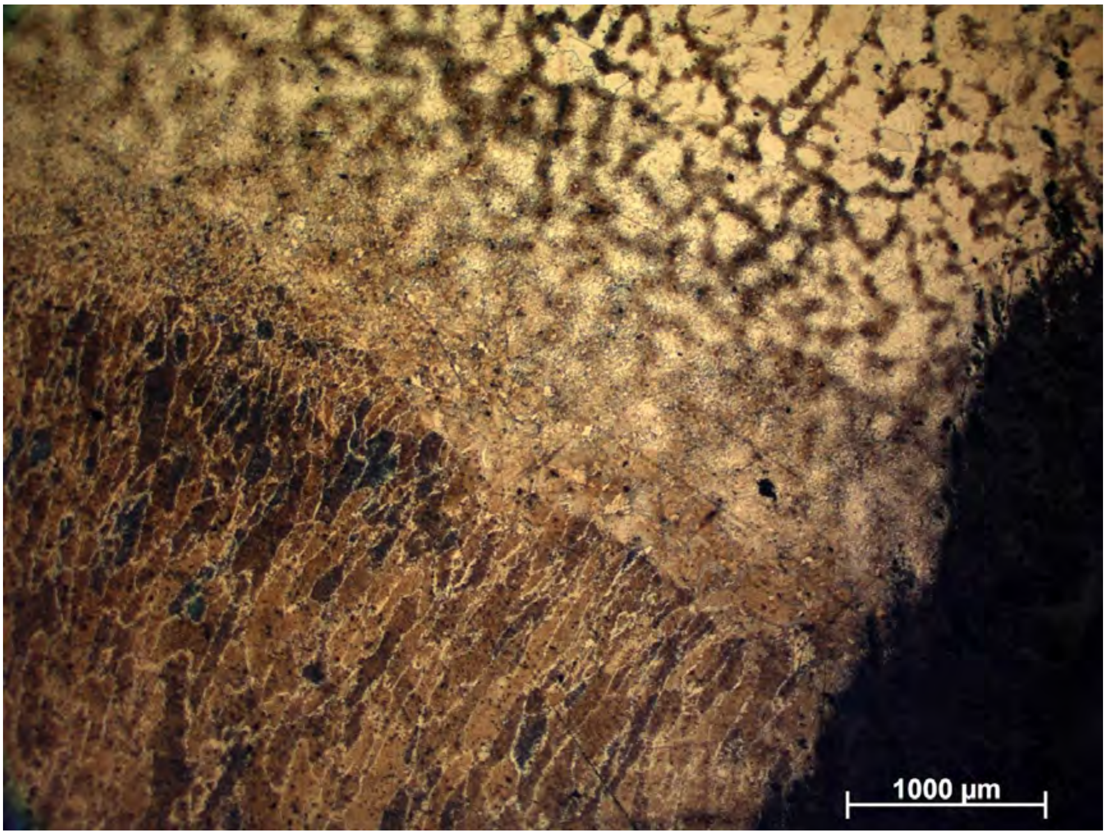


Figure 13-Cast steel microstructure is confirmed. Sample 5L, side weld bead

For overview images at lower magnification, a stereo microscope with illumination via a ring light was used. These micrographs appear darker and were mainly used to estimate the HAZ depths. Figure 14 shows how the HAZ thickness appears on those images. Comparing the two pictures gives the impression that the HAZ thickness increases with preheating even if the current value was lower. Another observation is that in sample 3.2MK with higher current input, the HAZ appears with more distinct borders. The cast, dendritic microstructure is clearly shown in the bottom image.

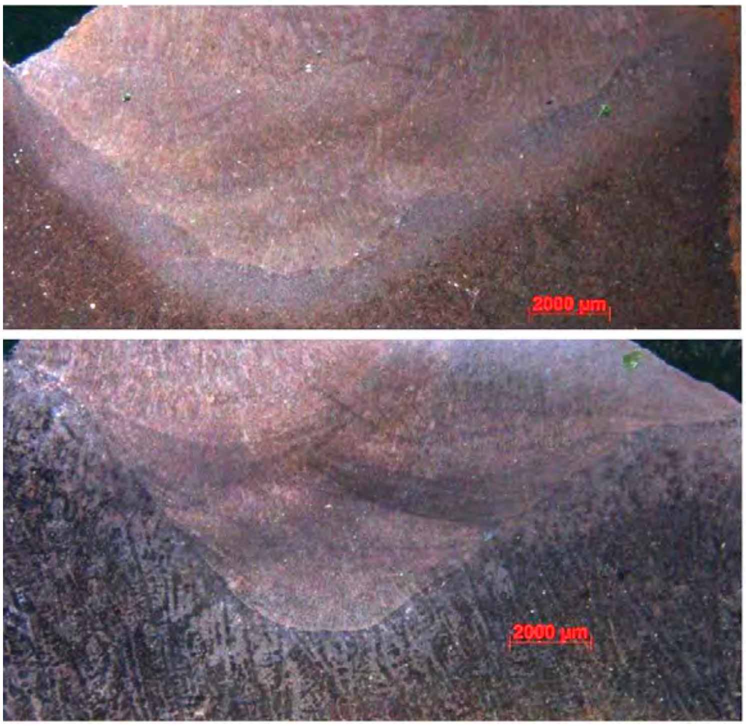


Figure 14- The top image is of sample 3.2MK while the bottom image is from 3.2L.

As seen in Figure 15, the HAZ thickness increases with an increase in electrode diameter. This probably has to do with the higher current setting and higher deposition rate from the higher electrode diameter and following higher heat input.

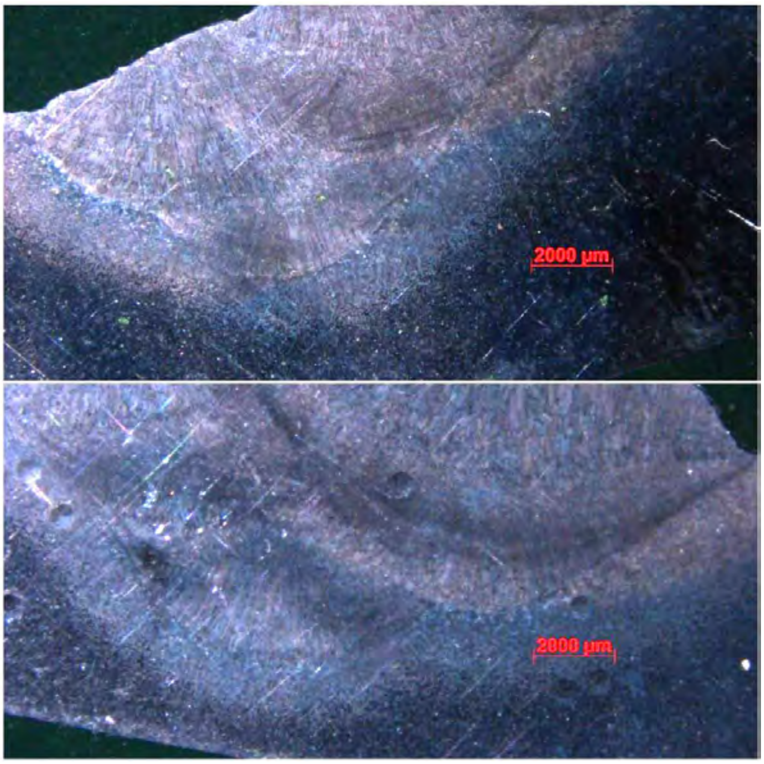


Figure 15- The top picture shows sample 3.2HK while the bottom picture is of sample 5HK.

Figure 16 shows the base material (BM) of sample 5MK in the top left part of the picture, the HAZ, and in the lower right corner some columnar grains in the weld metal. Three hardness indents made with a spherical indenter are also seen.

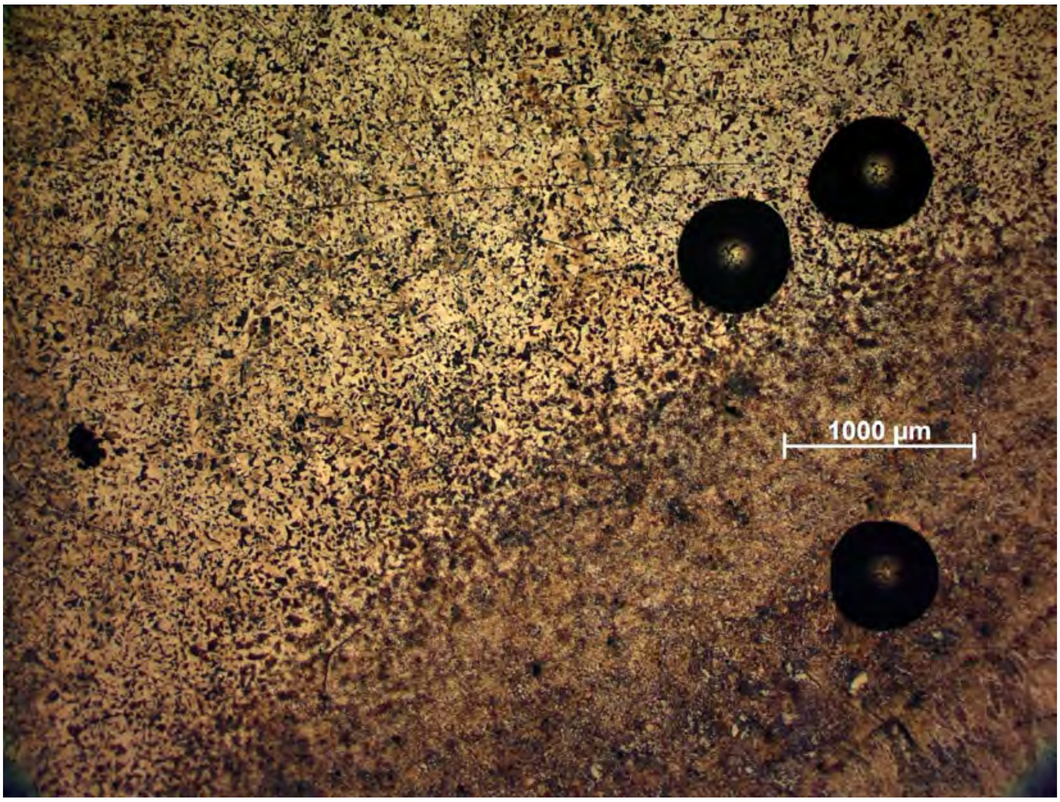


Figure 16- 5MK with hardness indents in the base metal (top left) and in HAZ.

Figure 17 is a higher magnification picture from the HAZ of sample 5MK. It shows the presence of Widmanstätten ferrite which is typical for welds in low carbon steels. Figure 18 shows the same sample but is taken from the base metal. It does not show the cast dendritic structure, but a heat-treated ferritic microstructure with around 20% pearlite.

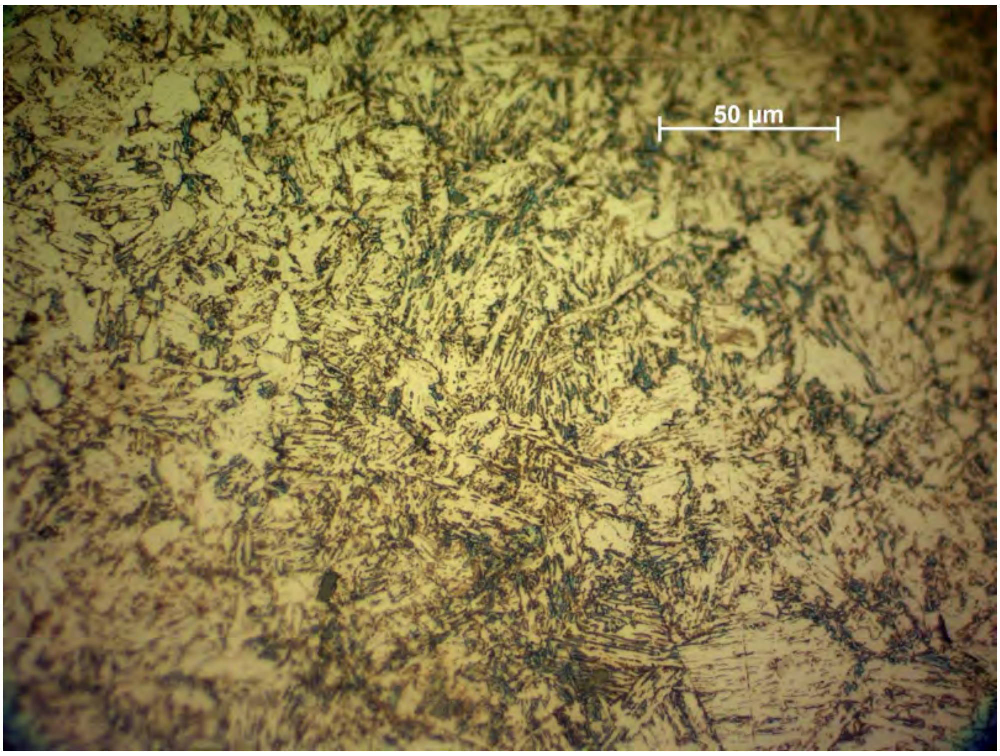


Figure 17-Widmannstätten structure in the HAZ of sample 5MK

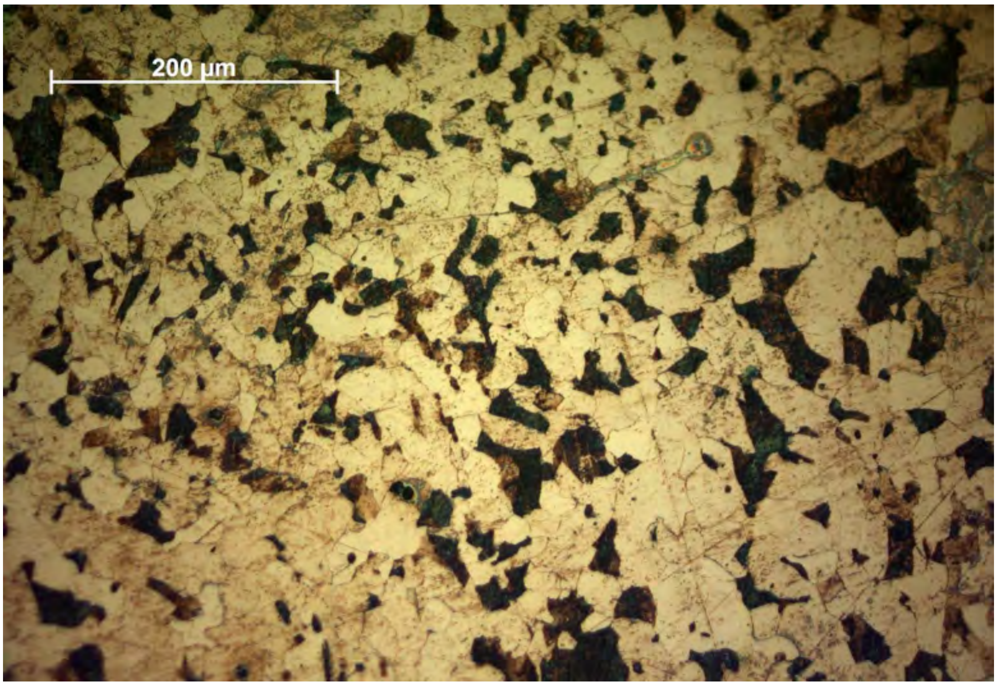


Figure 18-Ferritic pearlitic structure in the base material of sample 5MK

Figure 19 is picturing the side weld bead of sample 3.2HK. The base metal is showing at the top right, and the HAZ contains different constituents with a gradual change. The cellular growth of the weld metal is similar to what was seen in picture 13. However, the base metal looks somewhat different at higher magnification, see figure 19. It is evident that the base material constitutes of acicular ferrite grains with pearlite regions. No dendrites are showing.

Based on Figure 18, 20 and Table 5, it can be concluded that plate 2 had a different microstructure than plates 1 and 3. This is also in agreement with the difference in plate curvature seen in Figure 12. In the following section, the hardness measured in all three base materials are reported.

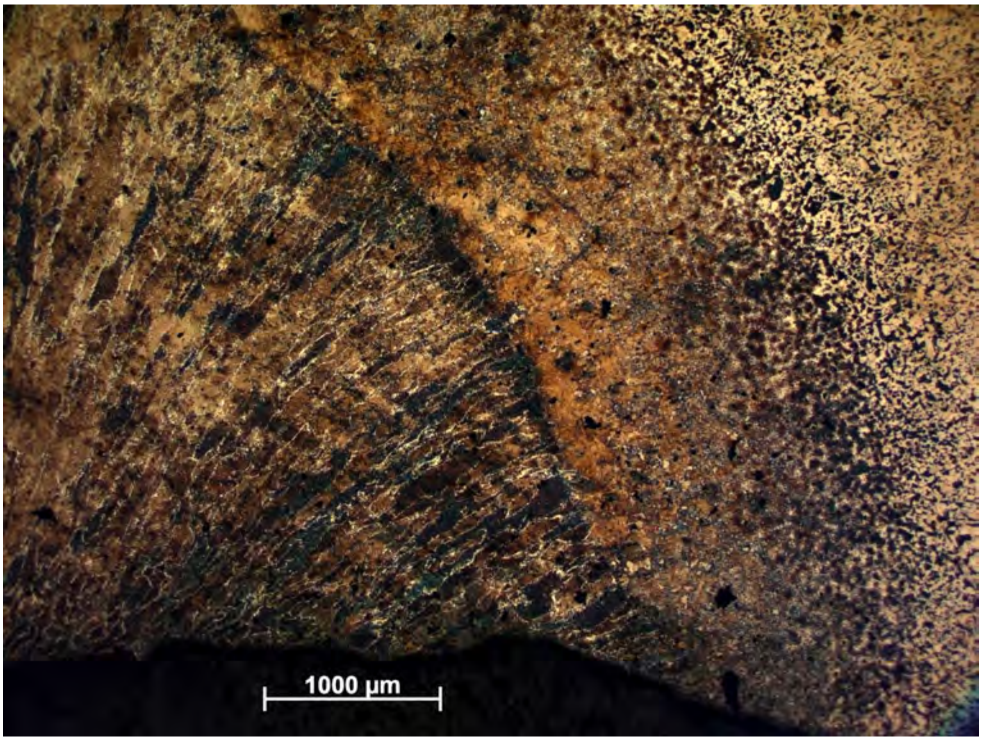


Figure 19-3.2HK sample with hardness indents

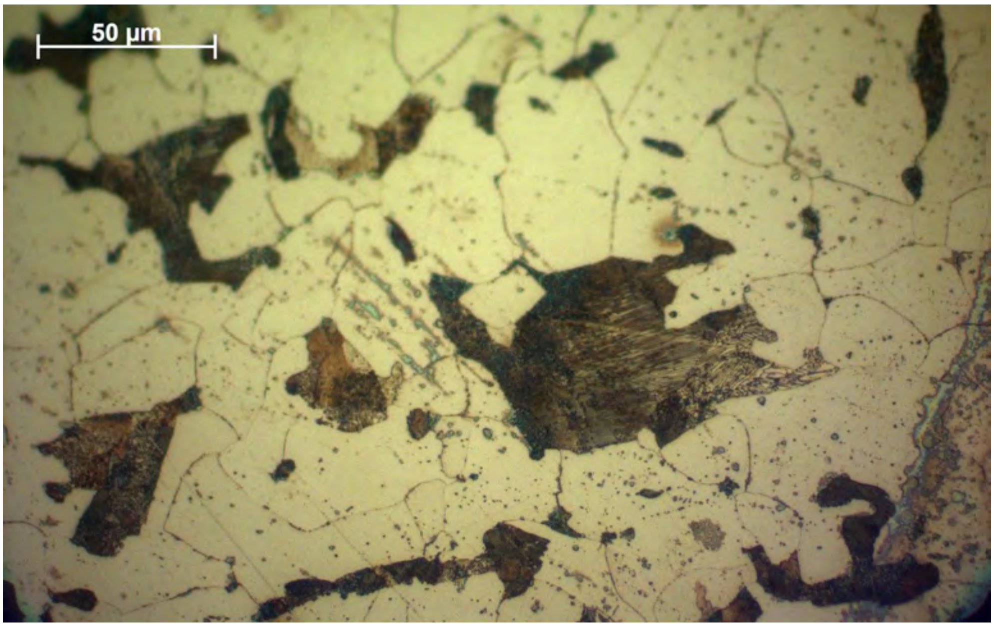
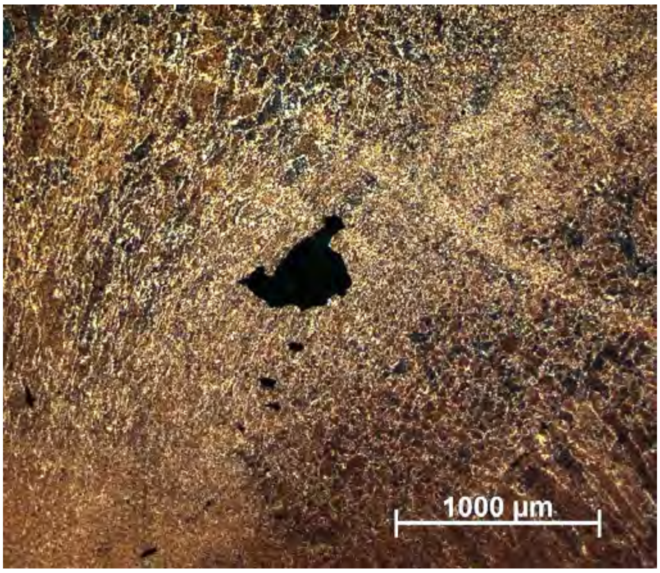


Figure 20- Ferritic + pearlitic structure (dark lamellas clearly visible) is proved at high magnification in the 3.2HK sample.

This section presented a selection of results from the microscopy studies, further micrographs are found in the Appendix.

Pores and defects

In this brief section, two examples of pores found are presented. Generally, not much porosity was found, but as pointed out the statistical sample is very small. Radiographic techniques are more efficient for sampling pore distribution, but this lies outside the scope of this thesis. Figure 20 shows a pore formed in between two weld beads while Figure 21 shows a pore in the base material. It cannot be concluded how the pores have formed.



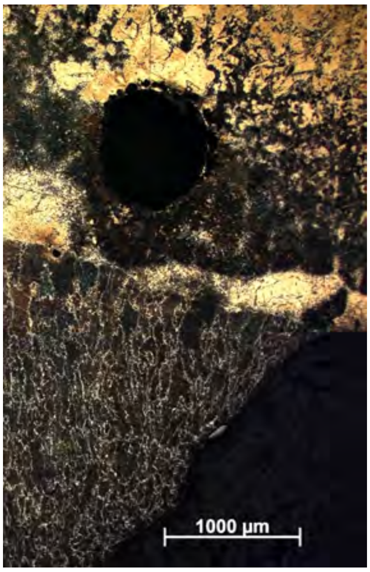


Figure 20- Pore in between two weld beads **Figure 21- Pore in BM**

Hardness

Table 6 shows the hardness test results of selected samples. The hardness of the weld metal is in all cases higher than the base metal. The base metal hardness is fairly even between the different plates, even though plate 2 with a different microstructure has a significantly higher hardness (152 as compared to 140 and 136).

Table 6 Vickers Hardness (HV30) Test Results

Sample Name	Hardness Value I	Hardness value 2	Hardness Value 3	Mean Value
2H (Base metal)	136	135	137	136
2H (Weld metal)	202	191	168	187
3.2LK (Base metal)	150	155	152	152
3.2LK (Weld metal)	198	189	194	194
3.2M (Base metal)	140	136	145	140
3.2M (Weld metal)	202	198	184	195

HAZ thickness

Table 7 shows the HAZ thickness for all samples analysed in microscope. The difficulty to estimate the depth arises from the variations along the welds, and the different quality of the preparation of microstructures, but the best estimates are given.

Table 7: HAZ thickness, including test parameters

Sample Name	HAZ Thickness (mm)	Current (A)	Preheating Temperature (℃)	Electrode Diameter (mm)
2L	<1	45	150	2
2M	<1	60	150	2
2H	<1	75	150	2
3.2L	1	100	150	3.2
3.2M	2	117	150	3.2
5L	2.1	180	150	5
5M	2.9	215	150	5
2LK	0.8	45	30	2
2MK	0.8	60	30	2
3.2LK	1	100	30	3.2
3.2MK	1.2	117	30	3.2
3.2HK	2.0	135	30	3.2
5LK	2.5	180	30	5
5MK	2.5	215	30	5
5HK	3.5	250	30	5

It is not easy to interpret trends based on the HAZ measurements, but a few observations can be made. First, the samples welded with the 2 mm electrode exhibit a low HAZ thickness, up to 1.8 mm at most. The high current welds with the 5 mm electrodes clearly show larger thickness. Preheating to 150 °C gives no drastic effect on HAZ thickness.

Discussion

The welding experiments were performed using different welding parameters, it can be observed that the HAZ tends to increase with the high energy input that can be due to the increase in current, voltage or using the electrode of the higher diameter. Widmanstätten structure can be observed in the heat affected zone while the base metal shows the pearlitic microstructure in certain samples. While coherency can be observed between the structures of the samples taken from one plate there seems to be variation of the structures and hardness values between the samples taken from 3 different plates meaning that the structure of plate 1 is different from plate 2 and plate 3. The 3 plates were taken from the waste of the same part. This can mean that to study the effect of welding it would be beneficial to compare the effects of the change in the microstructure at various stages of the processing of the material. For example, how the structure has changed after the various machine operations and due to the impact of the additional load due to the various parts (being stacked one above the other) at the assembly stage. But since the experiments were performed at the repair welding shop and the weld operation performed here cannot be always uniform(meaning that if there is some crack in the material it requires the operator experience into dig or “open” the material before filling the crack with the welding gun) and since the contours of the material vary with the specimen(position and size of the cracks vary along with the dimensions of the material) that would make it difficult to achieve higher degree of automation of perform the operation at the automatic welding table.

However, when welding is performed on the steel plates as done on the 3 steel plates generally the degree of fusion between the different layers of the weld metal and base metal. Though some pores were observed but that can be due to the imperfections in the microstructure of the material so the quality of the welding at the repair shop is of quite high standards.

Conclusion

Welding was performed and the casted specimens were analysed. The results of the welding weld metal were found to match with the literature study. The quality of the welding at the workshop in general was good but it would be really beneficial for the future analysis to analyse the changes in the microstructure in the material of different parts of the parts after every individual stage of the machining, production or the assembly operations.

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19)FILARC 35, ESAB

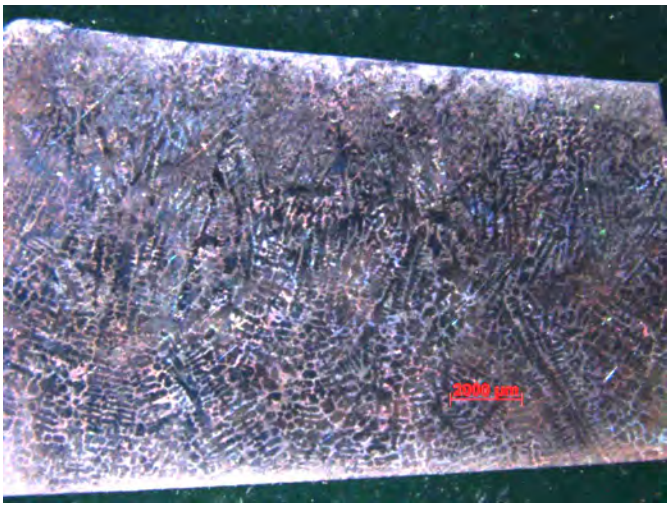
https://www.esab.se/se/se/products/filler-metals/covered-stick-electrodes-smaw/mild-steel-electrodes/filarc-35.cfm

20) Dekra-Internal report

Appendix 1: Micrographs, Stereomicroscopy

2L

2M



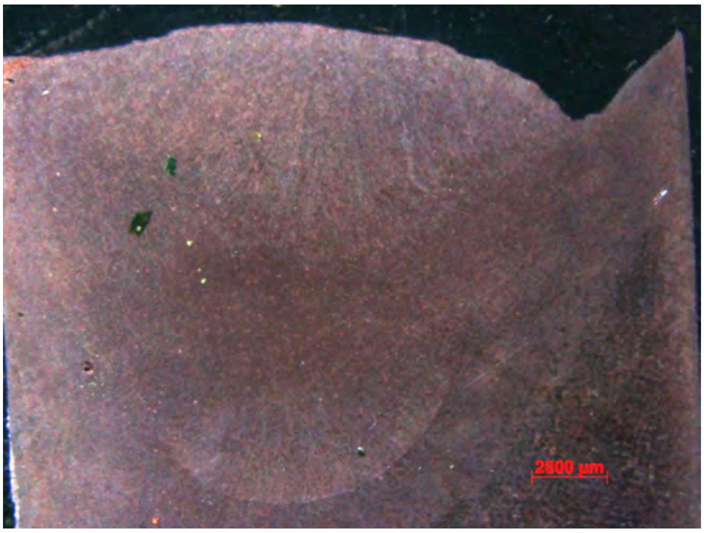
2H

3.2L

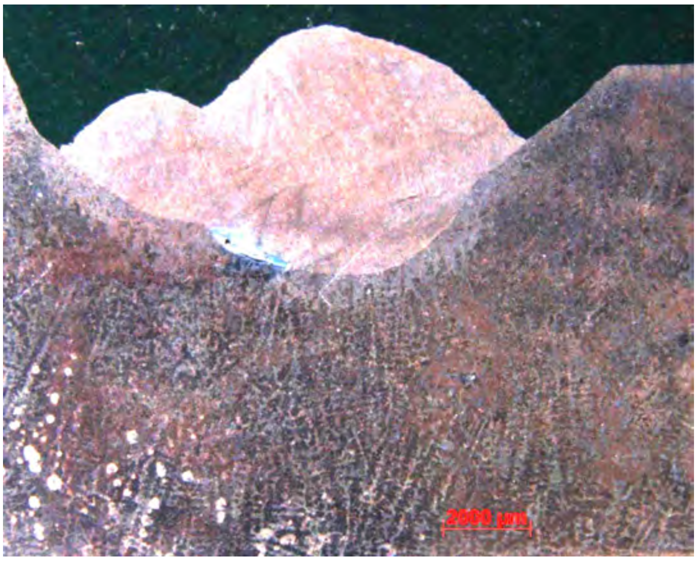
3.2M

5L

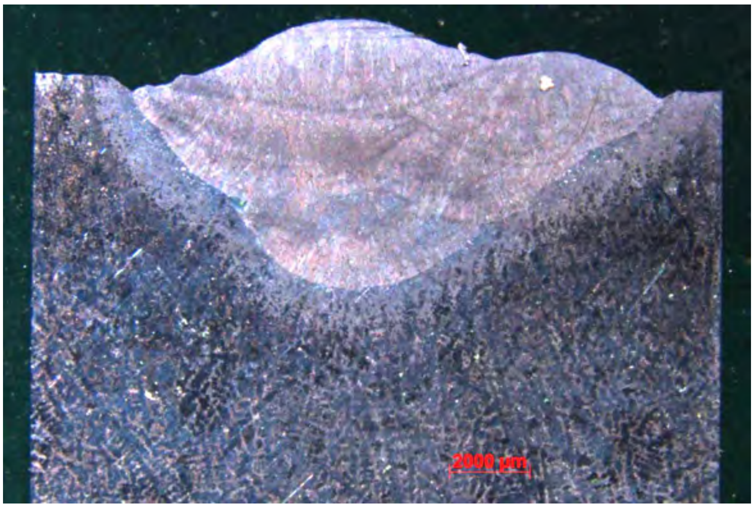
5M



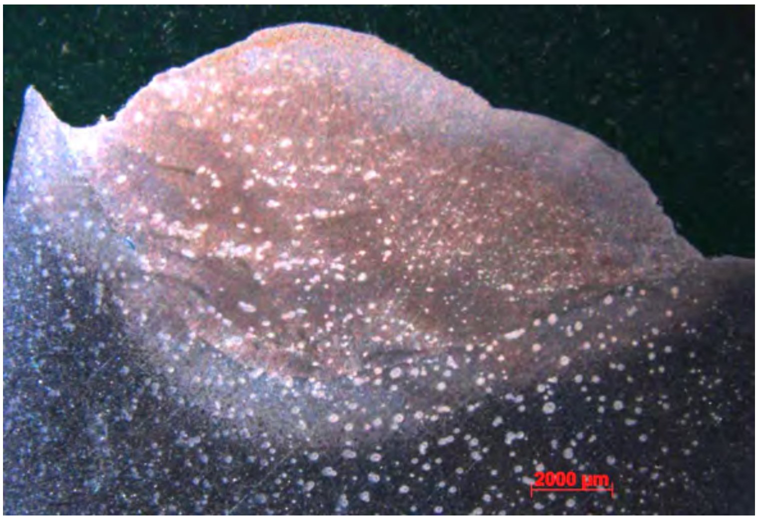
2LK



2MK

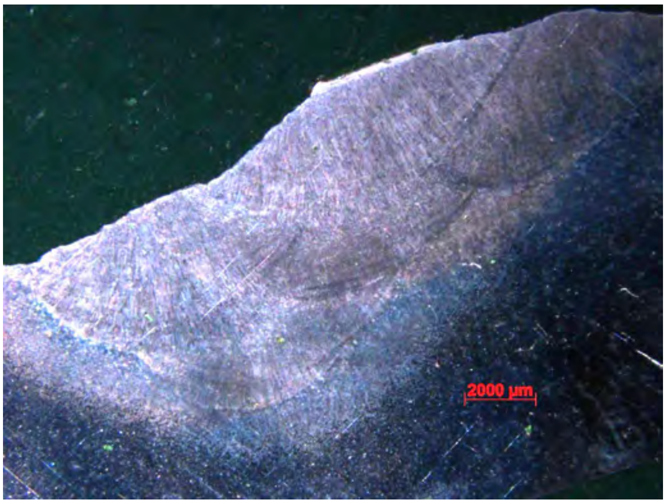


3.2LK The dot pattern is due to bad sample preparation (i.e. dirt)



3.2MK.

3.2HK

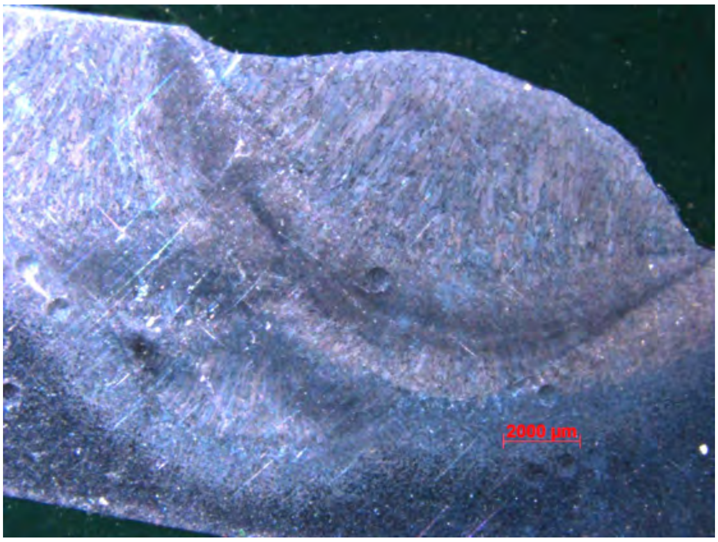


5LK

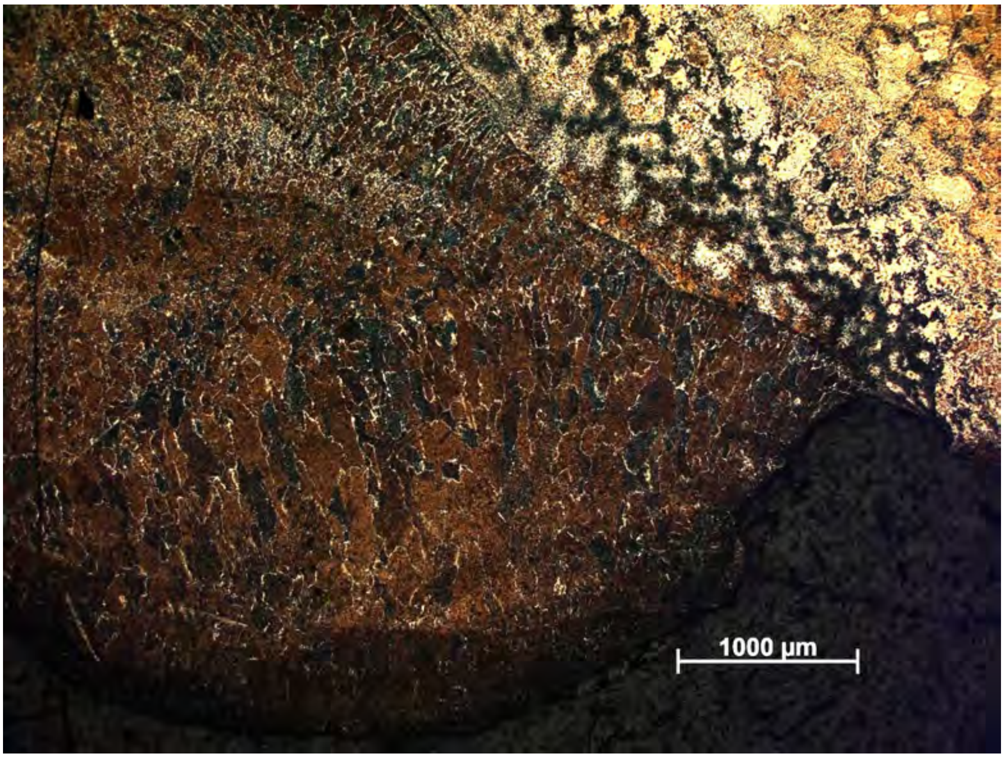
5MK

No Stereo microscope picture available for 5MK, please look at the Optical micrograph instead

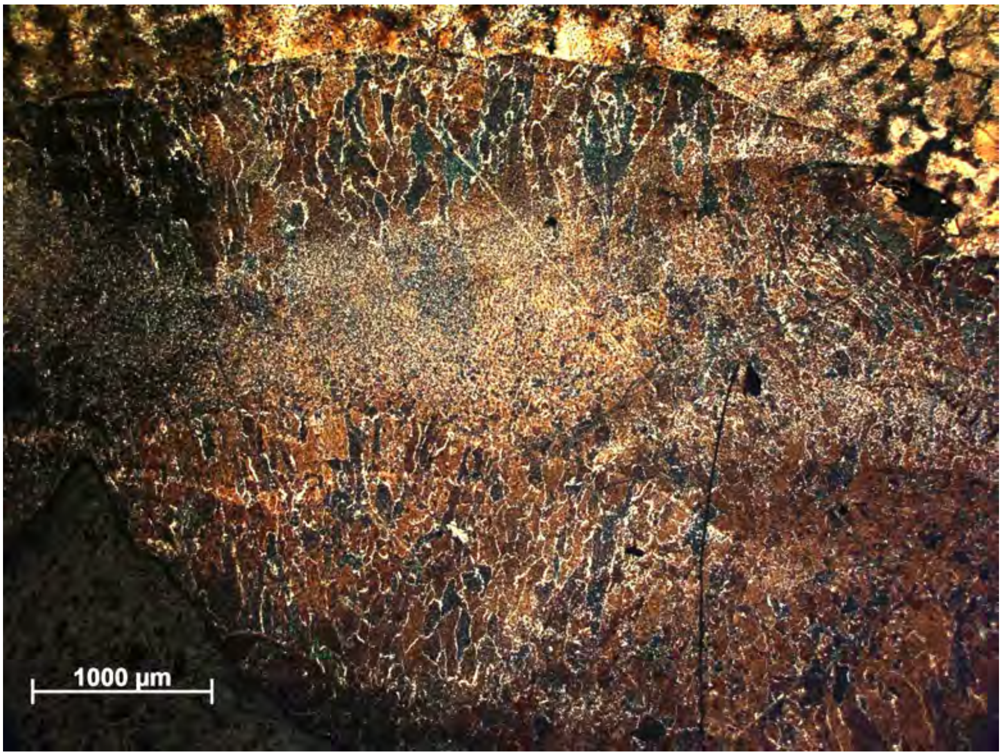
5HK



Appendix 2: Micrographs Optical microscopy



2L side weld bead

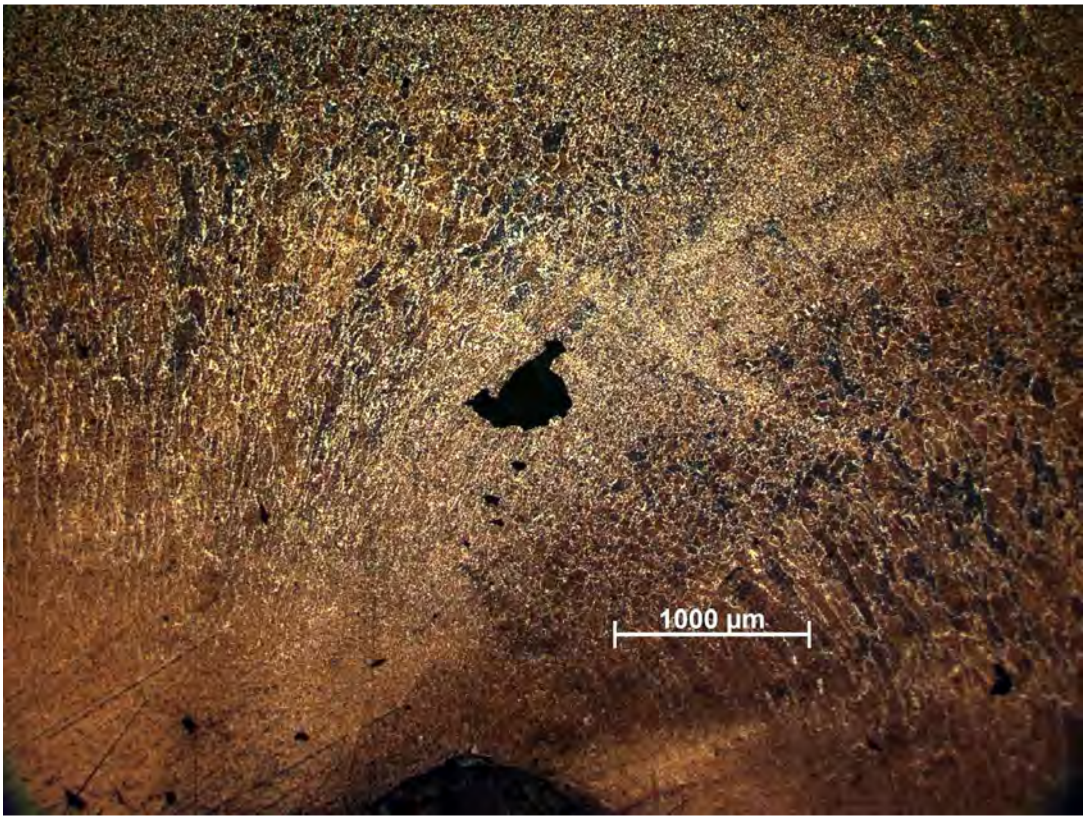


2L weld bead transition

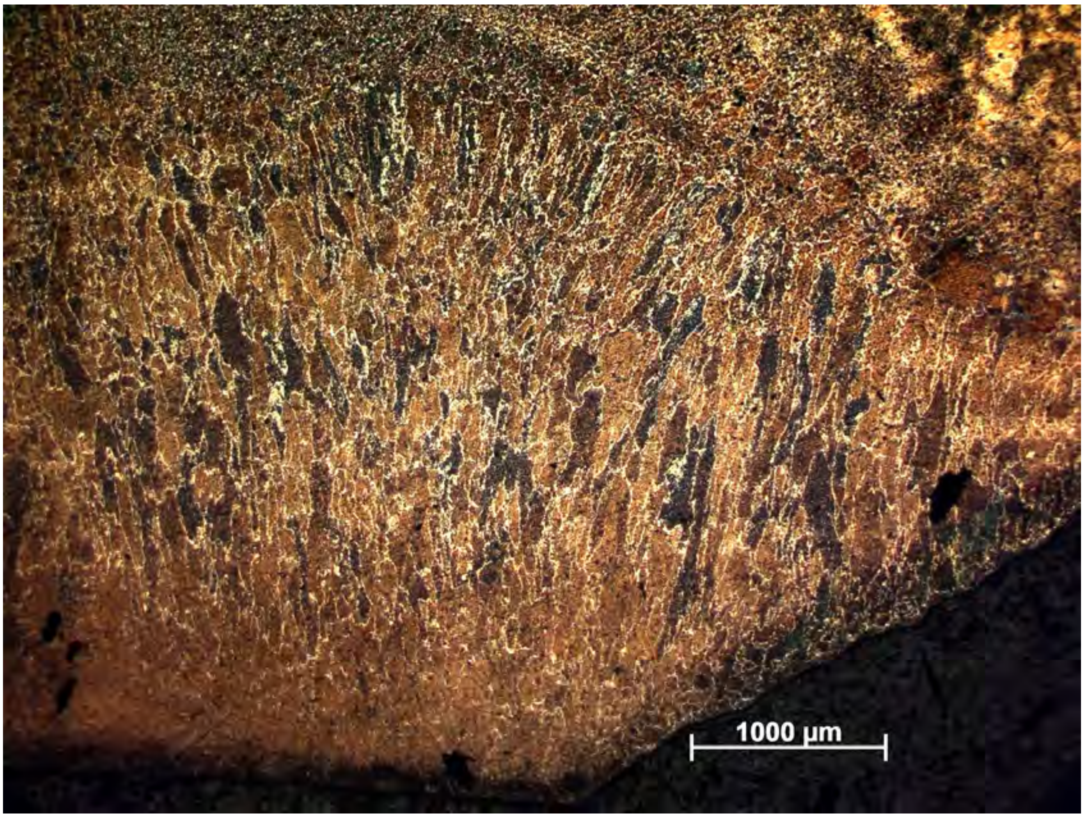
2H

2H side weld bead

3.2L

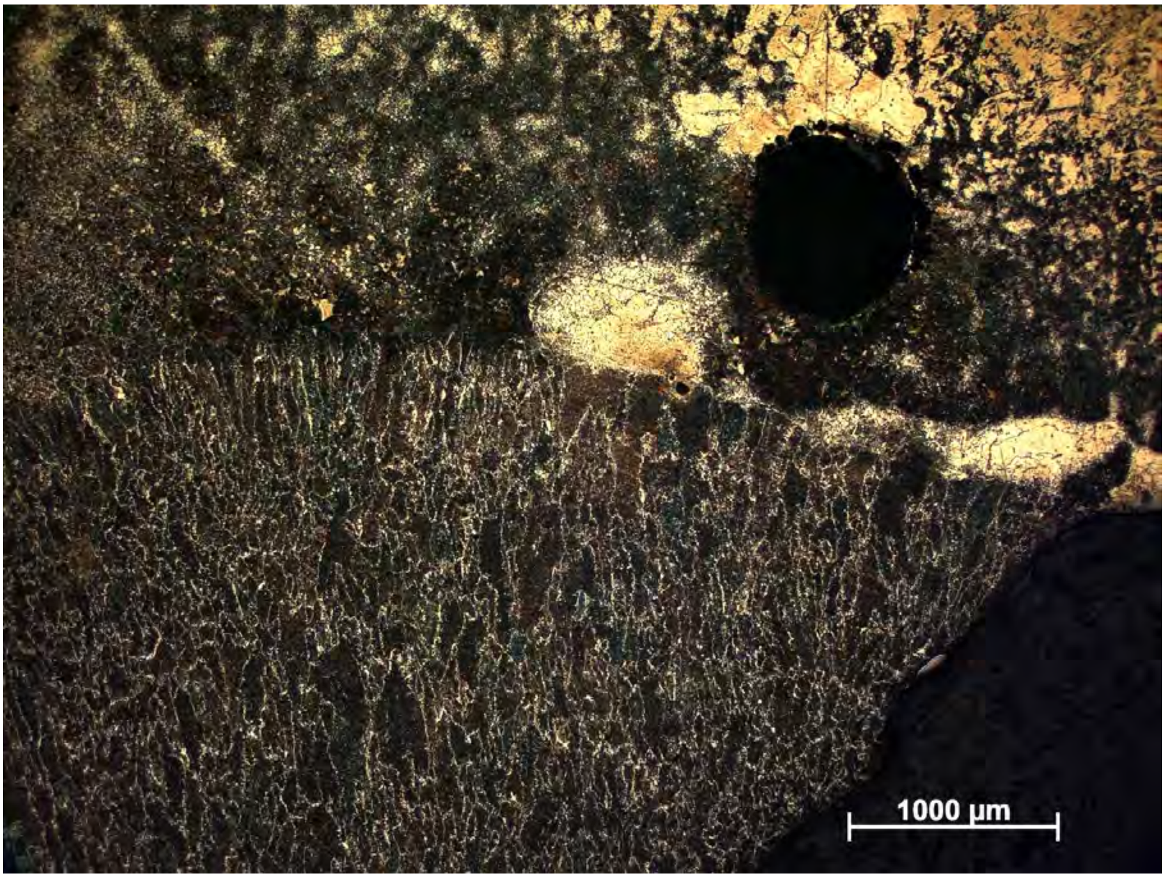


3.2L pores in between successive weld beads



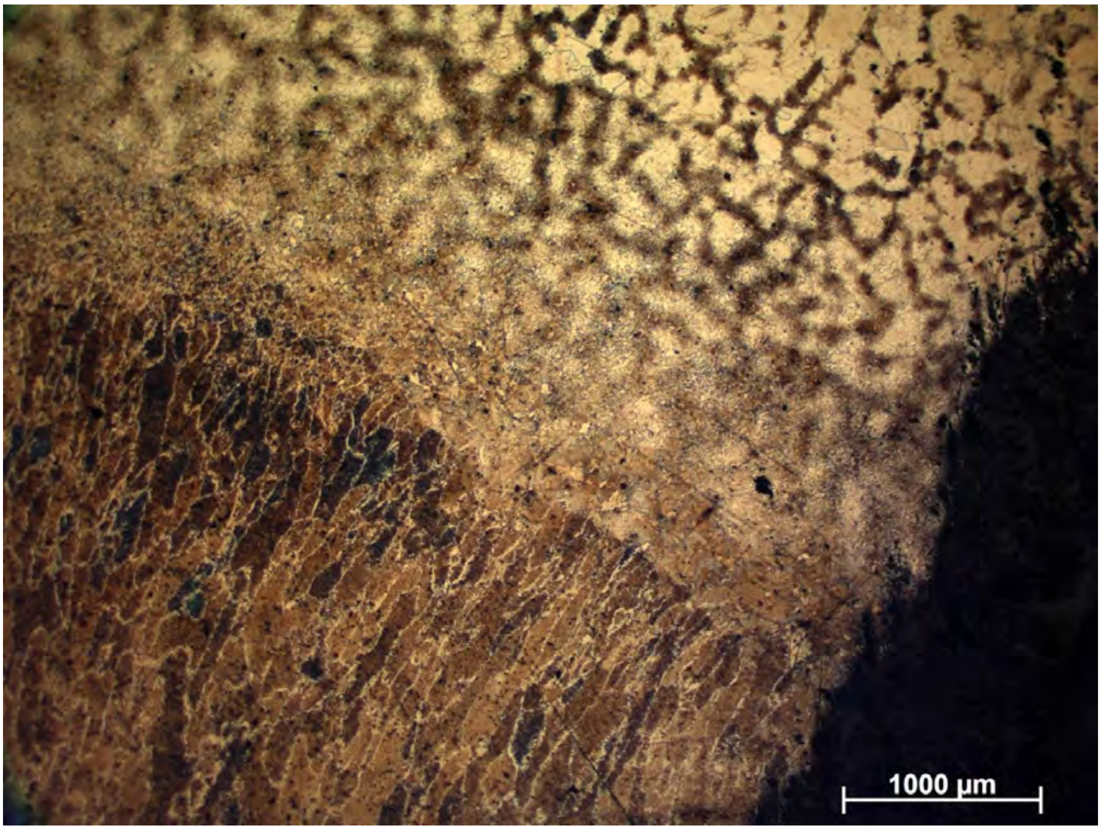
3.2L top weld bead

3.2M

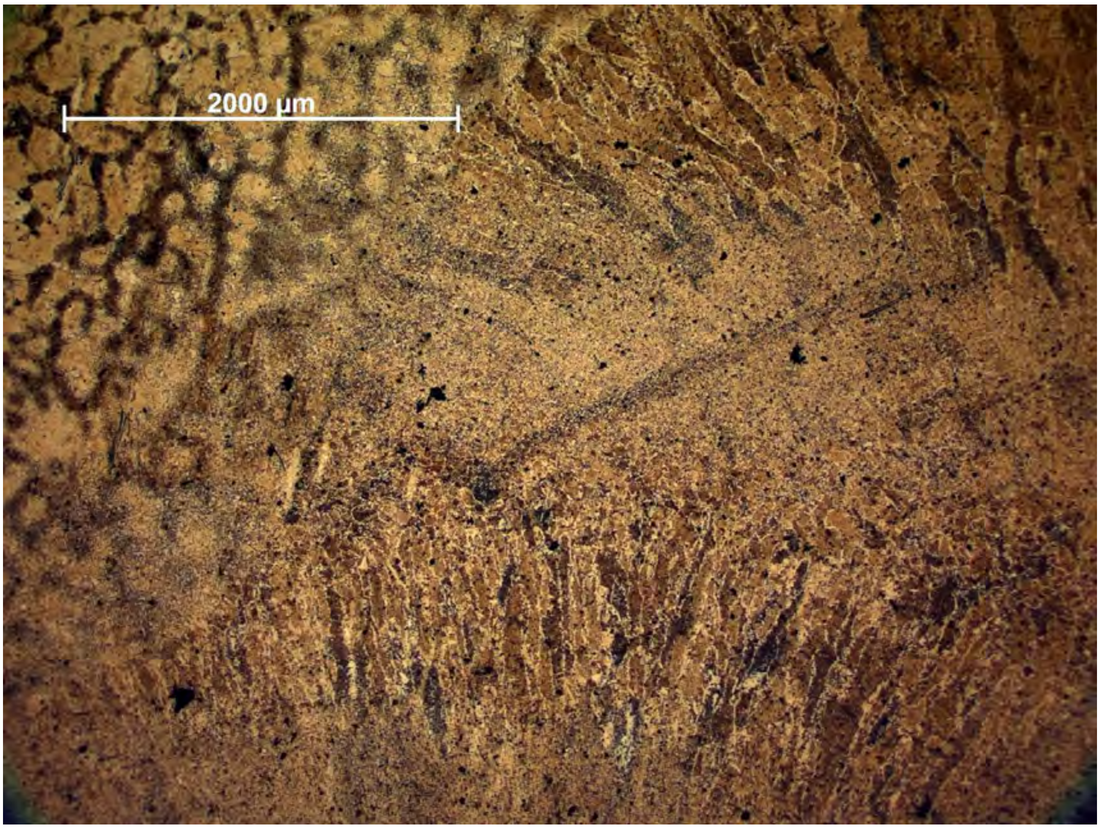


3.2M top weld bead with big pore in BM (over etched)

5L

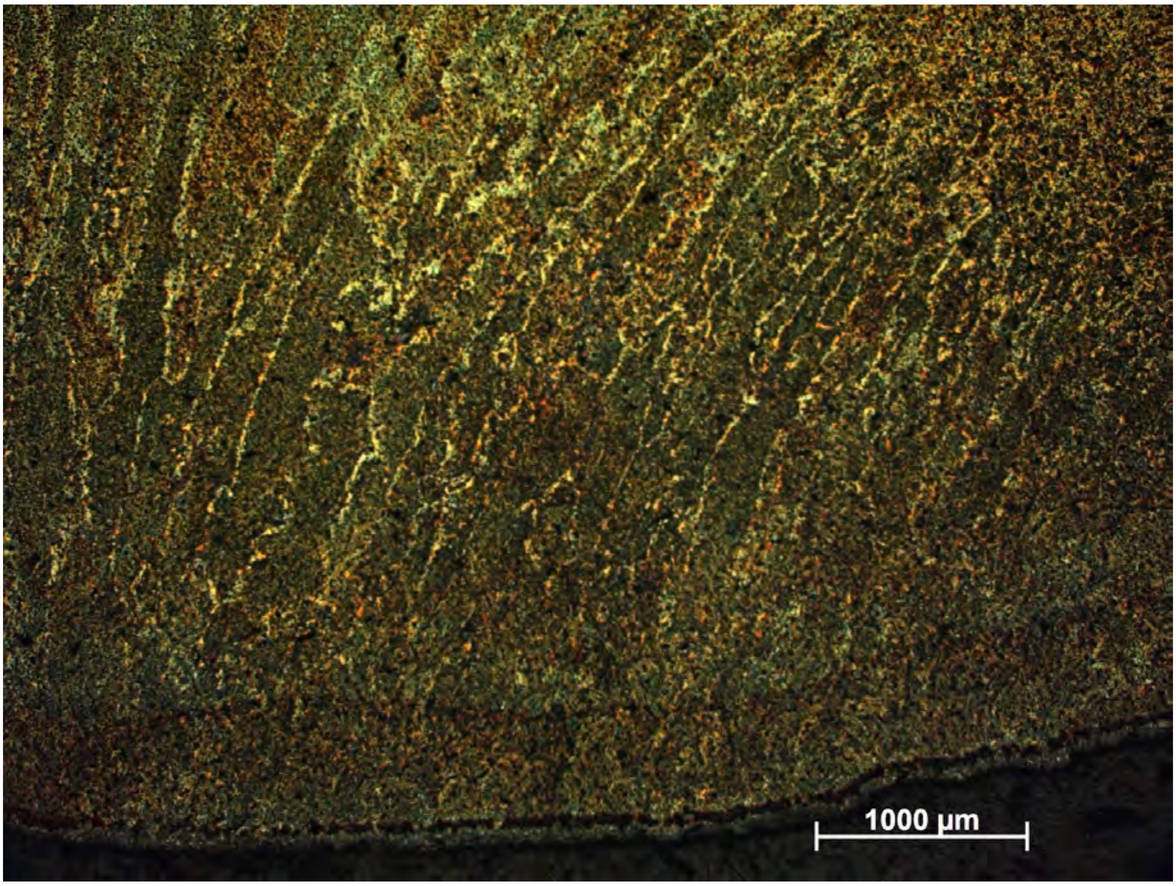


5L side weld bead



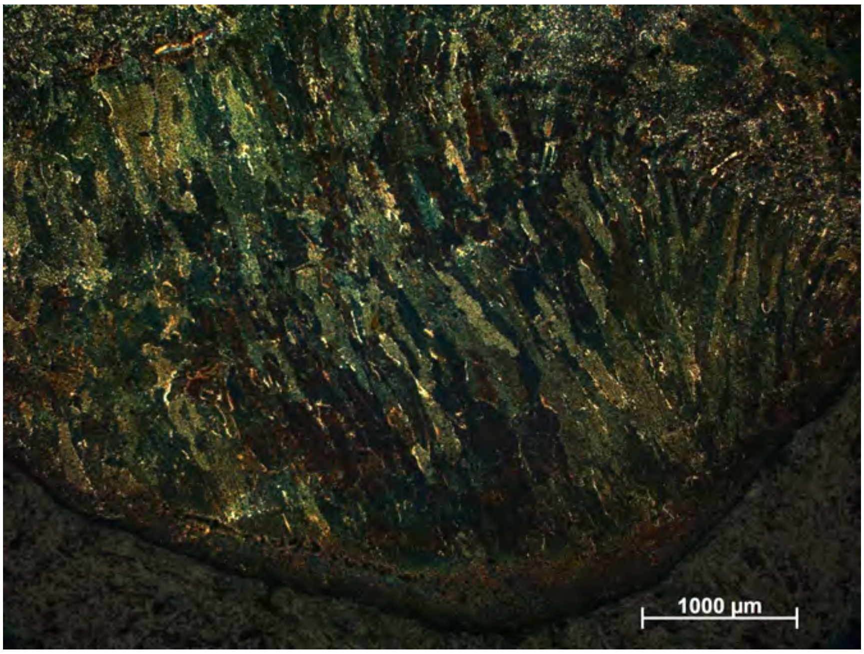
5L weld bead transitions. The HAZ in the first weld bead contains recrystallized grains.

5M



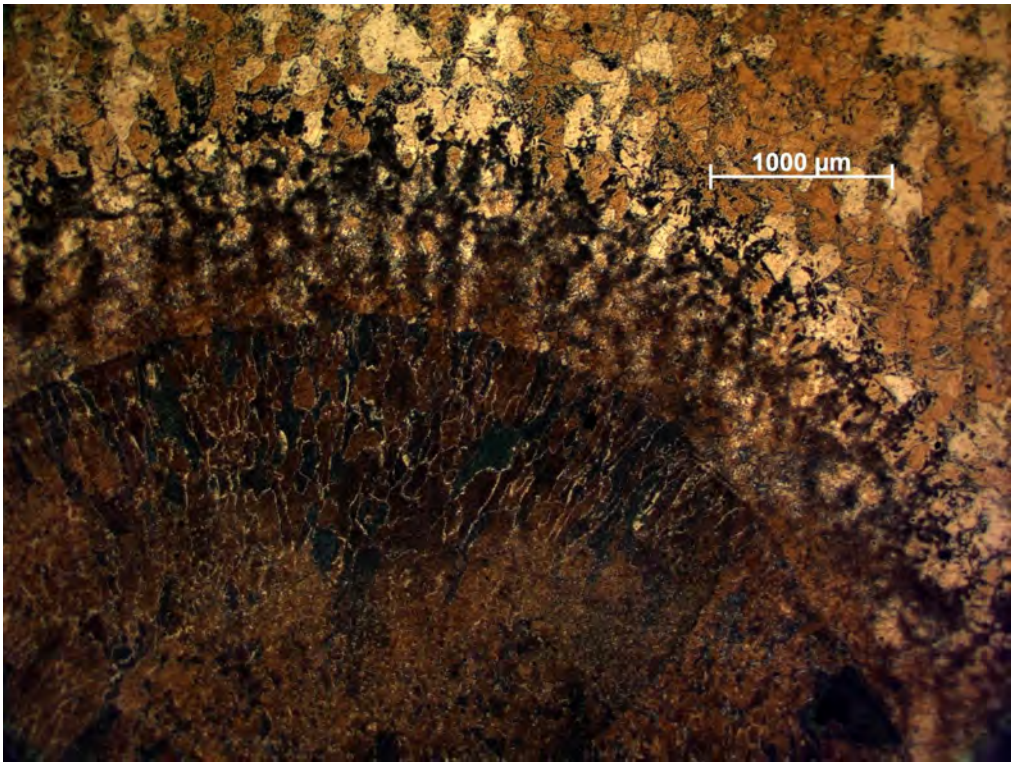
5M top weld bead over-etched

2LK

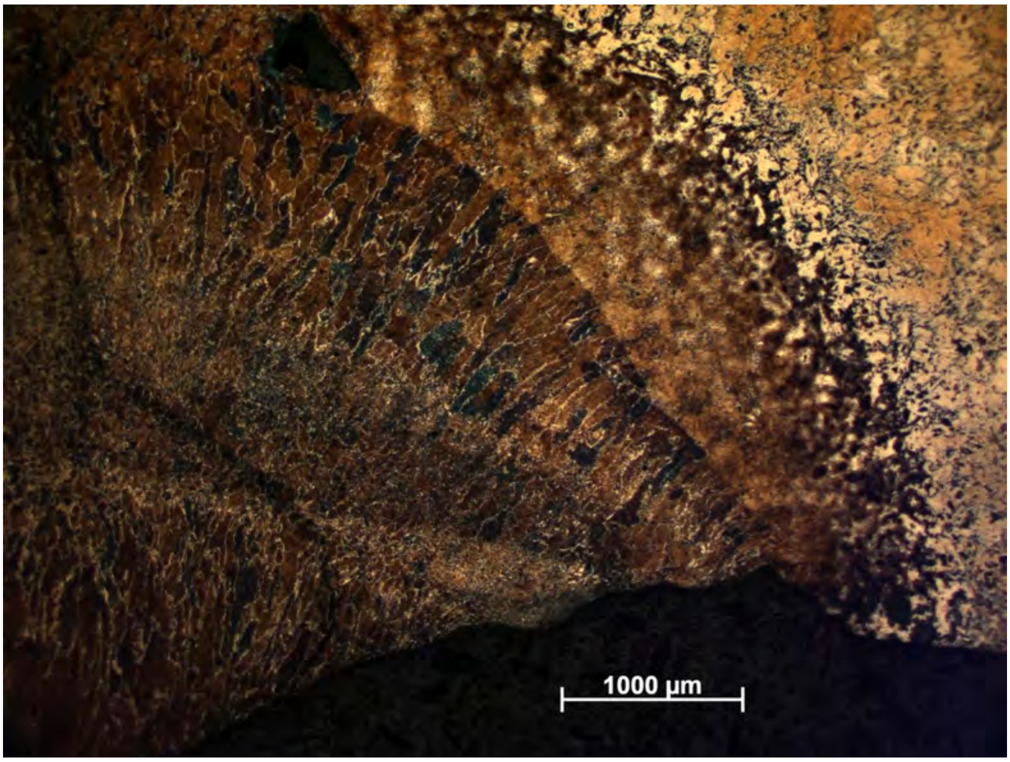


2LK top weld bead

2MK

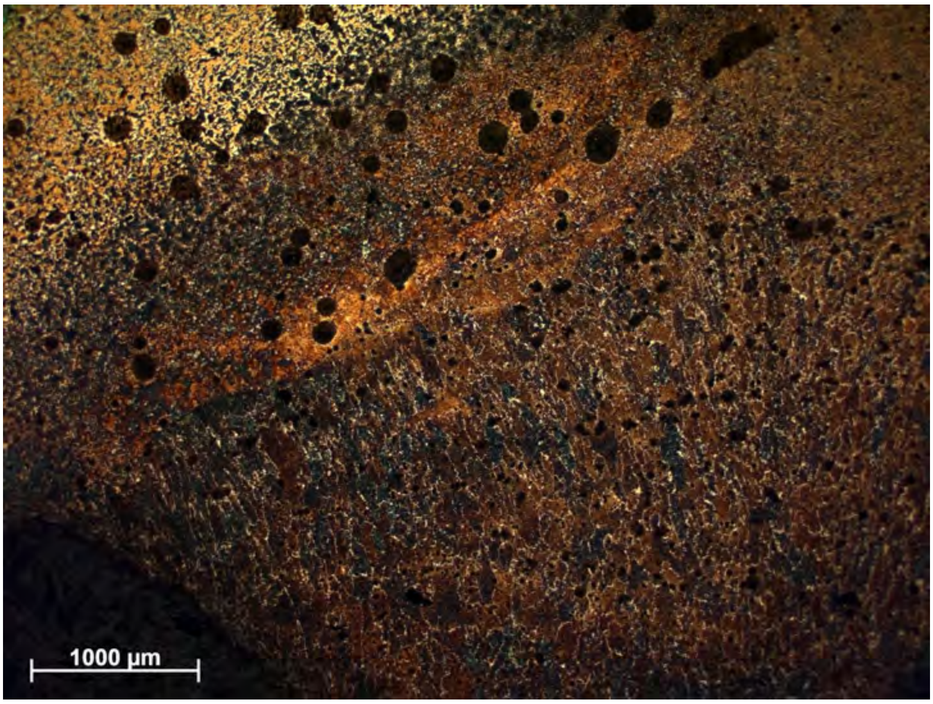


2MK bottom weld bead



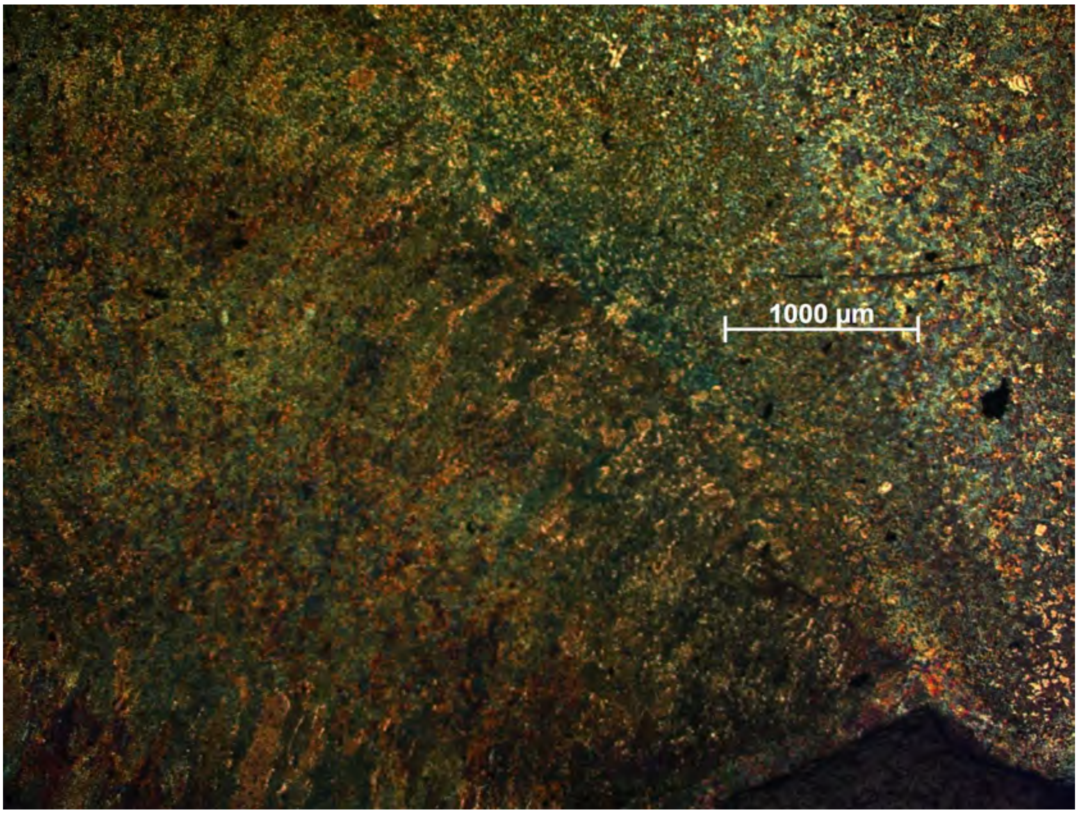
2MK side weld bead

3.2LK



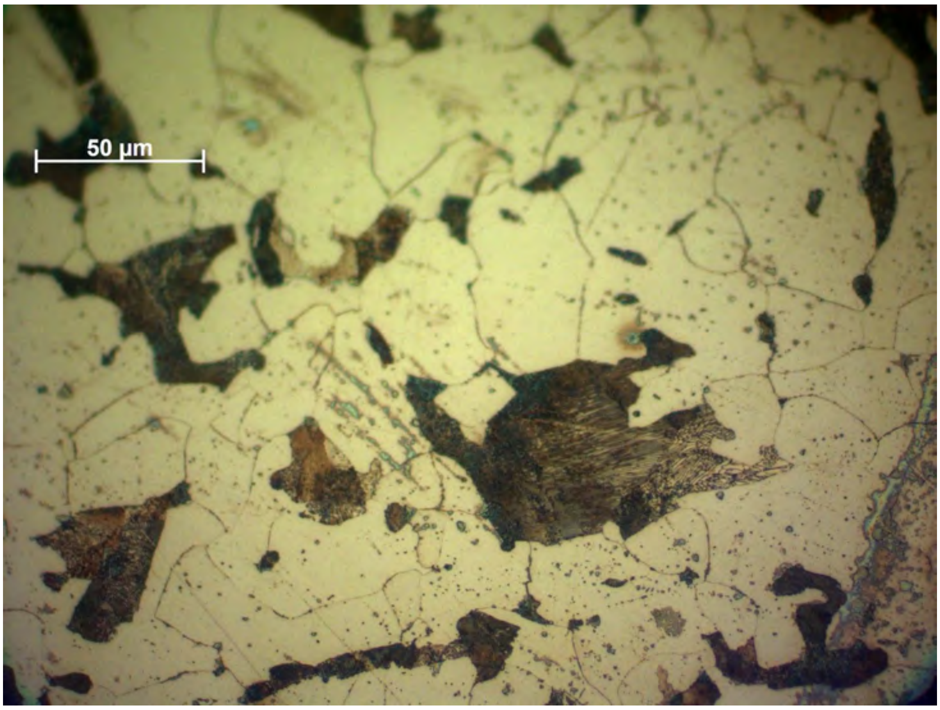
3.2LK side weld bead. The dotted pattern is probably due to bad sample preparation (not pores)

3.2MK

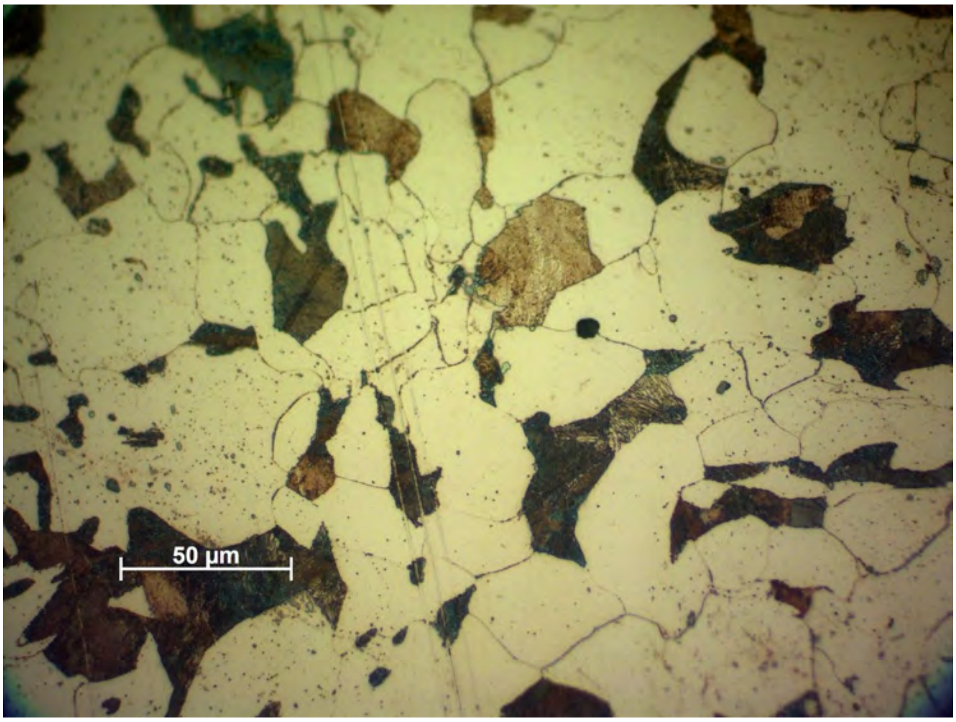


3.2MK side weld bead

3.2HK

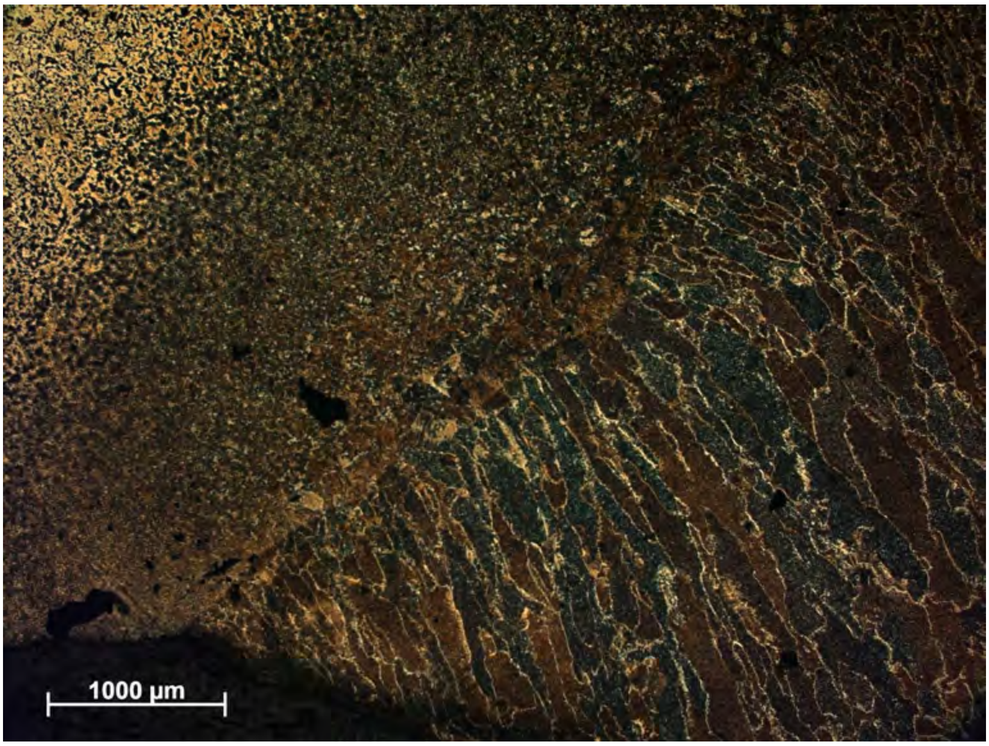


3.2HK BM with pearlite (lamellar, darker micro constituent)

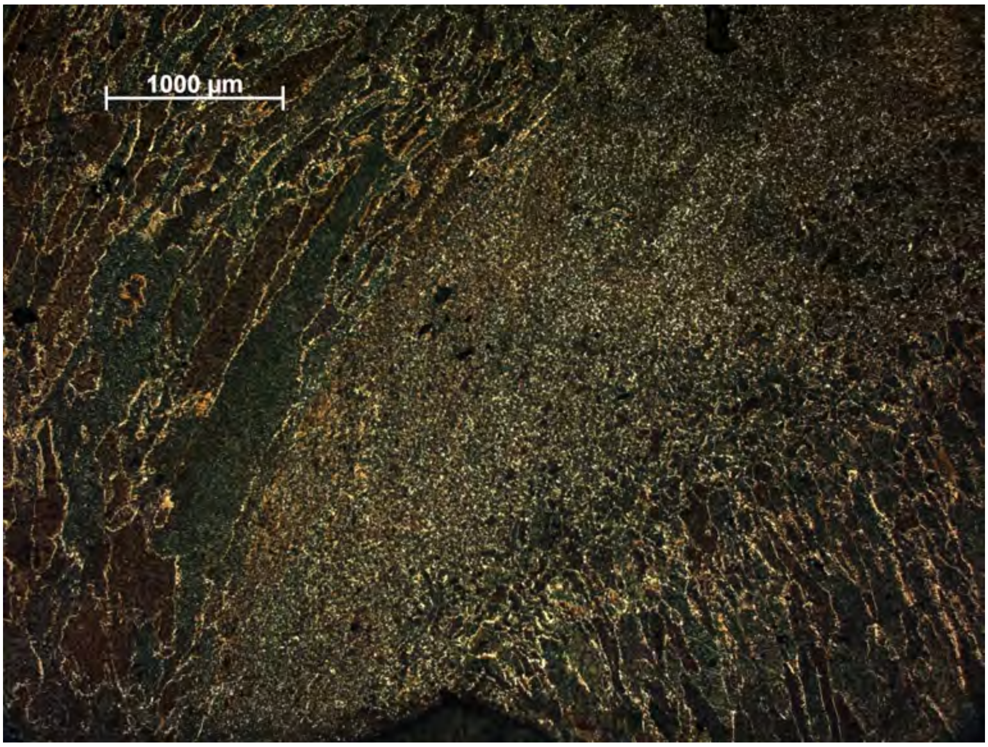


3.2HK BM with pearlite

5LK

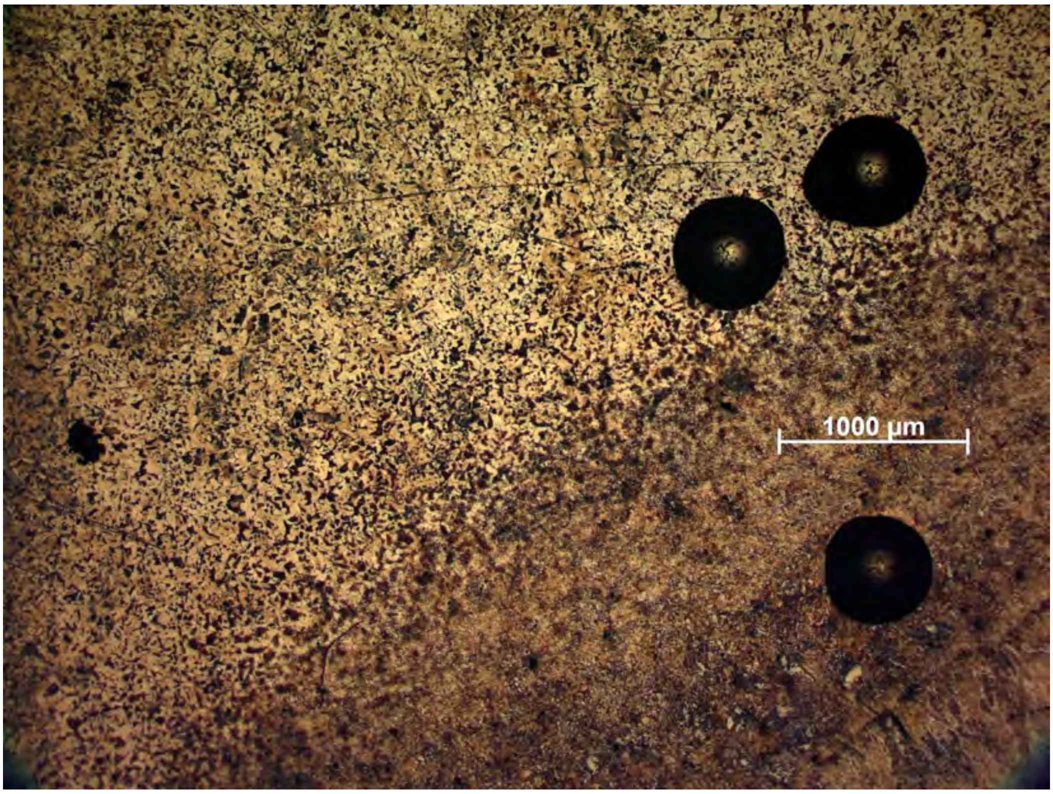


5LK side weld bead

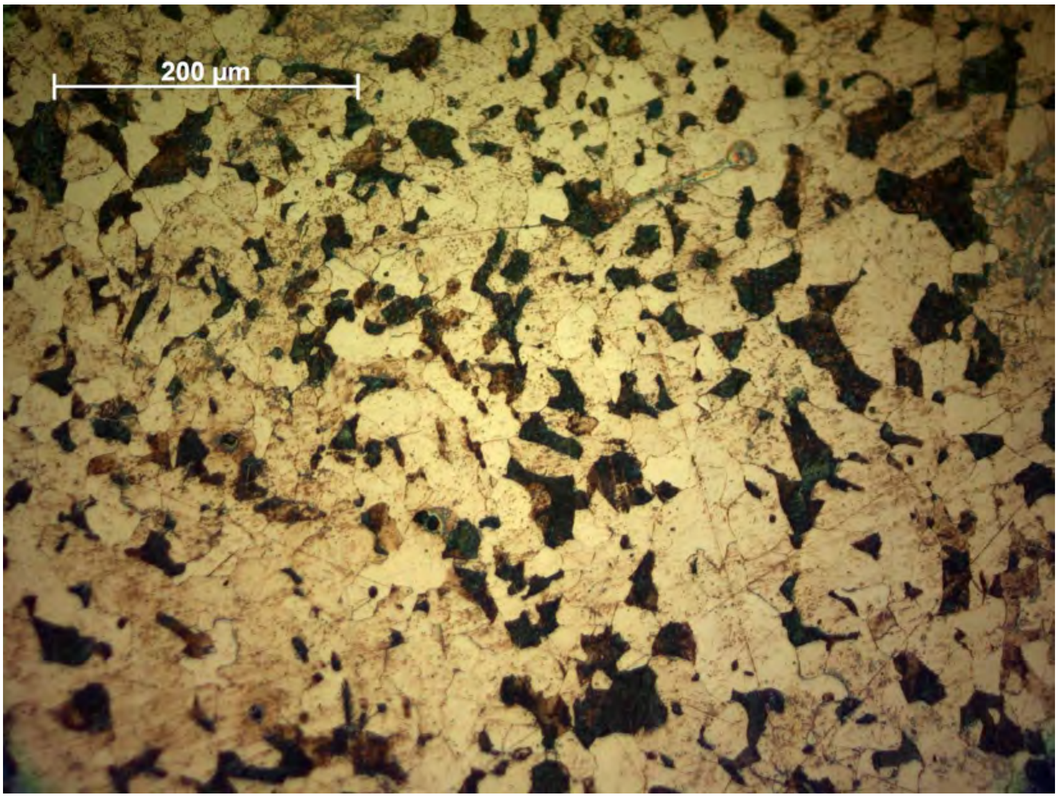


5LK weld bead transition

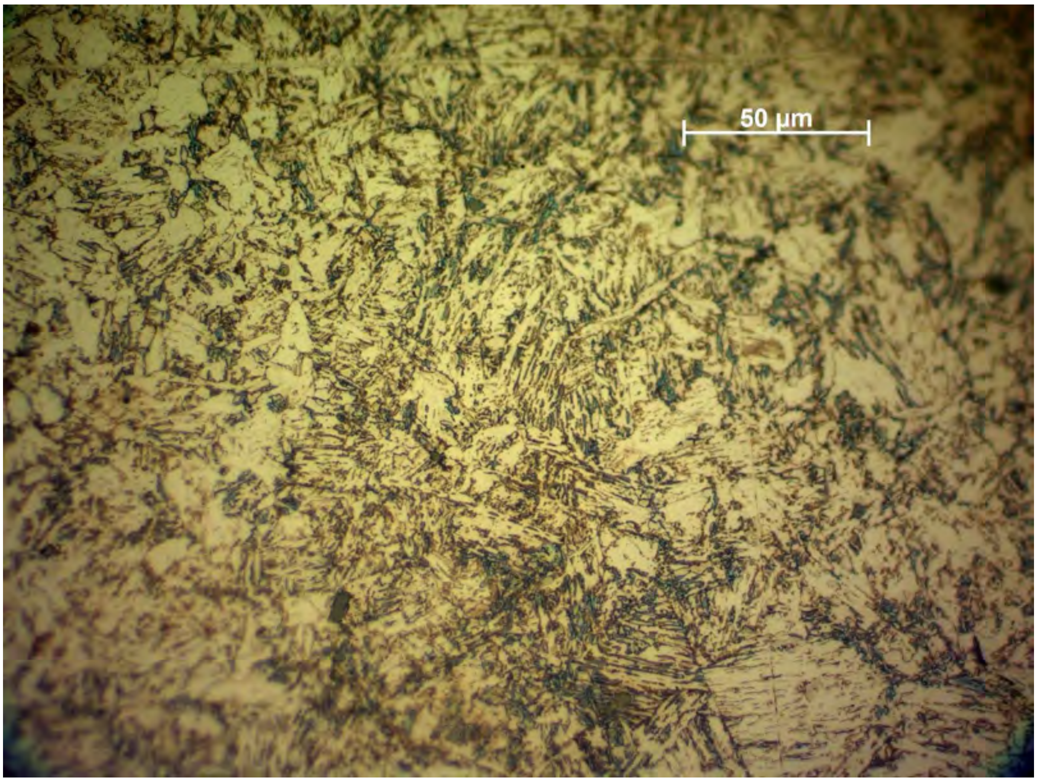
5MK



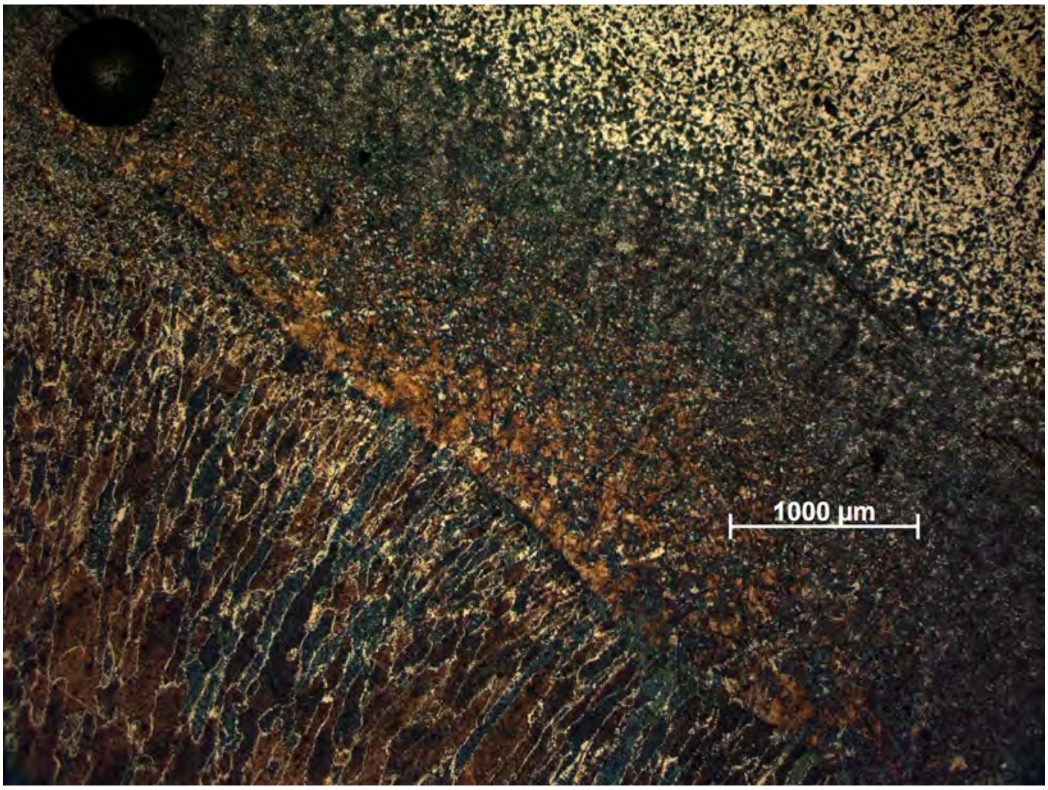
5MK BM and HAZ with hardness indents



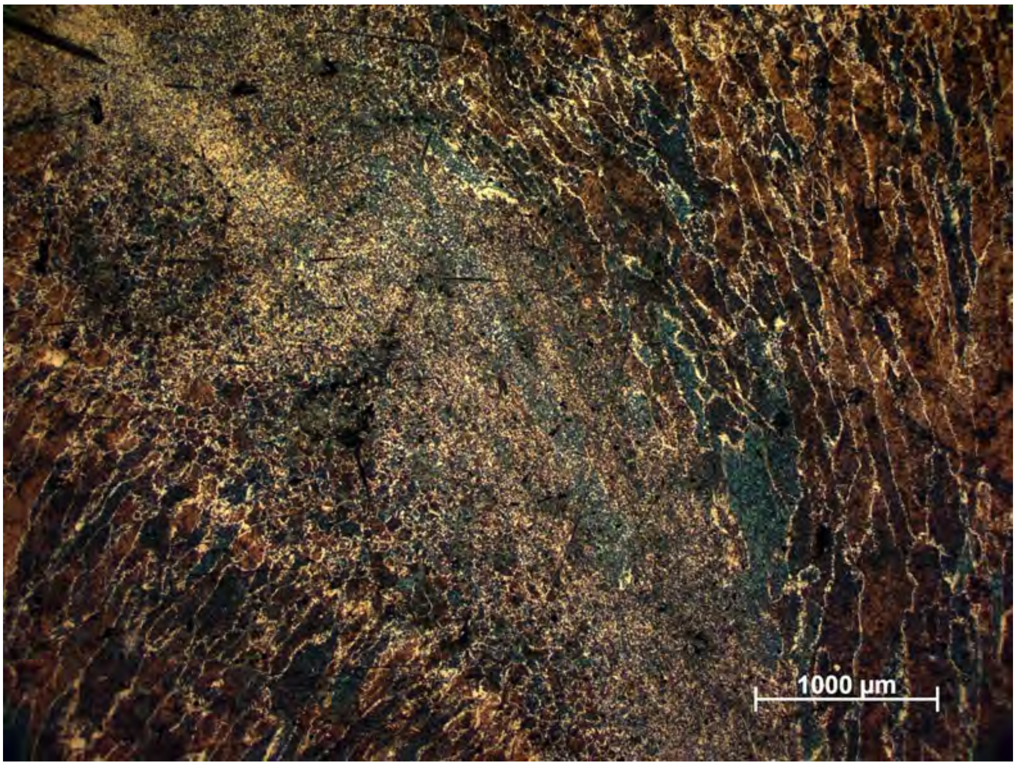
5MK BM higher mag



5MK HAZ with Widmannstätten structure



5MK side weld bead with hardness indent



5MK weld bead transition

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