# Repair of the steam turbine rotor by welding.

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# INDEX

# STEAM TURBINES

## History

The shape and operation of the steam turbines are reminiscent of the hydraulic wheels that can still be seen in some rivers and that are moved by the force of the water flow.

The first device that can be classified as a reaction steam turbine was the classic Aeolipile, described in the first century by Hero of Alexandria in Roman Egypt. In 1551, Taqi al-Din in Ottoman Egypt described a steam turbine with the practical application of rotating a spittle. Steam turbines were also described by the Italian Giovanni Branca (1629) and John Wilkins in England (1648). The devices described by Taqi al-Din and Wilkins are now known as steam intakes. In 1672, Ferdinand Verbiest designed a car driven by impulse turbine. A more modern version of this car was produced sometime in the late eighteenth century by an unknown German mechanic. In 1775, in Soho James Watt designed a reaction turbine that went to work there.

*Figure 1. Aeolipile.*

The modern steam turbine was invented in 1884 by Sir Charles Parsons, whose first model was connected to a dynamo that generated 7.5 kW (10 hp) of electricity. The invention of the Parsons steam turbine made cheap and abundant electricity possible and revolutionized shipping and naval warfare. Parsons' design was a kind of reaction. His patent was authorized and the turbine was expanded shortly after by an American, George Westinghouse. The Parsons turbine also proved to be easy to expand. Parsons had the satisfaction of seeing his invention adopted for all the most important power plants in the world, and the size of the generators increased from his first configuration of 7.5 kW to the 50,000 kW capacity units. Within the life of Parson, the generating capacity of a unit was expanded some 10,000 times, and the total production of the turbo-generators built by its firm CA Parsons and Company and its licensees, only for land purposes, had exceeded thirty years. million horsepower.

Several other variations of turbines that work effectively with steam have been developed. The Laval turbine (invented by Gustaf de Laval) accelerated the steam at full speed before operating it against a turbine blade. The De Laval impulse turbine is simpler, less expensive and does not need to be pressure-proof. It can operate at any steam pressure, but it is considerably less efficient. Auguste Rateau developed a pressure-driven impulse turbine using the Laval principle as early as 1896, he obtained a US patent. UU in 1903 he applied the Turbine to a French torpedo boat in 1904. He taught at the École des mines de Saint-Étienne for a decade until 1897, and later founded a successful company that joined the firm Alstom after his death. One of the founders of the modern theory of steam and gas turbines was Aurel Stodola, a Slovak physicist and engineer and professor at the Swiss Polytechnic Institute (now ETH) in Zurich. His work Die Dampfturbinen und ihre Aussichten als Wärmekraftmaschinen (in English: The Steam Turbine and its possible use as Heat Engine) was published in Berlin in 1903. Another book was published Dampf und Gas-Turbinen (English: Steam and Gas Turbines) in 1922.

The Brown-Curtis turbine, a type of impulse, that had been developed and patented originally by the US company International Curtis Marine Turbine Company, was developed in the 1900s along with John Brown & Company. It was used on merchant ships and warships with John Brown engine, including line ships and warships of the Royal Navy.

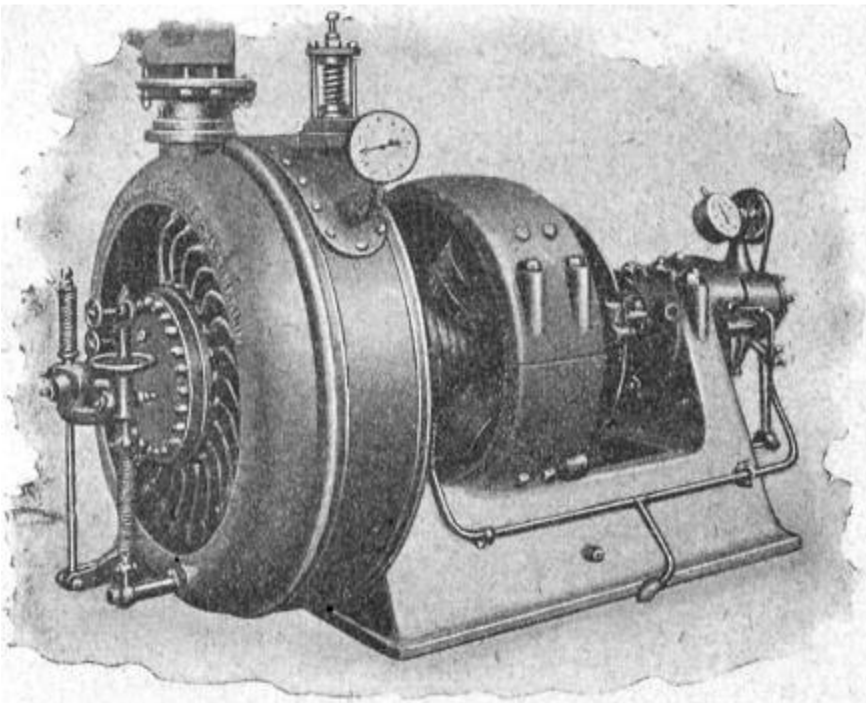

*Figure 2. Old steam turbine.*

## Steam turbine

The steam turbine is a rotating external combustion thermal machine that transforms the kinetic energy of steam into rotational energy.

To clarify this definition a bit, I explain some concepts below:

Thermal machine: performs work by heat (heat in work). In this case the heat that is needed to generate the steam that moves it. It converts the heat of the generated steam into rotation work.

External thermal machine: the combustion is done outside the machine itself, that is, the production of steam by heat is done outside the turbine.

Kinetic energy: energy of movement. In our case, the kinetic energy of the steam due to the pressure to which it is transformed when it hits the turbine, in the rotation movement of the turbine. The steam will lose heat and pressure (speed) when hitting the turbine.

## Steam turbine work

In a boiler you get steam by boiling water. The fuel to heat the water can be gas, oil, coal or even uranium in nuclear power plants.

The water vapor produced is a high-pressure steam and high-speed steam.

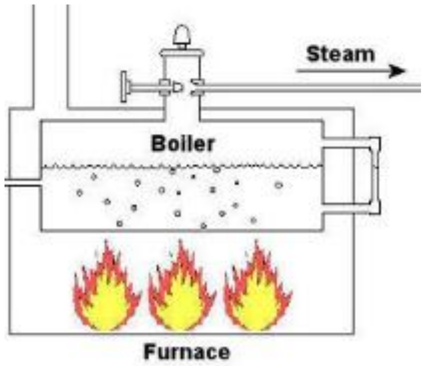


*Figure 3. Boiler with steam going out at high pressure and velocity.*

Through tubes, called nozzles, the steam generated in the boiler is carried to the turbine.

This steam carried by the nozzles to the turbine, when it reaches the turbine, hits the blades and turns the turbine and its shaft. The shaft of the turbine is called a rotor.

A row of vanes is called a reel. You can see that a turbine is made up of several reels and each reel has several blades.

In short, the chemical energy of the fuel used to heat the water is transformed into kinetic energy (rotation of the shaft). If the rotor is hooked, for example, to a dynamo or an electricity generator, moving it will produce electrical current.

In the following image you can see the main parts of a steam turbine. The boiler where steam is generated is not part of the turbine.

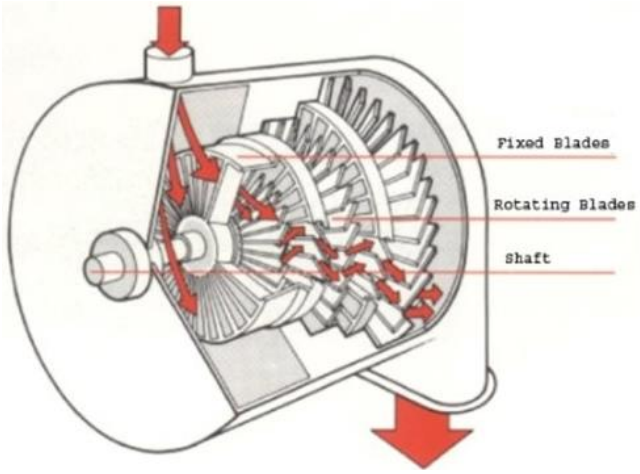


*Figure 4. Scheme of a steam turbine.*

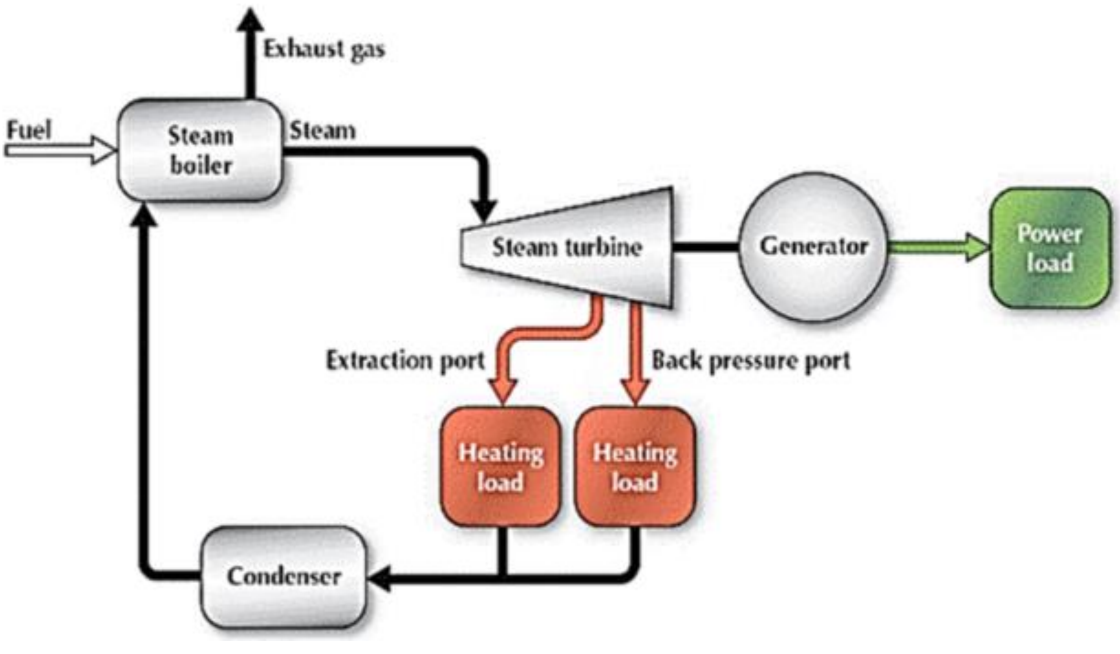


*Figure 5. Power generation plant with steam turbine.*

Once the steam leaves the turbine it has lost its strength and part of its heat, but the steam that remains at the exit will be used to condensing it (converting it from gaseous vapor to liquid) and we will take it back to the boiler to later return to heat it and use it again in the circuit.

It is a closed circuit of vapor-liquid. In this way we take advantage of the heat and the residual pressure of the steam at the exit of the turbine, being much smaller the losses that if we sent it to the outside (atmosphere) losing it. In this way the losses are lower and the performance of the machine is much higher.

The way to condense the steam at the outlet of the turbine is by means of a condenser. The condenser contains tubes of cold water, which, when in contact with the steam of the turbine, cool the steam and condense it. The condensed vapor, now liquid, still has heat and therefore reaches the boiler with that heat, which will make it easier to pass it back to steam to carry out the cycle again. In this way we are saving energy. This saving is very important because the performance is increased and the amount of fuel to be contributed is reduced, since it is always easier to raise the water to 100ºC from 30ºC than from 0ºC.

In the figure we see the machine in closed circuit and its diagram. The pump below is a pump necessary to bring condensed steam from the condenser to the boiler.

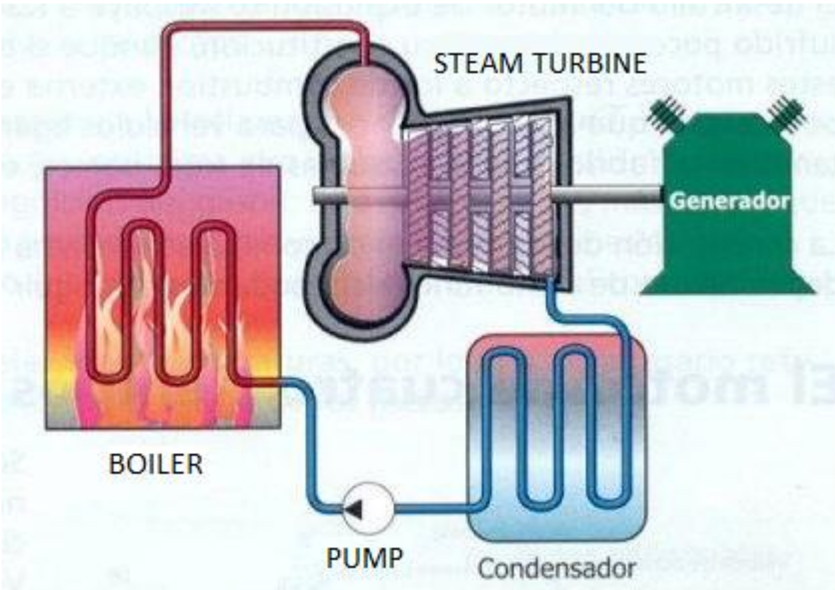


*Figure 6. Diagram of a closed cycle of steam turbine.*

To improve the performance, sometimes the turbines have two or three different turbines attached to their axis, so that the steam hits the first one first, then the next one, and then one by one until the last one comes out. What we achieve with this is to make the most of the steam power, hitting several turbines, instead of just one. It's about getting out of the turbine with the minimum pressure, and that everything you had is used to the maximum before it leaves the turbine.

If you have 3 turbines, they are called, respectively, high, medium and low-pressure turbine. The first will be the one that hits the steam at high pressure, the second turbine will be hit with steam at medium pressure and the last at low pressure. This improves, again, the performance of the machine.

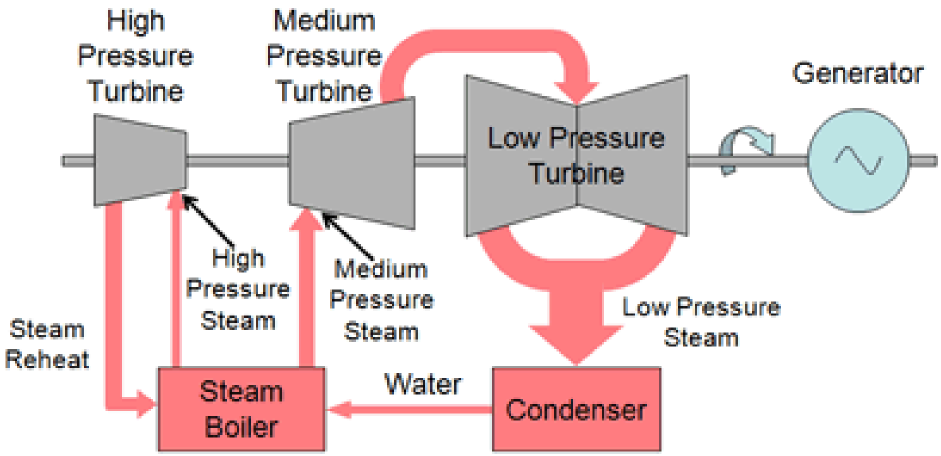


*Figure 7. Multistage steam turbine generator.*

## Applications of steam turbines.

Steam turbines have many applications thanks to their versatility. Initially they served as boat engines that required a lot of power. The first steam turbine ship was the Turbinia de Parsons, launched in 1895.

In industry, steam turbines are used mostly in compressors and pumps. Although the most important application is electric power generation. It is estimated that steam turbines are involved in 75% of the electrical energy produced in the world. They are used both in thermal power plants (coal, gas, biomass, etc.) and in nuclear power plants.

Currently, in some industrial applications gas turbines are used, internal combustion engines such as cars, and they use the gas produced by burning the fuel directly on the blades to produce the rotation. These turbines work at higher temperatures with gases at 1,000ºC or even at 1,300ºC for turbines for aeronautical use in aircraft.

## Parts of a steam turbine

The turbine consists of three main parts:

- The body of the rotor, which contains the rotating crowns of blades.
- The case, containing the fixed nozzle crowns.
- Blades.

In addition, it has a series of structural, mechanical and auxiliary elements, such as bearings, regulating valves, lubrication system, cooling system, toner, control system, vapor extraction system, oil control system and sealing steam system.

Next, I will briefly explain each of them.

## The rotor

It is the shaft of the turbine. They are usually made of cast steel and alloyed with nickel or chromium to obtain greater tenacity. Its diameter is uniform. In it the wheels containing the blades are coupled. To place these wheels on the rotor, a hot process is usually followed. There is the possibility of manufacturing a single piece forged to the rotor, machining slots in which the blades are subsequently placed.

*Figure 8. Steam turbine rotor.*

We can divide the same turbine into three clearly differentiated parts. These three parts are high, medium and low pressure. The rotor in high power turbines may be made of one piece, but it would have the disadvantage that, due to its own weight, it could bend and oscillate. That is why it is common to make the rotor in parts and to give each one of them the necessary support.

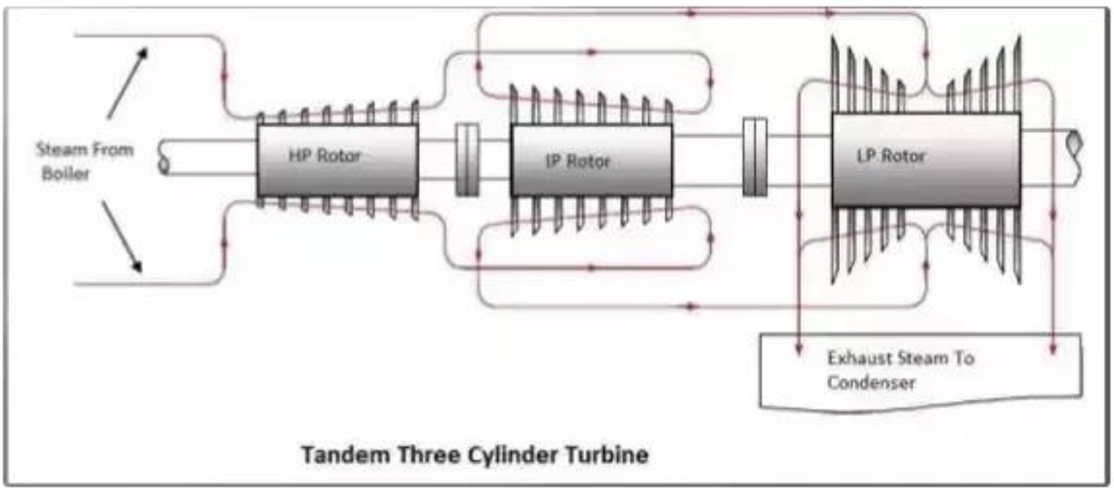


*Figure 9. Diagram of the rotor parts of a steam turbine.*

## The case

The case can be divided into two parts: the lower part, which is attached to the bedplate and the upper part, removable to access the rotor. The two parts contain the fixed crowns of nozzles or fixed blades. The cases are usually made of iron, steel or steel alloys. The material is chosen depending on the working conditions, obviously the parts of the case in the high-pressure part are made of more resistant materials than in the part of the outlet. The maximum humidity should be 10% for the last stages to avoid corrosion phenomena.

The case usually has an insulating coating to not dissipate heat to the outside or reduce losses to the maximum. In this way the steam will not lose so much energy and therefore the turbine will not decrease its performance. The insulating coating usually has a waterproof fabric that prevents wear and facilitates maintenance.

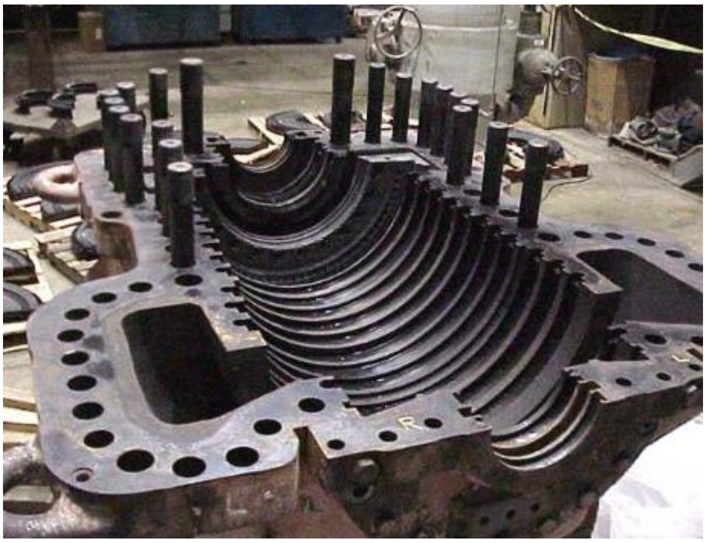

*Figure 10. Steam turbine case.*

### Blades

They are the main elements of a turbine. They are placed in the grooves of the rotor and the case. They can be fixed one by one or by groups, either by means of a bolt-shaped latch or a rivet. They are fixed by one of their ends directly to the rotor or to the case, or to a wheel. When the blades acquire a certain length, it is common to tie them together so that they acquire greater rigidity.

The blades are usually made of stainless steels, iron-chromium alloys. Regarding their shape, they are given the appropriate design curvature according to the steam inlet and outlet angles and at the required speeds. All this is possible thanks to the triangles of speed. The last stages of the turbine require special attention because in them there may be water particles, which can cause serious damage to the blades eroding them. To avoid this possible erosion process, it is common to weld a metal strip on the leading edge of each blade.

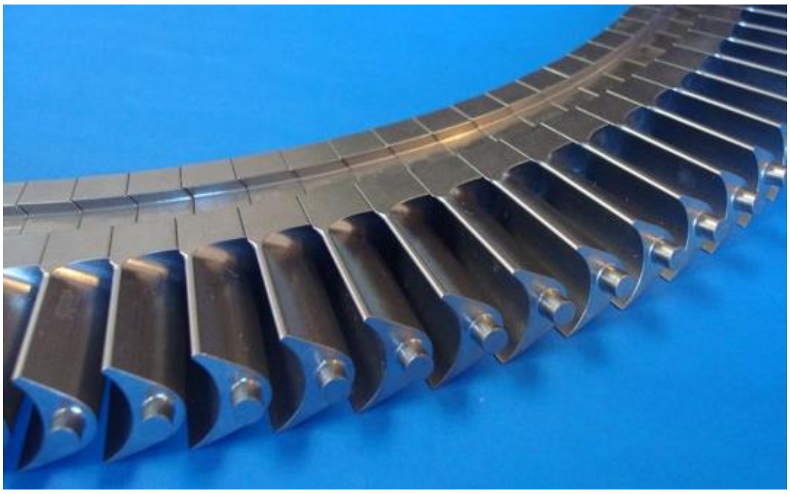

*Figure 11. Steam turbine blades.*

### Bench

It is the foundation that prevents the vibrations caused by the turbine to be propagated to the rest of the plant when it is in operation. It is usually built in cement to support the entire weight of the turbine structure.

### Regulation valve

It is also one of the most important elements of the turbine. Its function is the regulation of the input flow to the turbine. This valve is hydraulically operated with the help of an oil pressure group called control oil. It can also be pneumatically operated. This valve takes part both in the control of turbine speed and in power.

### Support, bench or radial bearings

They are the elements on which the rotor rotates. They are normally made of a soft material and are coated with a lubricant layer that reduces friction. Being subject to heavy wear, it is necessary to change them periodically. For its proper functioning, a frequency of periodic change is usually established, although they are also substituted if, when observing its surface, we see that they are in a poor state.

*Figure 12. Radial bearings.*

### Thrust or axial bearing

This bearing is responsible for restricting the rotor movement of the shaft direction. This bearing is not in direct contact with the shaft, but it is in contact with a disk that rotates with the shaft. Thanks to this element, the axial thrust to which the shaft is subjected by the effect of steam, does not propagate to the reducer as it could seriously damage it.

These elements are usually constructed of a soft material and, like the previous ones, are covered by a lubricating material that reduces the friction between the disc and the bearing.

As a follow-up of the state of the bearing, its temperature, vibrations on the shaft and axial displacement are measured. If it exceeds the established limit, the control system will order the stop of the equipment, or prevent it from being put into operation.

*Figure 13. Thrust bearings.*

### Lubrication system

It is responsible for providing the lubricant to the computer. Normally the lubricant is oil. For the circulation of the lubricant to be carried out correctly, this system has three pumps:

- Main mechanical pump: it is coupled to the shaft of the turbine, in such a way that, when the turbine rotates, the pump also rotates. In this way the pump pressure is ensured better than with an electric pump. Because at the start this pump does not give enough pressure it is necessary to have one more pump.
- Auxiliary pump: it is the pump of which it spoke in the previous section. It is used in starts and stops nothing more. Its function is to provide sufficient oil pressure until the main pump can provide it. This pump is connected before the turbine starts and disconnects after a few revolutions after starting. Once the pressure is required, change from the auxiliary pump to the main one.

- Emergency pump: this pump works with direct current coming from a battery system. It is only activated in case there is no power supply in the plant, because during that stop, the turbine would be without lubrication since the auxiliary pump could not work.

### Mist extraction system

It serves to make vacuum in the oil tank, to get it usually carries an extractor. This vacuum is necessary to avoid the possibility of leakage of oil to the outside. Since the oil reservoir is at a lower atmospheric pressure due to this vacuum, it is thus easier to extract oil vapours.

### Oil cooling system

As the oil advances in the path of the equipment, it is gaining temperature. This increase in temperature produces changes in the viscosity, which can make its lubrication capacity not so effective, and can degrade if the temperature is excessive. So that this phenomenon does not happen, the lubrication system has exchangers that cool the oil. These exchangers can be: air-oil or water-oil. In the air-oil exchangers the heat is emitted to the atmosphere, while in the others the heat passes to a closed cooling circuit of water in the plant.

### Control oil system

In the moment when the regulating valve is switch on oleo hydraulically, a pressure group for the control oil circuit is activated. This system must maintain the pressure between 50 and 200 bars. It is also the one who directs the equipment's outlet valve, which brings the oil back to the steam inlet regulating valve at the required pressure.

### Steam sealing system

To ensure that the steam does not escape into the atmosphere, a vapor sealing system is used. Thanks to this system we manage to retain all the steam and increase the thermal efficiency of the turbine. That is why the turbines are equipped with carbon seals that fit perfectly to the shaft or with steam labyrinths.

### Yaw motor

It is a normally hydraulic motor, although it can be electric, which turns the turbine slowly when it is not working. It is used so that the rotor is not deformed, that is, it does not become curved due to its own weight or temperature. This system works at very low speed, it may take several minutes to complete an entire lap. This part of the turbine is essential for the rotor to maintain its straightness.

### Compensator

It is the connecting element between the output of the turbine and the rest of the installation. Normally it connects the output of the turbine with the pipes that lead to the condenser or with the condenser itself. This element is very important to control and cushion the large expansions and contractions suffered by the case due to temperature changes.

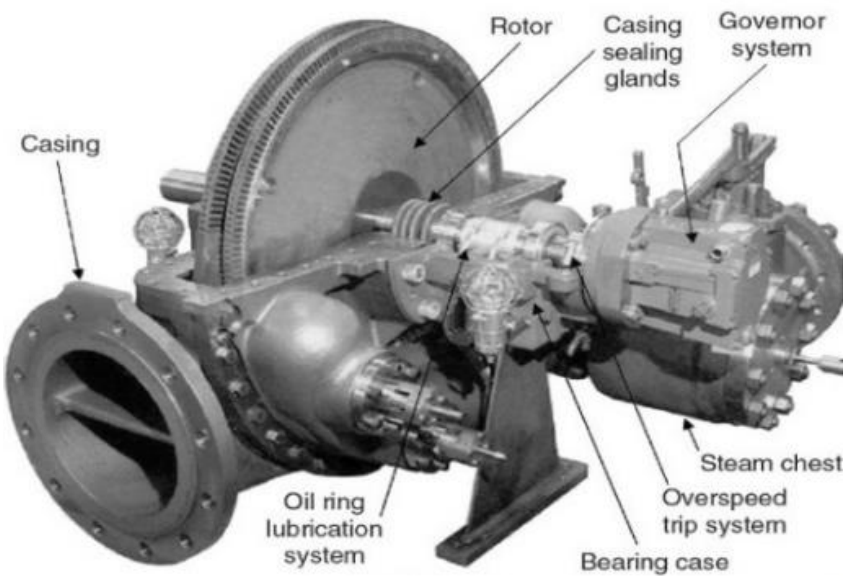


*Figure 14. Steam turbine main parts.*

## Operation and maintenance

Steam turbines and their covers have great thermal inertia because of the material used for their construction and because they work at high pressures. When the heating process for the use of the turbine begins, the steam stop valves are diverted so that the steam generated passes to the system lines and reaches the turbine. To achieve uniform heating when there is no steam, the turbine turns slowly. Thanks to this rotation uneven expansions are avoided. Once the turbine has already turned, the turning gear is disconnected and steam enters the turbine. First hit the astern blades and then with the ahead blades spinning the turbine slowly to heat it, 10-15 rpm. In large turbines this process can last more than ten hours.

As time passes, the turbine acquires a higher rotation speed. As I mentioned earlier this can cause a rotor imbalance. This imbalance can trigger in the separation of a blade. That is why work is continuously done to balance the turbine and thus avoid that risk.

The steam used is superheated (dry) or saturated steam, which contains very little moisture. In this way the risk of erosion of the blades is also reduced. Water that could enter the area of the blades could also damage the bearings, so the turbine installations are equipped with drains.

Considering all the risks of damage that can be in a turbine, it is necessary to carry out maintenance work every so often. Nowadays, modern steam turbines have simple and not very expensive requirements.

# ROTOR OF A STEAM TURBINE

## Introduction

The rotors of the turbines are one of the most critical and most loaded elements of the system. Normally the high pressure and high temperature turbines work in temperature ranges between 315 ° C and 565 ° C. Working at these temperatures the fragility that brings the tempering can affect the life of the rotor.

After the rotors of a turbine have been working for many years it is common that they present problems or potential problems such as the fragility of tempering, fatigue, thermal fatigue, creep, fragile fracture, erosion, corrosion and stress corrosion. Other problems that can arise in a rotor come from errors in design, manufacturing, operation or due to other factors.

When a catastrophic failure occurs in a turbine rotor, the most common is that it must stop. Due to this break, there will be significant economic losses. So that a failure does not come to cause the stop of the turbine has been investigated to develop methods and processes of repair in turbine rotors. These processes will serve to repair existing faults and to extend the life of the turbine.

These advances, especially in welding techniques, make it possible to repair severely damaged shafts of turbines. The repair of a rotor by welding is very profitable, because the cost of a new one is very high. In addition, if a good repair is made, the turbine's downtime will be much less than if the turbine ends up having a catastrophic failure. For the repair to be effective, the welding must be well designed and perform well. Conversely, if the weld is poorly designed or has not been properly executed, the rotor can reach catastrophic failure. If this failure occurs, the cost will be much greater than that of a repair. To guarantee the correct repair, every one of them must be evaluated considering all the aspects of the rotor and the working conditions. The objective of the repair will be that the repaired rotor has characteristics as similar as possible to those of a new one.

## Common damages in steam turbine rotors

Analysing the causes of the failures in the steam turbine rotors, three main groups can be distinguished:

- Causes related to the component: as design, installation, manufacture or defects of the material.
- Causes related to the operation: turbine control system failures, fragility of tempering, brittle fracture, fatigue, thermal fatigue, corrosion, stress corrosion, erosion or creep.
- Causes of others.

Normally the main failures that occur in steam turbine rotors are due to causes related to the product. The main causes of failure are:

- Damage by foreign objects.
- Rotor misalignment.
- Rotor unbalance.
- Failure in the control system.

*Figure 15. Damage caused by foreign objects.*

Next, I will expose some of the most common failures occurred in rotors.

## Fragile fracture

This fault is related to the material from which the rotor is made. The main cause of the sensitivity to fracture is hydrogen. It is common to find hydrogen in areas near the fracture. The presence of hydrogen is directly related to the fusion method and the thermal treatment to which the rotor is subjected.

In this type of fracture, it is also necessary to consider possible non-metallic inclusions, the grain size, thermal embrittlement of the material during the operation of the rotor and the residual stresses in the volume of the material.

*Figure 16. Fragile fracture example.*

## Fault fractures due to creep

The creep is the deformation of plastic type that a material can suffer when it is subjected to a high temperature for long periods. This failure is possible if the heat treatment was not adequate, for example, high austenitization temperature.

This type of fracture can be accelerated if the rotor has stress concentrators, such as grooves to support the blades or areas where there are residual stresses along with thermal stresses.

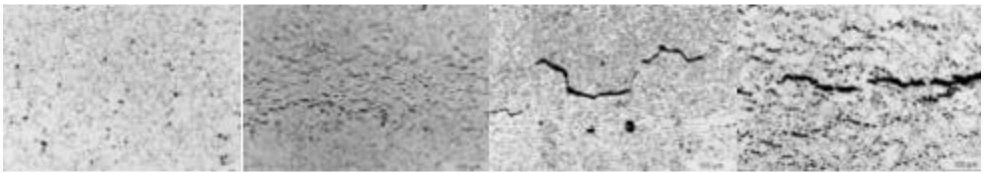

*Figure 17. Creep damage accumulation.*

## Equipment failures

There are faults that can be caused by other elements of the installation. If any of the other elements presents an incorrect behavior, this can result in a change in the stresses to which the rotor is subjected, generate large vibrations and thus lead to failure.

## Faults caused by the operation

This type of failure can be caused by the presence of water. If a cooling occurs at some point of the rotor, this can flex and cause a strong friction with the other fixed elements of the turbine. This would cause an increase in the load to which it is subjected, leading to large plastic deformations and subsequently to failure.

## Fatigue and fatigue assisted by corrosion

These phenomena are the cause of the failure of many rotors. Fatigue can occur due to variable loads, turbine stops frequently and cold starts. If there are also pores caused by erosion, corrosion or the presence of non-metallic inclusions, the failure can accelerate rapidly.

*Figure 18. Fatigue fracture.*

### Cracks due to stress corrosion

If the rotor is subjected to stable forces exceeding 50% of the elastic limit of the material, it is very likely that cracks will be generated and propagated, due to stress corrosion.

In general, the efforts always exceed 50% of the elastic limit, due to them and other factors cracks are created. The other factors are the stress efforts, the susceptibility of the material and the corrosive environment. This corrosive environment is created by the moisture that comes from the steam and other pollutants that the turbine flow carries. The pollutants are introduced into the flow of the turbine by the injection of chemicals, cleaning products, demineralization...

## Weldability

Normally the steam turbines rotors are made of low alloy steels. Its main alloying agents are usually chromium, molybdenum, nickel and vanadium. In these types of steel, the percentage of carbon does not exceed 0.35%. Generally, the steels used belong to the following specifications:

- ASTM A 470, clase 8 (1,25 Cr-1,25 Mo-0,25 V)
- ASTM A 471

To choose the filler material to use we have two options. The first is to use a Cr-Mo filler with a chemical composition like that of the rotor. The second is to use a filler material with a high chromium content to improve the properties at high temperatures. In the following table you can see several examples of filler materials for different rotor materials.

*Table 1. Welding filler metals for repair turbine rotors.*

| Rotor material | Welding process | Filler material |
|---|---|---|
| ASTM A 470 cl. 8 | SAW | 5 Cr<br>12Cr-1Mo-0.5W |
| | SMAW | 1.7Cr-0.9Mo-1.2Mn-0.9Si |
| | GTAW | 1Cr-0.5Mo-1.2Mn-0.9Si<br>9Cr-1Mo-1.25Cr-0.5Mo |
| ASTM A 293 cl.6 | SAW | 12 Cr |
| ASTM A 565 Gr. 616HT | SAW | 12Cr<br>2Cr-1Mo-0.25Si<br>12Cr-Mo-V-Nb |
| | SMAW | E410-16 |

To carry out a correct welding it is necessary to adjust the parameters very well.

### Preheating

It consists of elevating, totally or locally, the temperature of the pieces before the execution of the welding.

As the preheating temperature increases, the temperature gradients decrease, the temperatures in the different points and the residence times increase; and decreases the cooling speed. Therefore, it reduces the risk of fragile structures, reduces the tensional state and facilitates the diffusion of hydrogen.

The absence of preheating can induce very high internal stresses in the presence of significant amounts of hydrogen.

The preheating also involves a series of risks such as:

- It can alter previous treatments.
- Increases the risk of grain growth.
- Can accelerate precipitation phenomena of some steels.
- Increases the width of the thermally affected area.
- Expensive manufacturing.
- It is uncomfortable for the welder.

The preheating temperature is the minimum temperature value that the parts must have before welding to guarantee adequate cooling speeds.

This temperature depends on the composition of the material, the thickness and type of joint and the thermal input.

Manufacturing codes usually give general recommendations about preheating temperatures depending on the material to be welded.

### Post-welding treatment

This treatment is necessary to restore the tempering affected area after welding, obtain optimum ductility and impact properties; and relax the tensions created. In this treatment, a temperature of approximately 40 ° C is used below that of the first tempering of the rotor. The process usually reaches temperatures between 600 ° C and 700 ° C and lasts between 6 and 12 hours. The treatment can be in an oven or in situ, the latter is the most used. To apply this treatment the rotor is placed in vertical position and the entire circumference of the repaired area is heated. This local heating reduces the risk of deformations in the rotor. To avoid thermal gradients the preheating-cooling ratio should be in a range of 10 ° C to 40 ° C per hour.

## Evaluation

To evaluate the repair of the rotors more easily, a classification with different types was created. In this classification appear most repairs that are currently made.

Class 1. Repair by welding deposit in areas of low stress, such as stumps.

Class 2. Repair by welding deposit on the rotating elements, for example, on the vanes and on the lugs of the blades.

Class 3. Repair of the blade groove in the rotor integrated disc, by welding a segment of the circumference of the disc.

Class 4. Repair by replacement of the disc integrated by welding deposit. The cracked disk is machined until all damage is removed and then the diameter dimension of the disk is restored by solder deposit.

Class 5. Mechanized repair of a deep groove in the rotor body to eliminate a circumferential crack and then fill the groove by welding.

Class 6. Repair by cutting a damaged segment of the rotor and replacing this axial segment with a new forge welded to the rotor body.

Class 7. Repair by welding a partial or total circumferential section to recover the integral disc.

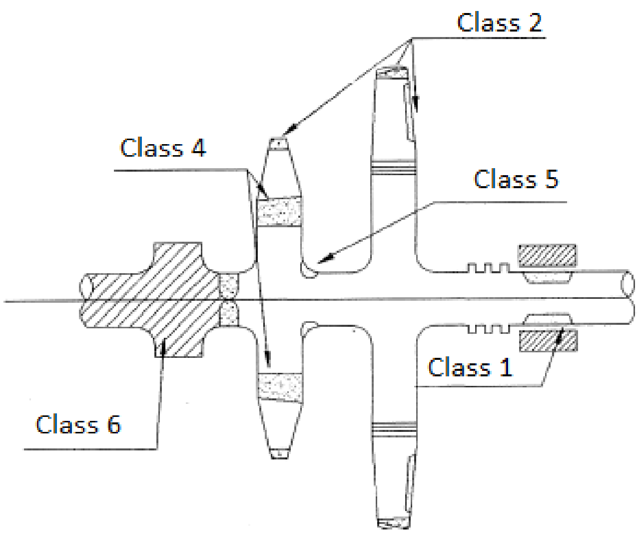


*Figure 19.Classification of the turbine rotors repair (Classes 1,2,4,5 and 6).*

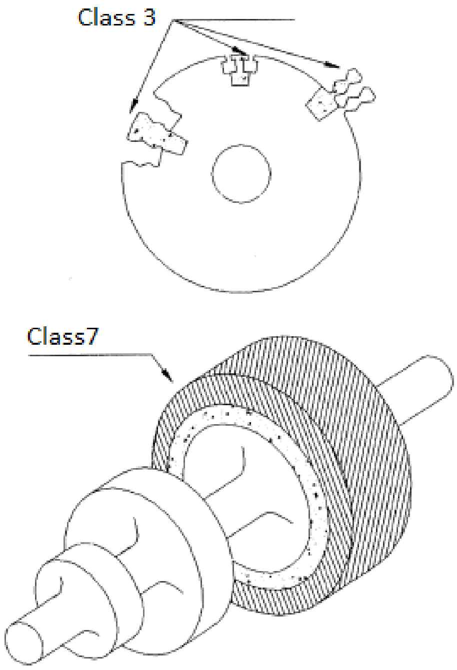


*Figure 20. Classification of the turbine rotors repair (classes 3 and 7).*

# WELDING PROCESSES

## SMAW

Shielded Metal Arc Welding

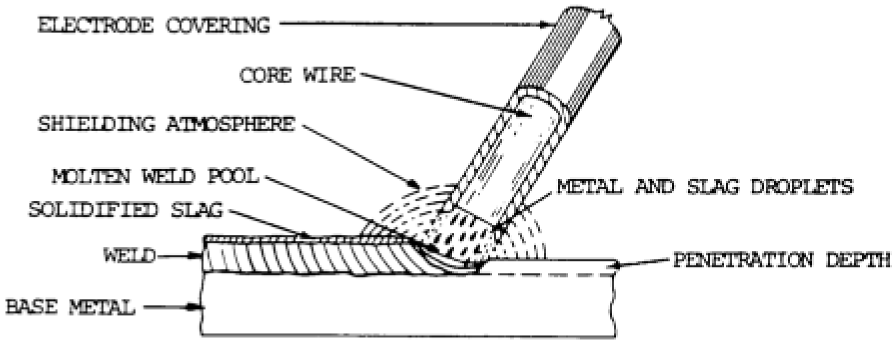


*Figure 21. Shielded metal arc welding process.*

It is one of the welding processes most used today. It is used mainly to weld carbon steels, although it is capable of welding many more materials. With the coated electrodes we can weld a wide range of thicknesses, it is very effective from 5mm thick. It is a good option if it is necessary to weld outside the workshop thanks to its portability, because it does not need protection gas and is cheap.

Consumables: this process only has one consumable, the electrode coated. This component has the function of filler material, electrode and weld pool protection. It is a metal rod covered with a ceramic-like material. The metal rod serves as filler material and is usually made of a material similar to that of the piece to be welded. When the electric arc breaks the metal rod begins to melt and leads to welding. The coating is done by compaction of several metals. These metals are responsible for two main functions: to provide stability to the arch and form a physical barrier to protect the weld pool. The coating must melt at the same time as the metal rod and have a lower density so that when the two materials melt, the coating floats and creates that protective barrier. This barrier is responsible for protecting the weld from environmental contamination and oxidation; It is called slag. The slag must be removed once the welding has been carried out.

*Figure 22. Coated electrodes.*

In this process the welder must control all the variables, it is a manual process. It is a slow process because it requires changing the electrodes and removing the slag.

Advantages

- The welding equipment is simple, economical and portable.
- The filler metal and the protection come from the coated electrode.
- It is less sensitive to wind and air currents than processes with gaseous protection.
- Does not require the external supply of a protective gas or granular flux
- It can be used in areas of limited access.
- It can be used in any position.
- Applicable to most thicknesses and materials.

Disadvantages

- Applicable to thicknesses greater than 5mm.
- It is a slow process that requires removing the slag.
- It requires the skill of the welder.
- The deposition rate is low, because the electrode can only be consumed up to a minimum length (about 5cm).
- It is not productive for thicknesses greater than 28 mm.
- It is not applicable to metals of low melting point, because the intense heat of the arc is excessive for them.

## SAW

Submerged arc welding

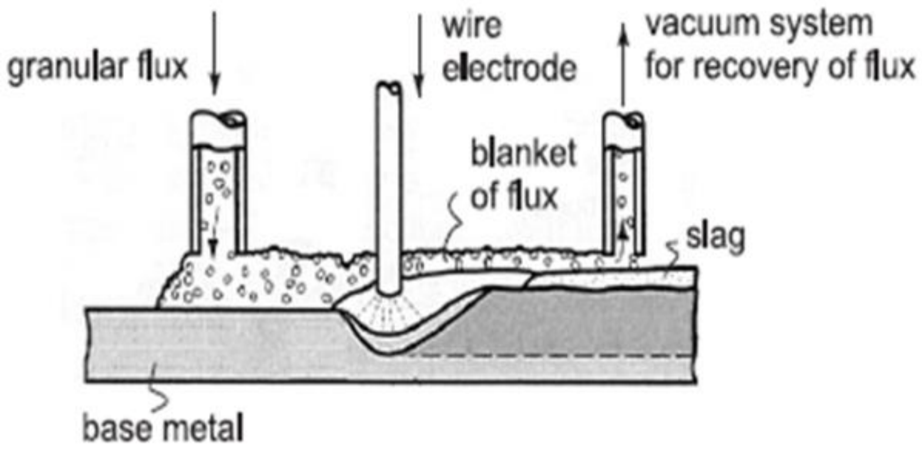


*Figure 23. Submerged arc welding process.*

This welding process is automatic and very cheap. The big problem is that it works at very high intensities, therefore, it is not possible to use it to weld sophisticated materials or thin pieces. With this process it is only possible to weld in two determined positions. This process is always used inside the workshop. The main materials for which it is used are carbon steels, low alloy steels and stainless steels.

Consumables: this process has two consumables. One of them is the filler material, which consists of a solid continuous rod. The other is the flux, the one in charge of protecting the welding.

*Figure 24. Real submerged arc welding.*

Advantages

- High productivity.
- Low cost in the preparation stage.
- The fact that it can be executed in a single pass, even in very thick materials.
- It is very reliable if the operation parameters are correct.
- Very low risk of cracking by Hydrogen.
- High deposition rates.
- High welding speeds

Disadvantages

- Portability (requires an external flux).
- Only flat or horizontal welding because the flux works by gravity.
- A good preparation of the board is required, since it is not visible during the process.
- The flux needs good storage and protection.
- Slag creation.

## GTAW

Gas tungsten arc welding.

It is a manual process although more and more applications arise to automate it. With this process good quality and penetration are achieved, but it is a very expensive process.

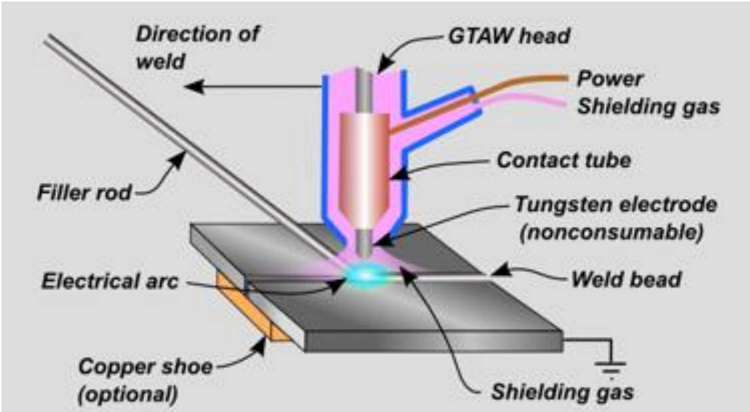


*Figure 25. Gas tungsten arc welding process.*

This process is carried out with a welding gun containing a tungsten electrode inside it. The electric arc jumps between the electrode and the piece to be welded. The electrode is not consumable. It can be done with or without filler material. When filler material is required, it is applied with rods that the welder handles. The protection of the fusion bath is carried out by means of an inert gas.

Consumables: in this case, as I said before, the electrode is not consumable. The only consumables of the process are the shielding gas and the filler material rods if necessary.

This process is only used for delicate materials or for parts with very little thickness. It is highly recommended for pieces between 0.5 and 5mm. It is also used to make the first pass of other welding processes because it avoids root healing. Its high price makes it be used only when it is strictly necessary.

### Advantages

- Appropriate process to join most metals.
- Stable and concentrated arch.
- No projections are produced.
- No slag is produced.
- It produces smooth and regular welds.
- It can be used with or without filler metal, depending on the application.
- It can be used in all types of joints and positions.
- High welding speed in thicknesses less than 3-4 mm
- You can get high quality welds
- It allows an excellent control of the penetration in the root pass.
- It allows independent control of the power source and the filler metal.

Disadvantages

- The deposition rate is lower than what can be achieved with other arc welding processes.
- Its manual application requires great skill on the part of the welder.
- It is not economical for thicknesses greater than 10mm.
- In the presence of air currents, it is difficult to achieve adequate protection of the welding zone.

*Figure 26. Welder executing GTAW welding.*

# STUDY OF THE REPAIR OF A ROTOR BY WELDING

## Rotor characteristics

Next, I will explain in detail the repair to which a rotor of a steam turbine has been subjected. This repair was made with the objective of restoring the control stage of the rotors of a high-speed turbine. This turbine rotor has a 30MW power and is forged with 26NiCrMoV14-7 Super Clean.

The turbine rotates at 12000rpm and the steam outlet temperature reaches 470 ℃ and 100 bar pressures. This turbine needs a shaft able to work both at high pressures and temperatures; as lows.

To carry out this repair, the welding method has been used: SAW, submerged arc welding. As a filler material rod SZW572SC was used and as a flux WP330.

## Padding weld technology

### Filler material

For the rotors, be able to withstand the conditions described above, they are manufactured with forged steel 26NiCrMoV14-7 SC following the norm NR417-07. This standard includes the requirements for working conditions that turbine parts must comply with.

The welding was carried out with a filling material with a chemical composition and toughness properties similar to those of the rotor, 27NiCrMoV16-7 Super Clean. This specimen was manufactured by the German company SAARSCHMIEDE. The dimensions of the specimen were 300x300 L=450mm, as required by standard NR 417-07. The following image shows a comparison of the chemical composition of the specimen with the standards.

| Element | Standard number NR 417-07 | | approved |
|---|---|---|---|
| | content of elements [%] | | |
| | Min. | Max. | Cast 171 446 |
| C | 0,22 | 0,30 | 0,26 |
| Si | - | 0,05 | 0,002 |
| Mn | - | 0,05 | 0,03 |
| P | - | 0,002 | 0,002 |
| S | - | 0,005 | 0,001 |
| Ni | 3,20 | 3,75 | 3,56 |
| Cr | 1,50 | 2,00 | 1,63 |
| Mo | 0,30 | 0,50 | 0,41 |
| V | 0,07 | 0,15 | 0,09 |
| Cu | - | 0,1 | 0,03 |
| Sn | - | 0,005 | 0,003 |
| As | - | 0,005 | 0,002 |
| Sb | - | 0,002 | 0,001 |
| Al | - | 0,005 | 0,003 |
| Co | - | - | 0,01 |

*Figure 27. Forging chemical composition.*

After analysis, the chemical composition of the forging material is said to meet the requirements of standard NR417-07 and structure.

## Padding weld characteristics

A SZW572SC welding rod following HTF651137 has been used as the filler material for the quilting welding. WP330 according to HTF65111115 was used as the flux. A Bohler welding rod with 3NiCrMo2.5-UP (SZW572SC) composition was used as the welding material.

## Padding weld technology

The padding welding was done in a single pass and automatically. To carry it out, flux was used and it was made in a round shape. The welding rod had a diameter of 3mm, 36mm of padded welding were placed over a length of 200mm. Previously the piece was preheated to 300˚C. During the welding process the temperature remained between 230 ˚C and 250 ˚C.

Once the welding is done, the part is annealed to relieve the tensions generated. The annealing was carried out as follows:

- Oven heating to 580 ˚C.
- Place the piece in the oven for 12 hours.
- Cooling inside the oven up to 300 ˚C, at a rate of 30 ˚C per hour.

These parameters were chosen taking into account the standard NR471-07.

Once the annealing process was completed, the specimen was machined and then subjected to a series of tests.

## Test after welding

### Non- destructive tests

#### *Visual inspection*

One of the non-destructive testing methods to be performed first is visual inspection. This first check can detect many imperfections, saving you time and money by avoiding more expensive tests. As far as time is concerned, visual inspection takes place before, during and after welding.

#### *Penetrant test*

Penetrating liquid examination allows for the detection of discontinuities in the surface of non-porous solids. Among the imperfections detectable with this technique are cracks, surface porosities, craters at the ends of a cord, etc. There are several types of penetrating liquids, but the most commonly used ones are red, as they produce a very good contrast with the white of the developer.

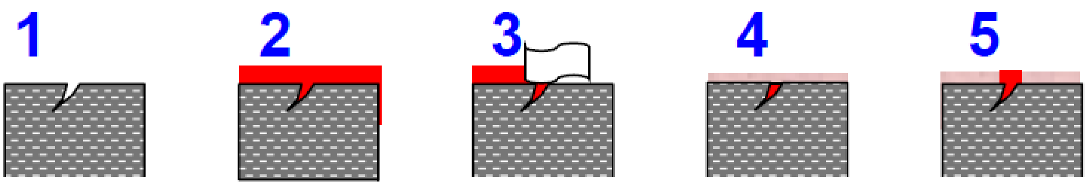


*Figure 28. Test stages with coloured penetrants*

1. The surface of the piece is cleaned to avoid rust, slag, grease, etc., as these could conceal a discontinuity. This cleaning is carried out with detergents, solvents or pickling solutions.
2. The penetrant is applied with the help of a sprayer. This liquid is usually bright red in colour. It must be left to work for a certain period of time so that it can be introduced through all the gaps.
3. Once this time has elapsed, the powdered surface is cleaned with a cloth to remove the penetrating liquid from the healthy surface.
4. In this step the developer is applied, also by spraying. This product is usually white in colour so that when it comes into contact with the penetrating liquid it dyes red and is easily perceived on the surface. If the developer dyes himself, he is indicating to us that there is an imperfection, and we will also see where he is.
5. The application time of the developer is an important variable because depending on the developer, the indications will be longer or shorter. Finally, the revelations are interpreted and it is decided whether the discontinuities are real, that is, they correspond to an imperfection in the weld.

### *Magnetic particles*

This type of test can detect surface and subsurface defects near the surface in magnetic materials. To carry out this test it is necessary to magnetize the piece and sprinkle iron powder on its surface. In this way, if there is a discontinuity, the magnetic field will be deflected, and the magnetic dust will clump together.

The surface of the workpiece must first be cleaned and then magnetised. Magnetization can be done by magnets or electromagnets; or by direct or electric current induced magnetization.

The most commonly used method of applying the particles is called the dry process. With this method, the particles are sprinkled with a rubber bulb or spray. Excess particles are removed with an air stream. Particles of different sizes are often mixed together because the small ones may become embedded in the pores of the material and the large ones are less sensitive to the method.

At the end of the test, the indications given by the magnetic field are evaluated and the piece is demagnetized. It is recommended to clean the part of particles.

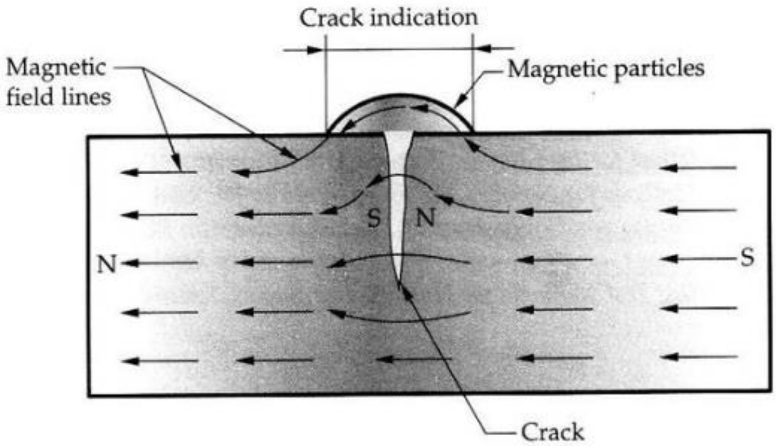


*Figure 29. Magnetic particles inspection.*

### *Ultrasonic inspection*

In this process ultrasonic waves are generated through the piezoelectric effect, there are materials that deformed by an external force produce electrical charges on its surface.

The element that emits the waves is called a probe. It is composed of a piezoelectric crystal sheet with a thin silver film on the front and back of which forms the electrodes. The crystal forms like the dielectric of a capacitor and the plates are attached to a wire that conducts the electrical current. The assembly is surrounded by a cushioning plastic and all this is included in a metal casing.

When a voltage is applied to the electrodes, the crystal vibrates, and generates ultrasonic pulses that are transmitted to the material under investigation, which is in close contact with the probe.

The longitudinal or transverse waves transmitted through the tested material propagate in a straight line, are strongly attenuated by the distance travelled, and are reflected and transmitted by changing the density of the medium through which they move. When they reach the end of the metal piece, they meet the air, which causes almost the entire wave to reflect.

There are several methods for ultrasound testing:

- Resonance method. Allows accurate thickness measurement of parallel-surface sheets.
- Method of transparency or shadowing. Two probes are available: a transmitter and a receiver. When the waveform encounters an obstacle, the acoustic intensity picked up by the receiver decreases. The attenuation gives an idea of the magnitude of the obstacle.
- Echo-impulse method. This is the most widespread method of defect detection. When ultrasonic waves are transmitted through the interior of a solid and encounter an obstacle inside, they are almost completely reflected. By measuring the beam travel time and its echo at different points on the same sheet metal, it is possible to determine if there are any discontinuities in any area.

Ultrasonic interpretation is quite complex.

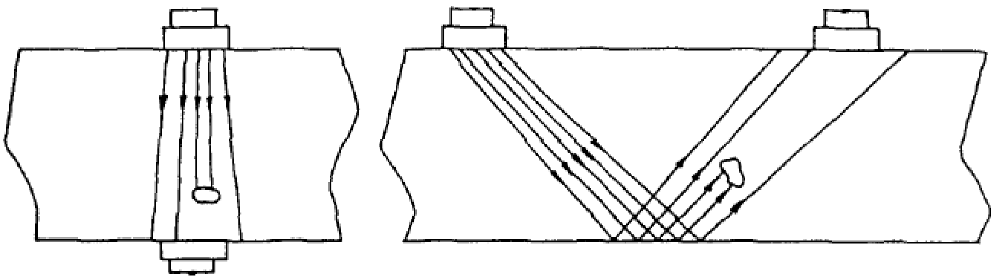

*Figure 30. Location of the ultrasonic probes.*

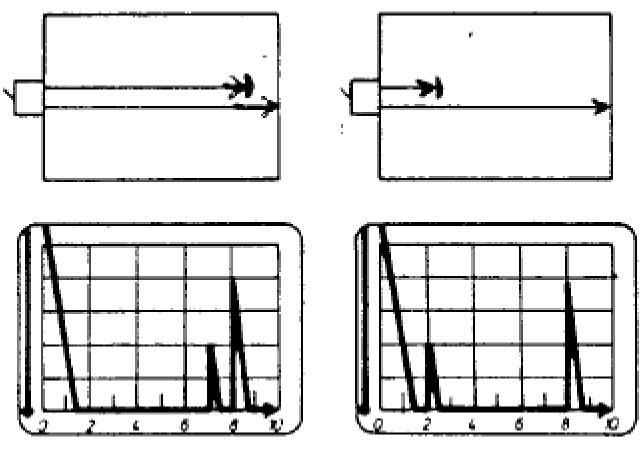

*Figure 31. Ultrasound response to the presence of two imperfections.*

*Radiographic control*

This type of control is based on the ability of certain radiations to pass through matter and impress photographic films by making an image appear on them.

The radiations conventionally used in the inspection of welded constructions are the X-rays and γ. They differ in their origin, because the X-rays come from electrically excited apparatus: they are produced when the electrons coming from the cathode and accelerated by a strong difference in potential collide with the anti-cathode; those from the spontaneous disintegration of radioactive elements. Both radiations propagate in a straight line, penetrate the opaque bodies in ordinary light, ionize the air and other gases, diffuse when they hit matter, impress photographic emulsions, excite the fluorescence of certain substances and have biological effects.

Better X-ray contrasts are obtained. In addition, since the outbreaks X-rays are more punctual and result in better X-rays, with fewer shadows. But they have the disadvantage of being less portable and more expensive, so the usual technique is the lightning γ.

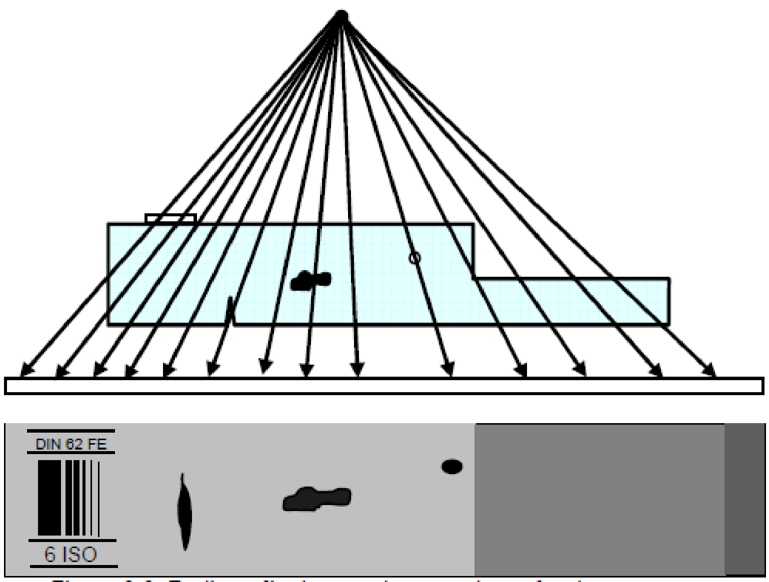


*Figure 32. X-ray of a piece with imperfections.*

## Metallurgy tests

### *Chemical composition*

The chemical composition has been analyzed with a spectral method called SPEKTROPORT. This method uses argon spark over the cross sections of the weld. In the following image we can see the results of the test.

| Tested element | The content of elements [%] | | | | | | |
|---|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | Mo | Ni | V |
| **Forging** | 0,28 | <0,01 | 0,02 | 1,59 | 0,43 | 3,50 | 0,05 |
| **Padding** | 0,12 | 0,11 | 0,78 | 1,52 | 1,40 | 2,70 | 0,03 |

*Figure 33. Chemical composition of the padding weld.*

### *Macroscopic tests*

This type of test was performed on three different specimens that were taken from longitudinal sections around the forge that differed by 90 degrees. This was necessary to avoid overlap. The defects revealed by this test were evaluated according to PN EN ISO 6520-1: 2009 and were found to be negligible as they were not in the NDT failure range.

### *Toughness tests*

The test carried out to measure the strength of the part was Vickers HV10 according to PN-EN ISO6507: 2007 and was performed using the ZWICK 3212 hardness tester. The test was performed on the weld, on the heat affected zone and on the base material.

As a result of the test it was obtained that the weld has a resistance between 285 and 331 HV10 and that the base material has an average hardness of 297 HV10. Welding meets all requirements.

*Figure 34. ZWICK 3212 hardness tester.*

### *The microscopic tests*

Microscopic tests were carried out on the transversal section of the zone thermally affected by the weld. AXIOSKOP microscope according to PN-EN 1321: 2000 was used for this purpose. As a result, the filling material has a dendritic structure, composed of alpha ferrite and carbides. In the melting zone and the thermally affected zone we observe that there is bainite. Austenization has taken place over and above this grain refining. The base material consists of hardened bainite.

No microfractures or other discontinuities were found after this test.

*Figure 35. AXIOSKOP.*

### Strength tests

In this test several parameters of the weld were measured: yield strength, elongation, contraction, resilience and FATT50 padding weld factor. The ZWICK 5111 machine was used to carry out this test and the results were then compared with the standards of the NR417-07 standard. The resilience test was performed according to EN10045, A(KV).

The following image shows the test results compared to the requirements of standard NR417-07. All the values obtained are within the required requirements.

| Specimen | Rm | Re | A5 | Z | KV | | | FATT50 |
|---|---|---|---|---|---|---|---|---|
| | N/mm$^2$ | N/mm$^2$ | % | % | [J] w 0$^o$C | | | $^o$C |
| **Padding** | 877 | 778 | 15,5 | 60 | 51 | 41 | 43 | 11 |
| **NR417-07** | 800-950 | Min. 700 | Min. 14 | Min. 45 | śr. 54 | | | - 30 |

*Figure 36. Padding weld and forging toughness properties.*

In the previous image it can be seen that the resilience and the FATT50 factor are not the same in welding as in forging. Additional tests were performed to determine the fracture toughness factor K1C. To determine this parameter, the Begley-Longsdon method was used according to the HZKM620206 standard. The results of this test are hown in the following graph.

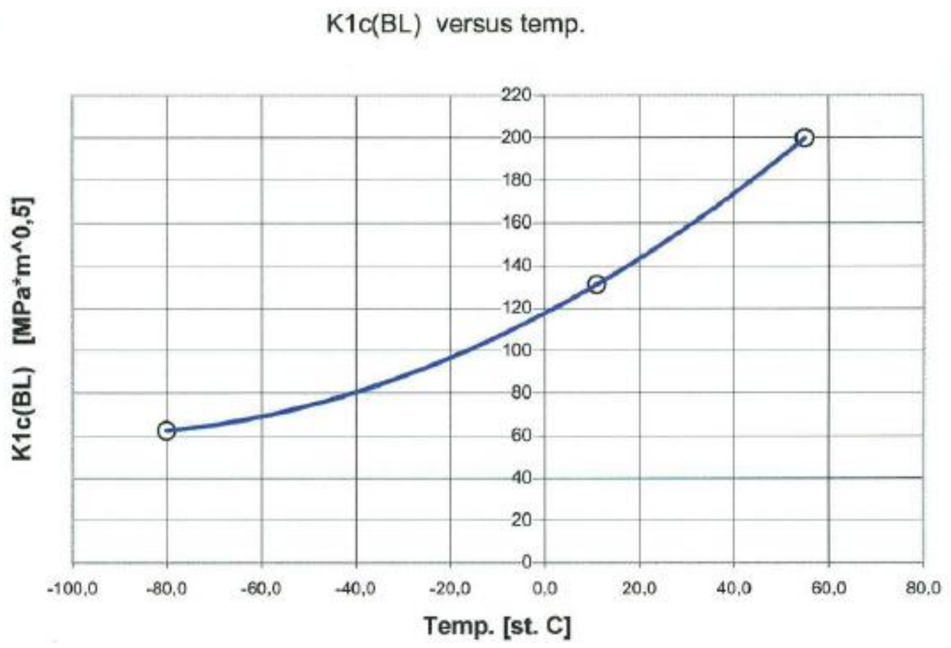


*Figure 37. K1C factor.*

Once these results are obtained by the Begley-Longsdon method and compared with the brittle fracture factor standards indicated in HTGD662121 for 26NiCrMoV14-7 Classic, it is concluded that it does not meet the requirements.

## Results

After carrying out all the tests, it is concluded that the welding was carried out correctly.

In the non-destructive tests no defects were found that could lead to the failure of the stage.

In contrast, metallurgical tests have detected defects caused by macrofractures caused by rotor operation. They have been especially detected in the control stage, as this is where the highest temperatures and voltages connected to the blades are reached. In these tests the composition of the material was analyzed and we could observe that the filler weld presents alpha ferrite and carbides, but no delta ferrite appears. The thermally affected zone has a bainitic structure and measures 4mm. The melting line is practically negligible, about 0.5mm and has a hardness of approximately 330 HV10. With respect to welding, it is estimated that it has an average hardness of 305 HV10.

As I have already mentioned, both the hardness and the Re, Rm, A5 and Z parameters meet the required requirements. Weld resilience tests average 45J. According to standard NR417-07 this value must be from 54J to 0˚C and never less than 40J.

Therefore, it is noted that the results of resilience are not favourable, as they do not meet the requirements of the standard.

Regarding the FATT50 factor, we observe that the test results indicate that it is at +11 ˚C when 50% of the brittle and ductile fracture should be at -30 ˚C according to the NR417-07 standard. Therefore, it does not meet the requirements.

The fracture resistance factor also does not meet the requirements of the standard. Comparing the theoretical requirements and the experimental values we can conclude that the result is not favourable.

## Conclusions

- After the study we can say that it is possible to make a welding in 26NiCrMoV16-7 SC with a welding rod SZW572SC and flux WP330. This welding has been done with the SAW process, submerged arc welding.
- After interpreting the results of the tests carried out on a specimen prepared specifically for this study, we can state that the weld has no defects that could lead to the fracture.
- Once both the melting line and the thermally affected area have been examined, they are found to be free of microfractures and other defects.
- The welding process perfectly meets the requirements of the standard in terms of hardness, yield strength, elongation and contraction, as well as the parameters A5 and Z.
- After the resilience tests and the FATT50 factor, we observe that it obtains values that do not meet the requirements of the standard. Therefore, it is not recommended to repair the high-speed rotor control stage with the materials described in the first point, i.e. SZW572SC rod and WP330 flux.
- All the tests described in this study need to be supplemented with additional tests and observations in order to complete the study of welding behaviour.

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