UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Escuela Técnica Superior de Ingeniería del Diseño

Repair of ductile cast iron frames for heavy trucks used in quarries and mining

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Summary

1. Introduction and objectives

We use cast irons since centuries, and the types of cast irons and the way of welding them had evolved through this period. For example, the medieval cast iron had a microstructure similar to gray iron with white iron and nonmetallic inclusions, starting from the 18th century they created a new type of cast iron by adding a heat treatment in order to create malleable iron which is more ductile. What we call today spheroidal graphite was created in the middle of last century, the ductility was provided by the spheroid graphite and adding magnesium for example. Cast irons are this significant, thanks to the carbon which was added in saturation quantity. In fact cast irons are mainly alloys of iron, carbon and silicon which favors the formation of graphite. In ductile cast iron we keep the percentage of carbon under 4%, because over it creates too brittle structure. With a percentage higher than 2%, they are not considered as steel and have not the same mechanical properties, they are used in hydraulic valves, gears and transmission or shafts. [11]

Grey cast iron, for example, have a microstructure very brittle with graphite flakes in its microstructure that leads to discontinuities, they are not used to support mechanical efforts. However Ductile cast iron is different thanks to the alloy elements, in fact the presence of magnesium, magnesium-ferrosilicon and magnesium-nickel provides the formation of graphite nodules which gives to the microstructure a better ductility and toughness and without losing the ease of moulding cast irons. Also called nodular cast irons, this type of cast iron is used in many applications such as pipes for examples :

Figure 1 : Ductile cast iron pipes

They compete with polymeric materials such as PVC or polypropylene which are lighter, however they are less resistant too. Ductile cast iron is also used in automotive industry, including off-highway vehicles such as class 8 trucks. In the class 8 trucks, we find gross vehicles exceeding 15 tons, such as dump truck or haul trucks. The main parts of this trucks made with ductile cast iron are the frame and its surrounding parts. They need to be very resistant because they work in difficult conditions, it may lead to failures in certain conditions, so the goal of this study is to provide the best process to repair ductile cast iron cracks on haul truck frames by welding them, in order to answer this issue, we are going to study the need of heavy truck frames and their main component : the ductile cast iron. After this we are going to develop different solutions that already exist in the welding, the next point will talk about the adopted solution and its description before ending with an economic study of the chosen process.

2. Study of the need

1. Heavy trucks frames

Heavy haul trucks are off-highway vehicles which play a major role in the industry of mining and quarries, rigid haul trucks (see next figure) can support a payload from 30 to 360 tonnes resulting in a vehicle mass between 60 and 560 tonnes. They generally count 6 wheels and the load is distributed all of around these, the height of rigid haul trucks can reach 16 meters and also got a 10 meters wide and 15 meters long . Using generally a combustion engine this kind of trucks can be equipped with a hybrid powertrain as they have an electrical motor as well with a rear wheel drive.[1]

Figure 2 : Caterpillar 797F – rigid frame

There is another type of haul truck with an articulated frame, these are an all-wheel drive off road trucks, they have a payload of 20 to 60 tonnes and a vehicle mass up to 100 tonnes. All of the load is distributed all over the 6 wheels, they are smaller than rigid haul trucks and have a maximum height of 3 meters and 11 meters length (see next figure). [1]

Figure 3 : Volvo A60H

All of the dump transported on these kind of trucks and all of the equipment which are installed on the vehicle (motor, gearbox, battery, transmission, …) are supported by the chassis and the wheels (figure 4). So the frame is the backbone of the truck and need to support loads for long operating time. On the frame we can find defaults as voids of inclusions due to the manufacturing casting process, these little defaults can lead to cracks and failure under the working conditions. The cracks generally occurs at radius and thickness transitions in the chassis. The chassis is under different conditions as the acceleration/braking, the road surface and the temperature/pressure can change easily. Nevertheless a working cycle can be deduced as we have loading or dumping and empty or loaded travel which can lead to the fatigue of the chassis. [2]

Figure 4 : Haul truck frame with components

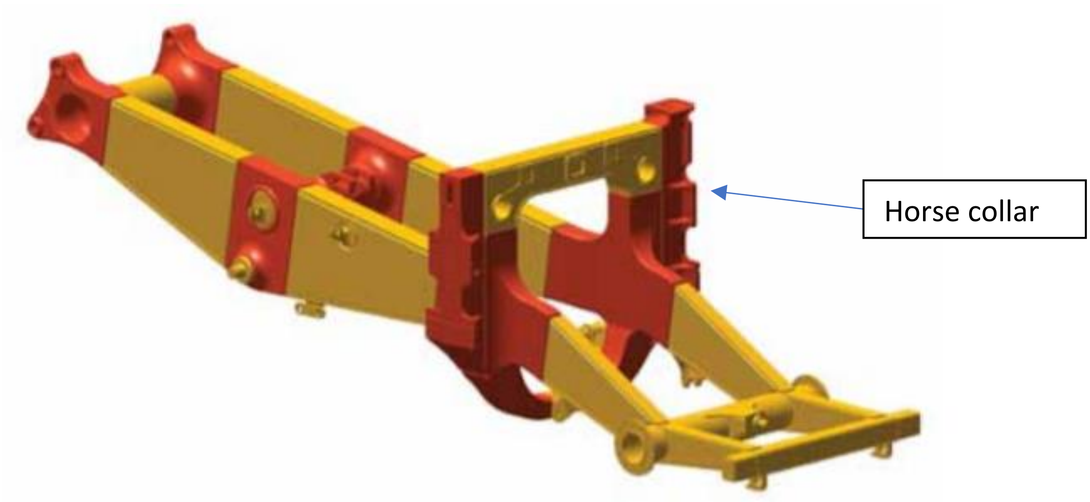


Figure 5 : Frame of a Komatsu 730E-8

In the frames we have two main parts the side rails, and the crossmembers between both side rails, this gives to the frame a form of ladder and it can be under three main types of load : vertical, torsional and side. The two side rails hold the engine, transmission, fuel tanks, suspensions and battery for example. While the crossmembers are used to provide torsional rigidity and also hold engine and transmission system. They also prevent the side rails from torsion due to side loads. [3] There is a neutral axis where there is no stress in the frame, so irregularities there won't cause failure. However the more you approach flanges, the more you can have failure. With the variation of the operating conditions and the working cycle we apply forces on different elements, by having stress and bending, leading to cracks created by fatigue.[3] However we can also have failures due to unusual one-time outside stresses. In the case of the Komatsu (see figure 5) the frame was designed to support 200 tons, and to increase the frame reliability, castings have been incorporated at important points such as pivot points and in bearings where critical load is applied on the frame. It includes two points generally : the rear body bearing and horse collar portion. [7] The frame was manufactured using different processes, one of them is shield metal arc welding (SMAW) as we can see Liebherr T 282 C assembling video. [9]

Figure 6 : Caterpillar 797F frame

As we can see in the Caterpillar 797F frame (see figure 6) we have quite a similar basis to the Komatsu frame. In our case here, the frame has also a box section design, this includes 2 forgings and 14 castings in the high stress areas with “deep penetrating and continuous wrap around welds to resist damage from twisting loads” [8]. There is also mild steel in the frame, to provide flexibility and durability to the system. However cast irons count for 80% of the frame’s mass (215 tons), they are the key to provide resistance in very difficult work conditions and ensure long life working. In the case of the Caterpillar 797F, we have a suspension system designed to dissipate impacts, loads and vibrations the best way they can. In fact the suspension is designed as an extension of the frame, we have rugged cylinders for the damping, in the back the rear cylinders allow oscillations and absorb torsion and bending rather than transmitting them to the frame. [8] (see all dimensions in the annexes)

So cracks can be formed during the manufacturing and during operating conditions, in all of the cases they can lead to loss of benefits for the manufacturer or the user. They must be fixed, and we are going to focus on the repair of failure using a welding method on ductile cast iron. It is hard to weld some parts of the frames because we commonly find variation of thickness or radius as we can see in the following figure :

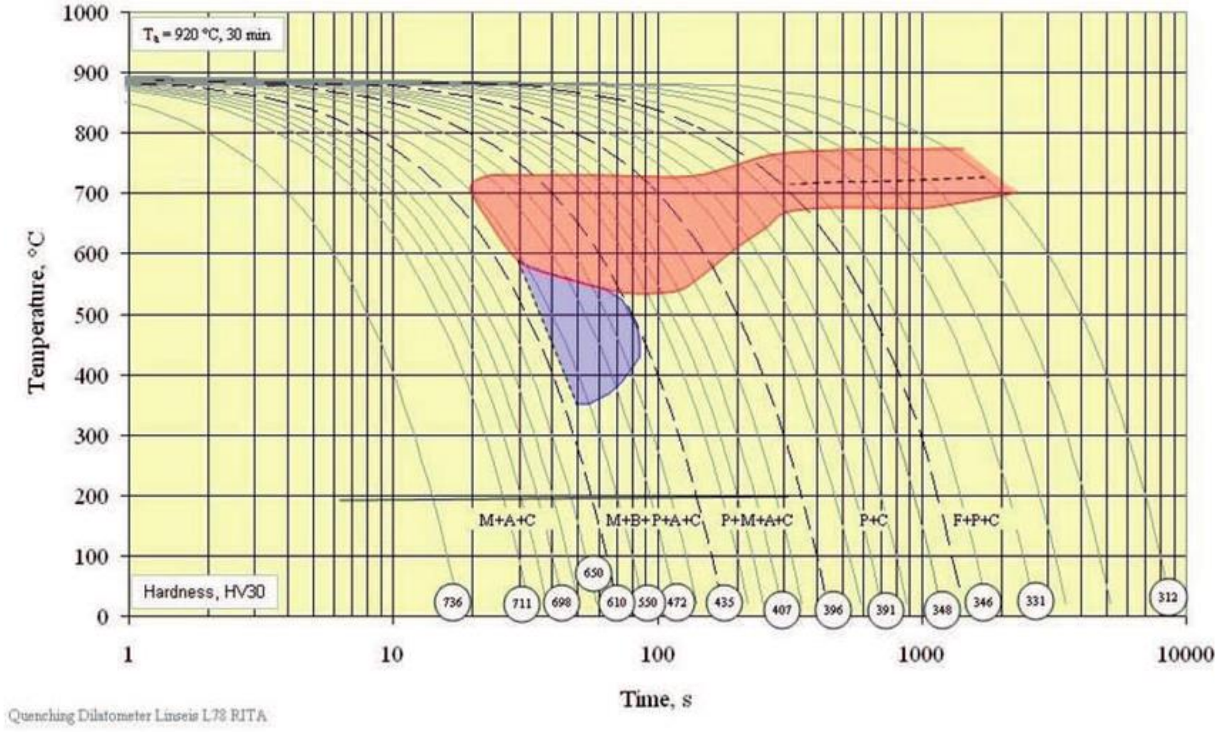
Figure 7 : Cast iron mine trucks parts

As we can see some parts are very complex such as the arm, moreover the majority are big and heavy we have to give priority to the repair than changing the part. For example wheel hub are a very critical part and a failure there is very costly and could lead to an accident, made of ductile cast iron the repair can made by welding however it is difficult to provide such a good result and that's what are going to study in this report.

2. Weldability of mine trucks parts

In case of cracks we should fix them using welding, however ductile cast irons are difficult to weld because of their properties. We keep using them despite their poor weldability and it's a challenge to improve the welding process. First of all the difficulty lies in the fact that we have complex geometry parts, reaching the broken zone with an electrode can be very hard as keeping a clean welding pass. Reaching and providing an homogenous welding pass through the failure can be difficult. Another difficulty comes from the variation of geometry of the parts, by variation of geometry we mean variation of radius or thickness for example or sharp angles. What makes ductile cast iron so difficult to weld is the consequences of the process on the microstructure of the metal. The melted zone reaches very high temperatures and the cooling is so fast that brittle microstructures precipitate making the structure harder but also more brittle and less tough. When we heat it up we form austenite a phase composed by iron and carbon and it transforms to other phases depending on the cooling rate.

In fact the carbon precipitates in different forms depending on the conditions, when the cooling of the melted zone and the heat affected zone is fast, martensite is formed. It gives a higher hardness however the toughness is lower due to the brittle aspect of the microstructure. (See annex 2 for the different forms of phases)



F – ferrite, P – pearlite, B – bainite, A – austenite, M – martensite, C – carbides

Figure 8 : Continuous cooling diagram transformation of nodular cast iron

(Chemical composition 3.78% C; 2.26% Si; 0.24% Mn; 0.89% Cr; 0.78% Ni; 1.50% Cu)

As we can see in the figure 8, generally when we weld cast iron, we increase the local temperature, indeed the melted zone surrounded by the heat affected zone get to very high temperature that changes the microstructure of the cast iron. We form austenite at 900°C and if the cooling occurs fast we tend to form martensite. The martensitic structure affects the toughness of the local structure, making the welded zone very brittle and having more chances of failure. This makes the welding difficult and creates the need of improving the welding process, or making necessary to add some pre or post processes to avoid this issues.

3. Approach to alternative solutions

1. Weldability of cast irons

Cast irons have a poor weldability, however we keep using them in lot of applications because of some of their useful properties. We have different types of cast irons, the general ones are white iron, gray iron, malleable iron, ductile iron and compacted graphite. Today it is still an important part of the industry and metallurgists keep producing complex cast irons assemblies and improving the methods of welding them. However, most of cast irons are quite weldable except white iron which isn't. [4] The weldability of cast irons depends on the matrix, the chemical composition, the welding process and the mechanical properties. Carbon is present in different forms in cast irons, for example it can be combined carbon (such as martensite, pearlite, cementite) and also as free carbon (graphite). In gray iron, the graphite appears as flake particles, in ductile iron the carbon appears as spheroid graphite and in malleable iron quasi-spheroidal graphite. The poor mechanical properties of the cast irons are the consequences of the graphite which is present in the matrix and produces discontinuities leading to the brittleness structure : this is the case of graphite flakes.

What makes the cast irons so difficult to weld is first of all the lack of plastic ductility, compared to steel the cast iron doesn't reach plastic behavior in a stress-strain curve and fracture occurs before the yield point. In the case of gray iron, the carbon precipitates as particles of graphite, this makes the gray iron have a good strength, nice damping properties but low ductility. This parameters in addition with others make the gray iron not very weldable. The case of white iron is not that far from this last one, in fact if the cooling is rapid, there isn't enough time for the graphite particles to form and most of the carbon may form cementite. The cementite reduces the ductility and the weldability, while it increases the hardness. The cementite is really brittle and this causes cracking in most of times, indeed this makes cementite composed cast irons not very weldable. Nevertheless, when carbon is present in the microstructure of the cast iron under graphite spheroids form, the weldability will be better than the gray iron. The exceed of carbon is another parameter that makes the cast irons not weldable, in fact when we reach high temperature at the melting point we affect the surrounding zone by heating. This heat affected zone brought to high temperatures makes carbon change form into austenite and cementite, and if the cooling is fast it precipitates to martensite which is very brittle and may crack fast. So the welded zone has some weaknesses and may fail under conditions, just the fact of welding cast iron change its microstructure by creating brittle phases, and this is a big issue.

2. Case of ductile cast iron

Before welding a ductile cast iron, we must focus on its original matrix structure, in our case we are studying a ductile cast iron with about 3.7% of carbon, graphite appear as nodules. [6] Compared to graphite flakes, the rounded form of the nodular graphite gives (see following figure) gives a better toughness and ductility. The nodules came by adding nodulizing elements such as magnesium which boils at 1100°C while iron melts at 1500°C. Indeed, magnesium eliminates the graphite's discontinuities, making it less brittle.

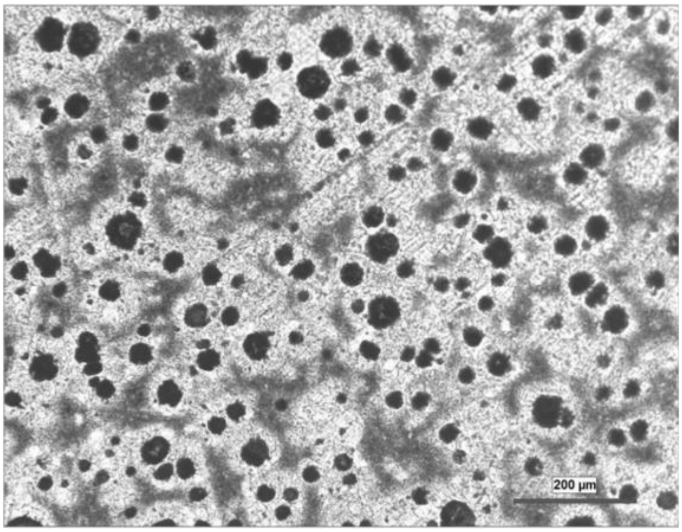


Figure 9 : Ductile cast iron microstructure with graphite nodules (zoom x100)

Generally, the ductile cast iron has a ferritic-perlitic matrix and it is difficult to obtain similar properties as the parent material when we weld it. Changes of structures always occur when we weld it and formation of martensite in the surrounded heat affected zone is a one of those problems related to the transformations. Austenitic and martensitic matrixes may appear when welding, and iron carbides may also appear as cementite for example.

3. Welding process :

SMAW process is the most used technic for ductile cast iron welding. In fact, this process is generally used in the industry because of its low cost fillers and the easiness of the welding process compared to others. It is interesting to preheat the electrode at 90°C for 24h [6], in order to improve the fluidity and the inclusion of the hydrogen, in order to prevent it from cracking. Ductile cast iron (see annex 2 for composition) was welded using only SMAW process with a filler of 97.6% Nickel, and another specimen was welded with TIG process and Inconel 625 for the root and then a filler pass with SMAW and nickel. [12] What was noticeable is that TIG root with Inconel made appear parts close to the white iron structure with martensite in ferritic structure. In these zones, the hardness was increased a lot and got losses in the ductility and toughness. In the following figure 10, the hardness reaches 520HV in the root to 610HV in the interface zone. This is caused by the Chromium in the Inconel which retains the carbides. In the Nickel bead made with SMAW, we have a hardness of 160HV in the welded zone , the ductility increased there, this is due to the Ni which dissolves the carbides in its structure.

Filler	Ni97.6 SMAW	Root TIG + Beads SMAW
R_m / MPa	320	300
R_y / MPa	310	285
A / %	8	7
T_l / MJ·m³	12,8	9,0
HV HAZ	194	210
HV Interface	320	610 325
HV WZ	227	520 160

Figure 10 : Mechanical properties of the weld [12]

Silicon made the graphite precipitate in the structure, we find it as graphite nodules which is good and different from a white iron structure. Moreover, if we focus on the interface between the root pass and the second pass, between the Inconel and the nickel, we can find that there is still Chromium which is in less quantity than into the root directly, however there are carbides in this zone and it affects the mechanical properties. If we now focus only on the 97.6% Ni SMAW process, we cans see that the hardness in the welded zone is lower 227HV, the mechanical properties are better with a higher ultimate strength for example. This is due to the nodular graphite in ferritic matrix which appeared at the interface and in the welded zone, this structure is closer to the parent material one. [12]

To compare both, generally the SMAW process has better results regarding to the ductility and toughness, it is less brittle and have less chances of fracture. However it has a higher cost and we need to take in into consideration, sometimes we can substitute this process by TIG for the root even if it is less efficient regarding to the microstructure.

Root pass :

A study has showed the effects of using a TIG process for the root pass (Inconel 625) and then Nickel electrode (97.6%) for the additional passes. TIG is recommended for the root pass, because of its efficiency for welding plates who has a thickness under 8mm. However, the additional passes with manual arc welding with electrode of 97.6% Ni have shown that carbides didn't appear in high quantity, as a matter of fact the hardness is way more lower and the elongation at fracture greater than the root weld with an Inconel 625 rod.

4. Pre or post processes

Effect of preheating on ductile cast iron:

Due to the higher amount of carbon in cast iron, the austenite precipitates into other brittle phases when we weld. These phases, as we have seen them before, are mainly martensite. The preheating conditions depend on the cast iron itself, of course the preheating temperature will depend on the percentage of carbon in the cast iron, the size of the welding wanted and the filler materials. What we want is to prevent the formation of martensite, in fact the preheating should be long enough to avoid this. The preheating reduces residual stresses, distortion and prevent cracking. Preheating also prevents apparition of porosity. It also reduces the hardness in the heat affected zone which prevent from cracking. Moreover the preheating reduce the size of the fusion zone and achieve good mechanical properties (elongation, hardness) . In fact when we preheat, the elongation of the material is increased in mechanical tests while the hardness is decreased due to less brittle phases. As a matter of fact, more pearlite tend to get formed in the melted zone. Preheating also offer a better mechanical resistance at the joint which can be considered twice better than the one without preheating in the case of a tensile test. Without preheating the mechanical resistance of the joint should be worse.

In the case of welding ductile cast iron with Oxyacetylene Welding (OAW), adding a preheat treatment at 350°C helped to avoid lot of issues : it relieved residual stresses, cooling rate was diminished and the chance of apparition of porosity and cracks was lower.[5] About the mechanical properties, it generally increased the ductility of the material. In the following figure we compare the microstructure of the welded zone with and without preheating at 350°C :

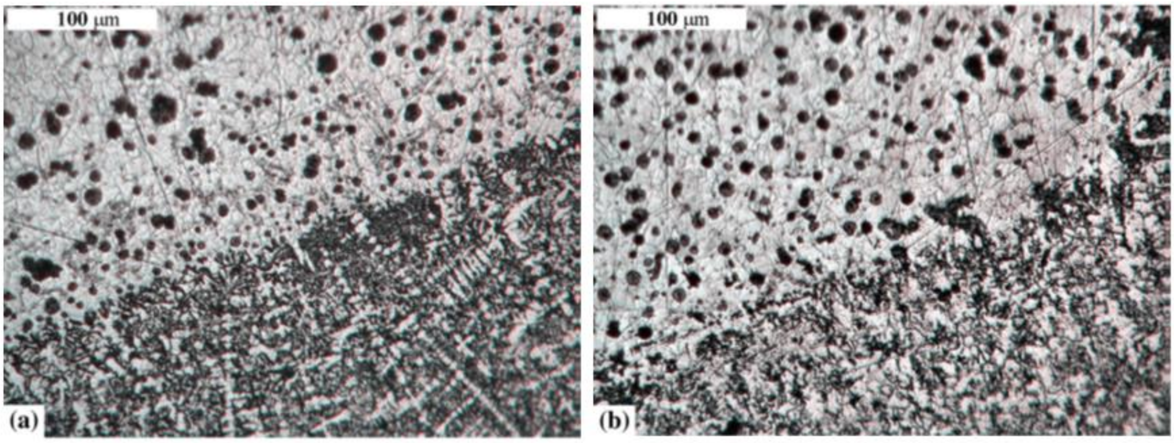


Figure 11 : Microstructure of parent medal-bead interface without (a) and with (b) preheat at 350°C with an OAW welding [5]

In case a, tensile tests had shown that fractures occurs at the interface between the bead and the parent material. As we can see, the figure 11.a has type D graphite flakes (see annex 4 for graphite types) which increases the hardness of the metal in the heat affected zone and this was due to the high cooling rate. In case b, when we added preheating, we have less type D graphite and the mechanical resistance of the interface is doubled and fracture usually occurs in the bead near the interface.

Post-treatment : annealing

The annealing has as a goal to reduce the number of hard phases, by annealing we force the microstructure to form more ferrite and pearlite which are less harder and brittle. Annealing has a pretty effective result on the joint, in fact studies have showed that for annealing at 900°C, we didn't have rest of brittle phases next to the fusion line. It also makes appear a ferritic phase at the heat affected zone with a low hardness (below 174HV). However annealing generally comes with decreasing of the strength. In fact we compared ductile cast iron which was welded used a TIG process with Inconel 625 for the root and then two filler passes using 97.6% Ni coated electrode, one specimen was preheated at 350°C, one was annealed at 900°C then cooled in the furnace and the third was directly air cooled. [6] The first specimen which has not been annealed shows that it had formed iron carbides such as cementite and martensite and the Vickers Hardness was about 460 mainly in the zone where carbides precipitated. Moreover the structure showed the beginning of fractures which can propagate as the structure is very brittle, this character is very close to white iron behavior.

Moreover micrographs have shown that annealing treatment relieved the martensitic structure and the white iron structure by producing a nodular graphite structure over the ferrite matrix. [6] This made de ductility increase a lot, and diminished the brittleness character. On the other hand, high amount of chromium lead to the formation of carbides and white iron phases, it is the opposite effect of Nickel and leads to fractures and cracks. However micrographs and spectrum analysis have shown that annealing treatments at 900°C counteract the effect of Chromium, in fact we have less Cr in the spectra when we anneal the metal on the weld interface pass made using electrode at 97.6% Ni. [6] On the other hand with a root welding with Inconel 625 (composed by Cr), the spectrum had shown that the annealing made the Chromium quantity decrease in the root weld. This means that annealing can help prevent issues coming from low quality rod such as Inconel 625 compared to 97.6% electrode.

The annealing and cooling in the furnace definitely help having longer values for elongation before fracture and prevent the formation of brittle phases.

5. Type of electrode and rods

Iron Rods :

In the case of welding ductile cast iron with Oxyacetylene Welding (OAW), we used two types of iron rods one of high quality (C 3.7%, Ni 0.6%, Si 2.9% and Mn 0.7%) and one of low quality (C 3%, Ni 0.6%). [5] We managed to see after the welding , that it increases ductility and static mechanical properties with a higher efficiency when we used the high quality iron rods. The absence of silicon in the second iron rod gave to the metal a higher hardness, the silicon in the high quality iron rod lead to ferritic structure at the bead and the interface where the graphite precipitates as type E graphite (see annex 4 for graphite types). The type E graphite reduce porosity and inclusions. [5] When we used the low quality iron rod, even preheat didn't have a good effect on the material, so we need to avoid this kind of iron rod.

Nickel electrode :

The nickel electrode has the characteristic of absorbing carbon when it is in contact with the melted zone. The nickel inhibits the formation of carbides, it dissolves the carbon in its microstructure, so it decreases hardness and increases ductility of the zone. [10] These effects depend on the quantity of nickel in the electrode and they have different consequences. If we tend to pure nickel electrode rather than a Ni-Fe for example, we will have a better ductility according to the uniform distribution of graphite in the bead. Moreover, Nickel prevent the formation of hard cementite by retaining austenite in the melted zone, in that case the carbon retained forms nodular graphite instead of iron carbides more similar to the parent element.[10] So with a Nickel electrode, we will have a less fragile behavior of the joint by improving static mechanical properties.

A comparison has showed that mechanical properties of a cast iron welded using Nickel electrode and SMAW method are better than the TIG method and additional passes with Nickel electrode and SMAW. By mechanical properties we mean the ductility, the toughness, the tensile, and the yield strength. [6]

In the case of welding ductile cast iron with SMAW process, we had a 98.4% Nickel electrode, we noticed that the diffusion of the Nickel in the microstructure of the metal leads to the absence of cementite in the interface, compared to a stainless electrode we had an apparition of carbides in the bead and interface mixed with cementite. We have seen that this composition leads to reduce the ductility and the weldability, while it increases the hardness.[5]

Inconel 625 :

In a study we have ductile cast iron which was welded used a TIG with Inconel 625 rod for the root and after two filler passes using 97.6% Ni coated electrode, a specimen was directly air cooled. [6] In the root the following spectra (figure 12) shows that there is a huge amount of chromium.

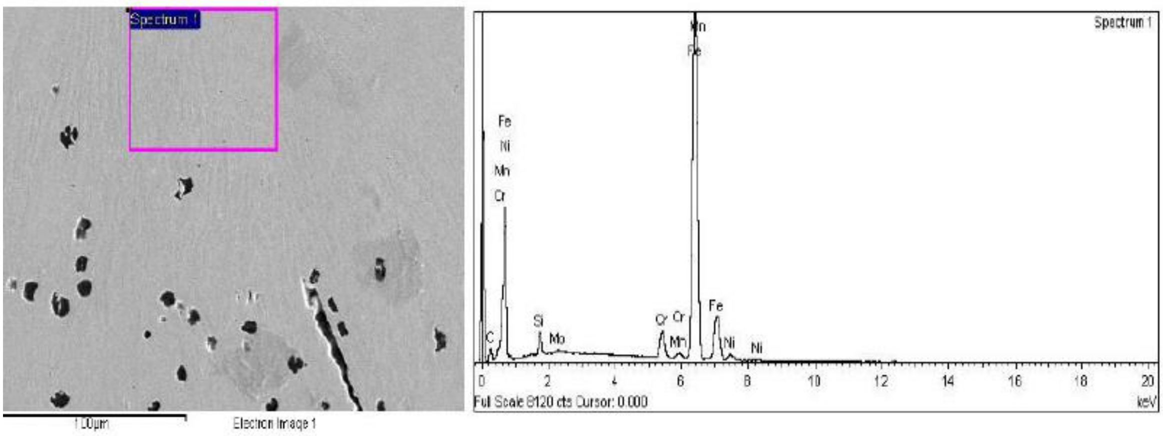


Figure 12 : SEM image and micrograph of the interface zone in a root weld using Inconel 625

The chromium is at the origin of the high hardness and low toughness of the welded zone which generally lead to failures. On the other hand we had the same experience conditions using a 97,6% Ni electrode, we can see in the figure 13 that the amount of chromium is lower than the Inconel case. The Inconel case lead to the formation of iron carbides and the chromium has an opposite effect to the Nickel.

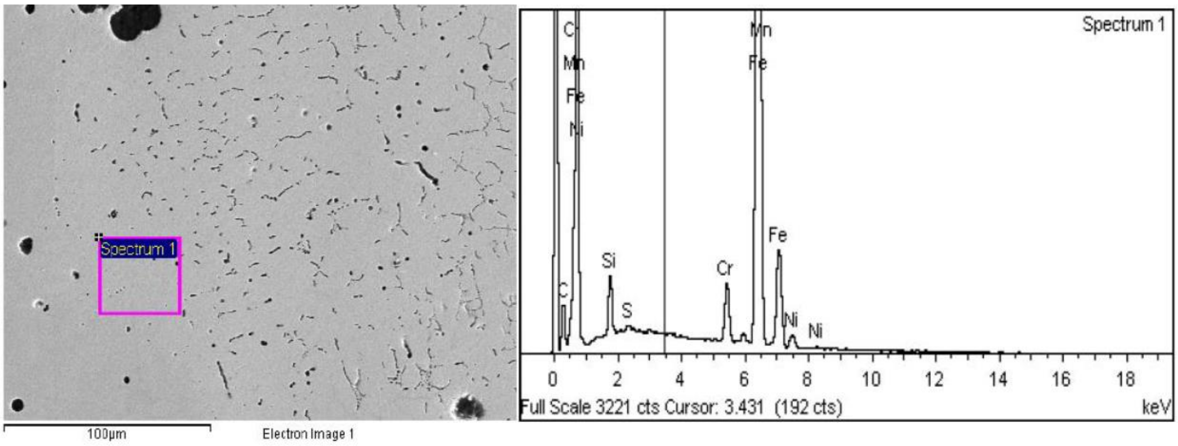


Figure 13 : SEM image and micrograph of the interface zone in a root weld using 97.6% Ni electrode

Nevertheless, Inconel 625 is cheaper and we have to take it into consideration for economic issues, depending on the weld quality needed and the means used we can assume that using Inconel 625 can be sufficient adding a post treatment like annealing to reduce the amount of chromium and its issues. In that case the hardness would be lower than without heat treatment even if it remains hard and fractures may occur more easily than using Nickel electrodes.

4. Adopted solution

Ductile iron can be welded with and without heat treatment, but the mechanical resistance of the joint is better when heat treated. SMAW Ni improves the ductility compared to OAW gray iron rods. We know also that multiple passes should be applied, the general goal is to find a compromise between the welding cost and the material properties we want to reach. To resume, we want to repair cracks and failures on ductile cast irons by using welding process. We know that changes in the microstructure may occur when we heat the metal while welding, these changes may modify the mechanical properties of the ductile cast iron in the welded zone and all around it. These changes of properties may lead to the failure of the metal, the cracks may occur in the weld bead, in the interface between the filler material and the parent material or in the parent material which was heat affected. In order to prevent this, we should find the best welding process and heat treatments to provide a good toughness and mechanical properties to the metal. In the following paragraphs we are going to describe the adopted solution.

For the root pass, it is recommended to use a TIG process, because of its efficiency for welding thick material, it is ideal economically. We have seen that using Inconel 625 rod is very common, however it can lead to problems. On cast irons, the Inconel is composed by elements that can make the weld crack, in fact Inconel is composed generally by 20-25% of chromium (see annex 5 for the total composition of rods), in our case the chromium makes appear brittle carbides as we have seen. The idea is to avoid this problems by using a 97.6% Nickel with a TIG process. As we know the nickel prevents the formation of iron carbides, forming generally nodular graphite which is less brittle and gives to the material a better toughness. So for the root pass, it is very interesting to combine the efficiency of TIG and the high quality of nickel rods, for the root pass.

Moreover, for the second pass, in order to fix a crack it is interesting to use SMAW process, it is the most used process to weld ductile cast iron, it has shown its efficiencies in a way or another compared to the other processes. The process is easy to apply and we can use different types of electrodes. What we advise is to keep absolutely nickel electrodes in our process, for the same reasons. However, it is interesting to preheat the electrode for 24h at 90°C in order to improve the fluidity and the penetration of the weld elements. The goal is to have less porosity and consequently less chances of cracking. The 97.6% Ni electrode has 0.4% of silicon, the silicon makes the graphite precipitates into graphite nodules in the structure, so it is another relevant point. The hardness achieved using SMAW with nickel electrode is low compared to the others, and we may reach structures closer to the parent material, it is considered that the toughness and ductility are good for a ductile cast iron. The microstructure is less brittle and have less chances of failure.

Now let’s focus on the welding process, we are going to take one type of crack and describe the welding process. First of all, to repair truck frames, it is highly recommended to start cleaning the welding area, we have to steam clean and to scrub the area surrounding the future weld. [13] The haul truck frames are used very dirty conditions with a lot of dust, so cleaning the welding area and its surroundings is very important to avoid the penetration of foreign matter. Then we should use an oxyfuel torch to dry the area and remove mill scale, then wire brush the area until we have a shiny metal. [13] We have seen in the pre-study of haul truck frames, that failures generally occurs at pivot points where we found bearing elements. So we are going to study this type of crack and the welding process on it. These bearing are placed in a hole generally drilled in a factory, the bearing elements may resist to the efforts, however cracks may occur on the hole frame structure. As we can see in the following example, we are going to take into account a C-channel however it works also for the box section of haul truck frames :

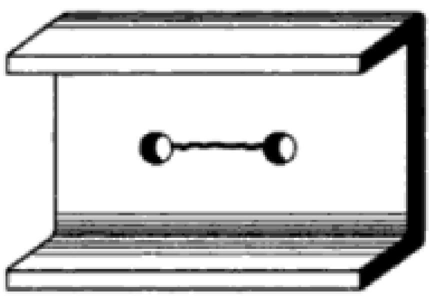


Figure 14: Horizontal crack between two holes [13]

Repair process [13] :

1. Grind a V-groove all along the crack and extend it by 1/5 of the fracture longer on both sides of the holes. The V-groove allows to make the surface smooth and to take off irregular relief, which can be at the origin of stresses. If it is possible use a copper plate on the other side of the crack to prevent foreign elements to enter on the back side of the weld. (Figure 15.b)
2. Using TIG and then SMAW process with their respective rods, fill the V-groove with the filler material. We should use a 130 A for the TIG root pass, with an inclination angle of 70° to 80° for the tungsten electrode when moving forward, and an angle of 20° over the horizontal for the nickel rod. Moreover for the second pass using SMAW process, a current of 140 A may be needed with an electrode angle of 60° from the horizontal in the welding direction. (Figure 15.c)
3. Grind the excess of weld material over the surface to make it as smooth as possible. If we leave irregularities, it may lead to stress and cracks.

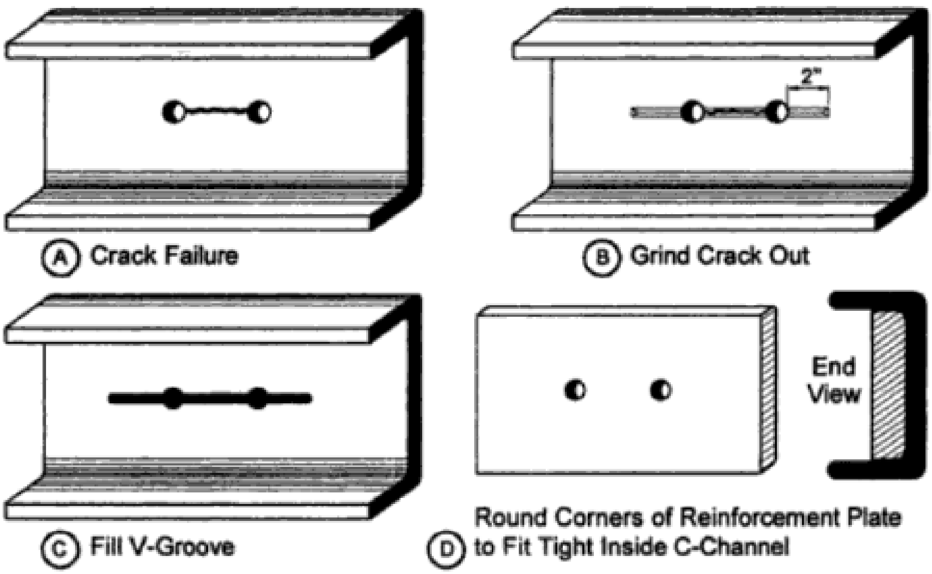


Figure 15 : Repair process of an horizontal crack between holes [13]

A second case of crack may be interesting to study, in the following figure 15 we can see a crack extending from the bottom to the upper side of a perpendicular angle. So the crack changes of direction, it is not planar anymore as it has gone from one plane to another perpendicular.

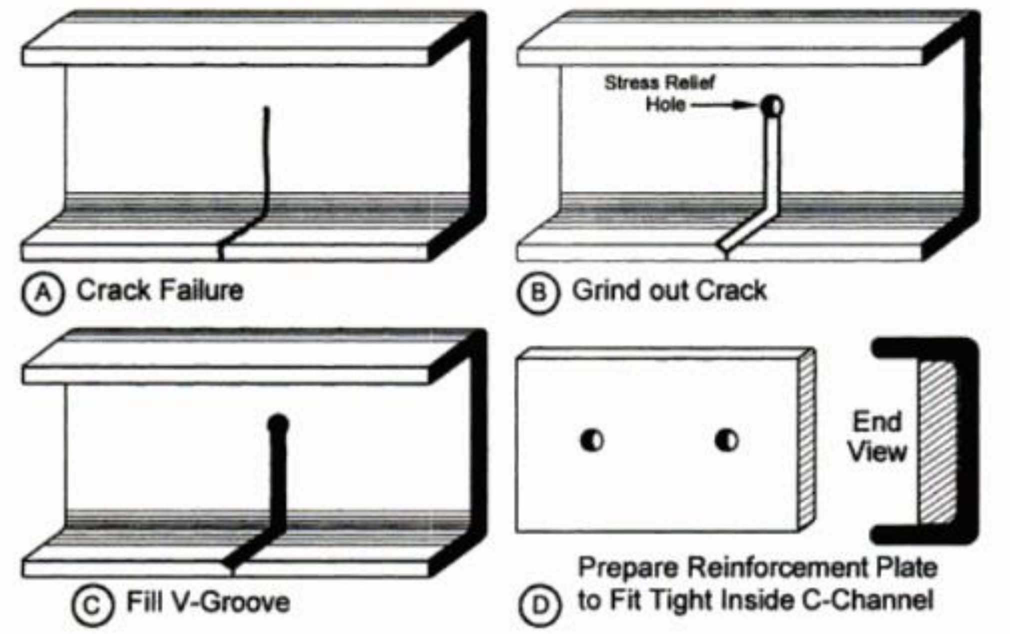


Figure 16: Repair process of a crack with a perpendicular changing direction [13]

In this case the repair process is a little bit different [13]:

1. Grind a V-groove all along the crack (figure 16.b)
2. Drill a hole at the end of the crack, the hole will prevent the spreading of the crack, in fact it is recommended to make the end of the crack's surface rounded in order to prevent crack propagation. figure 16.b)
3. Using TIG and SMAW process the same way to weld the crack. figure 16.c)

Let's now focus on post treatment as we have achieved the welding. We have seen that a heat treatment can have a lot of positive effects on the structure, by reducing its hardness and brittleness, however the big difference is that we can apply a heat treatment before or after the weld. Applying in both cases can be very expensive, so we need to take the one with the better efficiency. So we are going to compare the different effects of heat treatments on the structure and try to quantify the best influence on it. First of all we are comparing welding that has been made in the same conditions, we had 3 specimens, the first one was as plate welded without heat treatment, the second one was annealed after the weld at 900°C (1h and then furnace cooling) and the third was preheated at 450°C. Tensile test where made on the 3 ductile cast iron specimens and the following results went out :

Group	Ultimate Strength (MPa)	Yield Strength (MPa)	A%
Without heat treatment	370 ± 18	330 ± 18	9
900 °C postweld annealing	320 ± 11	295 ± 11	12
450 °C preheating	335 ± 10	310 ± 10	10.5

Figure 17 : Mechanical characteristics of the three cast iron welding [11]

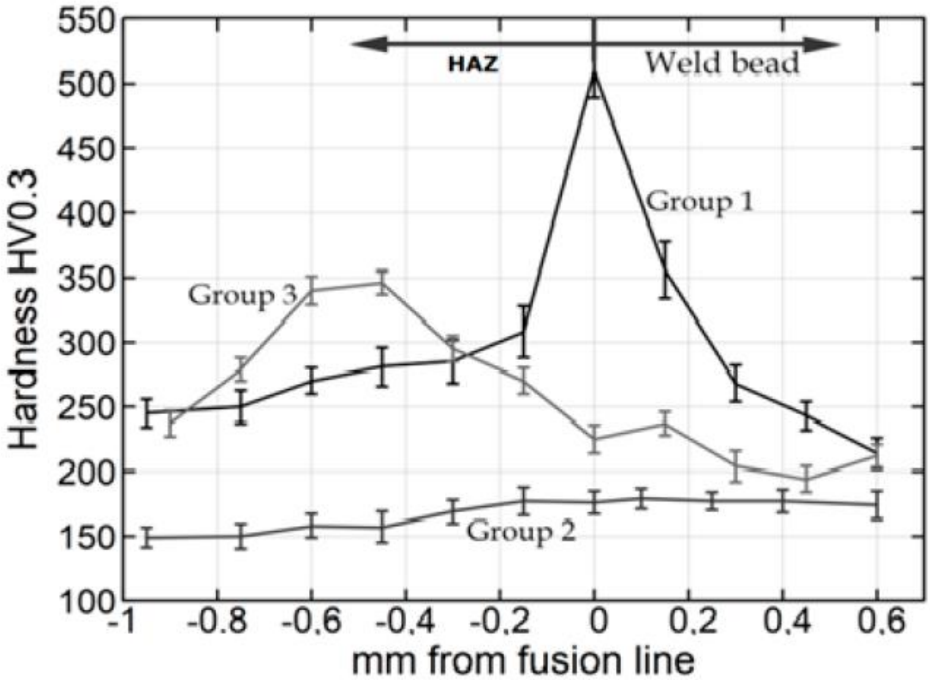


Figure 18 : Micro Vickers hardness evolution from the base metal to the weld bead for group 1 (no treatment), group 2 (annealed at 900°C) and group 3 (preheated at 450°C) [11]

What we can see in the figures above is that the annealing has the most efficient influence on the hardness taking it down to 174HV, when we preheat we decrease also the hardness in the fusion line, however the heat affected zone see its hardness increase a lot making the structure brittle. When we anneal, we have quite similar values on both sides of the fusion line making the total structure more tough and ductile. Micrographs show also that the microstructure is nodular at the heat affected zone. The elongation has also been improved by the annealing reaching 12%, even if it made decrease the yield strength and ultimate strength. This is due to the ferritic matrix which appeared after the annealing to take the place of the ferritic-perlitic matrix, which gives to the structure even a better ductility than the parent material. [11] To resume, if we should give priority to one heat treatment it has to be annealing at 900°C for 1 hour, because we have showed that the best mechanical properties were achieved, the hardness is enough constant from the fusion line to the surrounding zones. Even if the yield and ultimate strengths have decreased, they remain acceptable. Annealing lead to the disappearing of martensite structure and white iron structure, this is due to the nodular graphite structure produced that increases the toughness and ductility making the metal less brittle. The annealing also helps to counteract the effect of chromium if we use a chromium composed rod. As a matter of fact annealing showed its efficiency by counteracting the effect of low quality rods, even if it is more expensive as a heat treatment we should apply it because we can't take the risk of another failure in the case of a haul truck frame.

To resume the adopted solution, it is a 2 passes welding, first pass is done with TIG and a 97.6% Ni rod, the second pass is a SMAW with a 97.6% Ni electrode too. The passes should be performed with the upper description made. And to finish there should be a post treatment, which is annealing at 900°C for 1 hour and furnace cooling. Annealing will take the structure to its austenitic temperature and then we will shut down the furnace and let it cool slowly in order to give time to the structure to transform into more ductile phases. The finishing work is important in order to relieve irregular surfaces with sanding and scrubbing.

5. Economic study

1. Research budget

This section includes the costs of carrying out this project detailed into unit costs by human resources and by material resources.

The concepts corresponding to the engineering work are all those points that have been developed during the elaboration of the project. The following table summarizes the number of hours spent on each of them and their cost according to the engineering rates.

With this world health crisis, no experimental work had been made, all the work had been provided by a student in home office.

Concepts	Hours	Price (€/h)	Total (€)
Study of the Project	15	30	450
Research job and benchmarking	20	30	600
Development of the solution	40	30	1200
Report writing	45	30	1350
Total	120		3600

Table 1 : Study of the resources

The cost of the materials used to perform the work is developed in the following part. In this case it is limited to the use of a computer and the software licenses.

Equipment	Price (€)	Amortized price (Months)	Monthly cost (€)	Months	Total (€)
Computer	600	12	50	5	250
Office licence	149	12	12.5	4	50
Total					300

Table 2 : Material used for research

2. Manufacturing budget

The manufacturing budget take into account all the prices involved on the process of repairing the supposed following crack of 100mm long, when the crack is changing direction from a plane to another perpendicular plane :

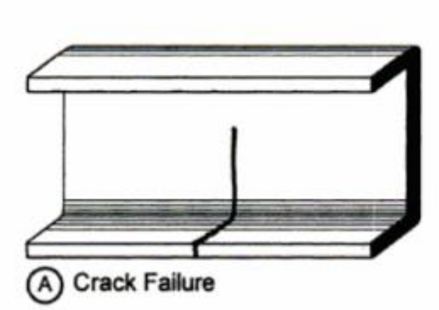


Figure 19 : Crack failure to be repaired

Material and equipment					
Ref.	Description	Units	Quantity	Unit Price (€)	Total Price (€)
A.1	97.6% Ni rod (TIG)	Unt	3	5	15
A.2	97,6% Ni electrode (SMAW)	Unt.	3	5	15
A.3	Tungsten Electrode	Unt.	1	5	5
A.4	Grinding wheel	Unt.	1	15	15
A.5	Wire brush	Unt.	1	5	5
A.6	Argon gas	Unt.	15	11	165
				Total (€)	220
Equipment					
Ref.	Description	Units	Quantity	Price (€/h)	Total Price (€)
B.1	Oxyfuel torch	h	0,25	50	12.5
B.2	Welding equipment	h	1	50	100
				Total (€)	112.5
Workforce					
Ref.	Description	Units	Quantity	Unit Price	Partial Price
C.1	Cleaning operation	h	0,5	50	25
C.2	Welding operation	h	1	50	50
C.3	Drilling operation	h	0.25	30	7,5
C.4	Annealing	h	2	50	150
C.5	Finition work	h	0,5	50	25
				Total (€)	257.5

Total (€)	590

Table 3 : Manufacturing equipment budget

The total price of the researches is 3600 €, and finally the manufacturing work which consists of repairing a 100mm long crack on a ductile cast iron haul truck frame costs 590€.

6. Conclusion

Welding ductile cast iron is something very difficult to achieve without problems, in fact as we have seen, this generally results in weakening of the metal structure. In fact heating up to melting temperatures changes the microstructure of the alloy, brittle elements such as carbides may precipitate. These elements give to the structure a great hardness however their brittleness reduce the toughness. All of this is the consequence of the cooling rate which is to fast to let the structure forms less brittle phases such as nodular graphite, characteristic of the microstructure of the ductile cast iron. As a matter of fact the melted zone, and also the surrounding heat affected zone see its structure change as we heat it up to add filler materiel in order to weld.

Haul truck frames are very complex parts, they are composed mainly by ductile cast iron and work under very hard conditions. The roads they take in mine and quarries, in addition with travel load they can support makes the frame suffer from strain and stress. In fact different movements of traction, compression or bending may occur, and if we add other factors of loads such as dumping, the frame may crack under these conditions in some weak parts such as pivots. The danger of a crack is that it can spread all over the frame an lead to horrible consequences. By consequences, we mean economic consequences but also regarding to the security of the workers. So when a crack is detected, we need to fix it, and by fixing we can weld the crack.

In order to weld, some electrodes such as nickel based electrodes are better than others in order to increase the nodular character of the structure. In fact Nickel electrodes helps the graphite to precipitate under the form of nodules and give the material a better ductility. Moreover it is interesting to use two types of processes, in fact using TIG for the root pass is the most efficient way to weld the basis, and using SMAW for the second pass is good because of its quality in welding ductile cast iron. It is important to not forget to clean the area before welding, to avoid penetration of foreign matter that can create irregularities and porosity leading to crack. The welding process must be performed by a professional, and a hole must be done at the end of the crack, in fact round termination of a crack prevent it from spreading comparing to the original peak shape.

Even if we used a process with high quality rods and lot of finesse in the work. It is important to add a post treatment such annealing at 900°C for 1 hour. This will relieve the remaining stresses and improve the ductility and toughness by removing the carbides. The most important point is to let the cooling occur slowly by shutting down the furnace and let it cool down.

To conclude, welding cast iron will remain a challenge for metallurgist, haul truck frames are very difficult to manufacture as well as they are difficult to repair. We need to take precautions and to use high quality materials, because even if the cost of repairing may be high, the immobilization of the truck and the damage that a crack can cause may cost much more. In the future it may be interesting to study how we can add a reinforcement plate by drilling holes or using existing ones. This may help prevent the welded zone from failure.

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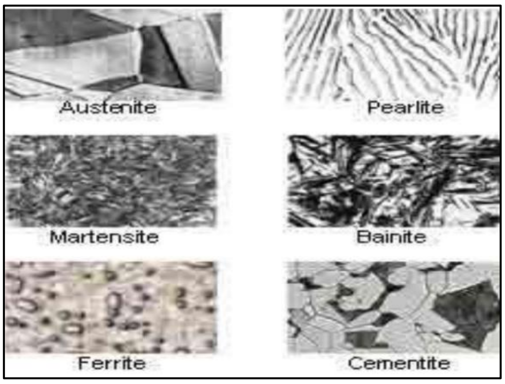
8. Annexes

1. Dimensions of Caterpillar 797F

DIMENSIONS	
Loading Height - Empty	6998 mm
Front Canopy Height - Empty	7709 mm
Height - Top of ROPS - Empty	6526 mm
Engine Guard Clearance - Loaded	1025 mm
Loaded Ground Clearance	786 mm
Overall Height - Body Raised	15701 mm
Inside Body Depth - Maximum	3363 mm
Rear Axle - Clearance - Loaded	947 mm
Overall Body Length	14802 mm
Inside Body Length	9976 mm
Overall Length	15080 mm
Wheel Base	7195 mm
Rear Axle - Tail	3944 mm
Dump Clearance	2017 mm
Centerline Front Tire Width	6534 mm
Overall Canopy Width	9116 mm
Outside Body Width	9755 mm
Inside Body Width	8513 mm
Centerline of Rear Dual Tire Width	6233 mm
Overall Tire Width	9529 mm

2. Microstructure of the different allotropes



3. Chemical composition of ductile cast iron and composition of filler materials [12]

Table 1 **Chemical composition / wt. %**

C	Si	S + P	Ni + Cu + Cr	Mg	Fe
3,7	2,5	< 0,03	< 0,08	0,03	rest

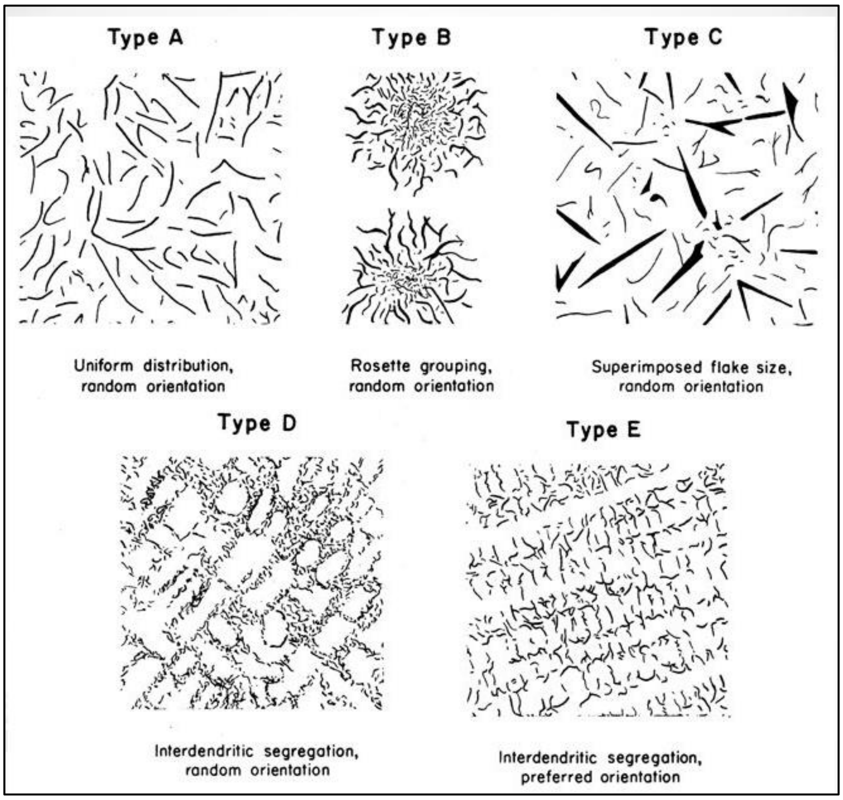
Table 2 **Mechanical properties of cast iron**

Mechanical characteristics	Ductile cast iron
Tensile strength, R_m / MPa	370
Yield strength, R_y / MPa	320
Break strain, A / %	6
Toughness index, T_I / MJ·m^{-3}	11,1
Elastic modulus, E / GPa	160

Table 3 **Chemical composition of fillers used to ductile iron welds / wt. %**

Filler	Ni	Cr	Mo	Ta	Nb	Fe
Inconel 625	58	23	10	4,5	3,5	rest
Ni97,6	97,6					rest

4. Different types of graphite



5. General chemical composition of filler materials

Electrode	Composition	
	Element	%
Inconel 625	Si	0.5
	Mn	0.5
	Ni	58
	Cr	20–25
	Nb	3.5
	Ta	4.5
	Mo	8–10
	Fe	Other
Ni 97.6%	C	<0.1
	Si	<0.4
	Mn	0.20
	Ni	97.61
	Fe	Other