Transformation of knowledge and technology from research and development to the commercial production of heavy steel castings and forgings for power engineering, made of advanced creep resistant steels

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ABSTRACT

Heavy steel castings and rotor forgings, made of creep resistant steels, play a key role in fossil fuel fired power plants for highly loaded components in the high and intermediate pressure sections of a turbine. Increasing operating temperatures in steam turbines results in higher efficiency and lower emissions. This is the base for the development of new creep resistant steels. For the development of higher efficiencies in the power plants and the improvement of creep resistance for the involved materials, also the casting and forging steel grades have to be adapted to the increased demands on material properties. As the task for designing these materials can not be covered by single companies or countries, all suppliers of power plant components were covered within one project, COST 501. After evaluation of the most promising alloy from laboratory melts and production of cast plates from this alloy, these plates were welded with a matching electrode, to perform a welding procedure qualification, and to start a testing programme for mechanical properties, microstructure and creep properties. Based on these screening programmes, for selection of chemical composition and heat treatment, a pilot valve body was cast, to verify castability, non-destructive testability and weldability. Welding consumables were developed parallel to that of the base metals for boilers and castings.

The introduction of the new 9-12 % Cr-steel castings into commercial production could be performed parallel to the ongoing research work. The production of more than 100 heavy steel castings of modified 9-10% Cr-steels in a weight range from 1 to 60 tons demonstrates that quality performance is as good as for 1% CrMo(V) steel castings traditionally used for steam turbine components.

Typical steels for rotor forgings in the HP- and IP sections are 1 % CrMoV-steels while for the LP-section 3 - 3,5 % NiCrMoV-steels are used. Over the last years the characteristics of these steels has been improved substantially by improved manufacturing. However these advantages in steel and manufacturing quality is limited. The new developed 10 % CrMoVNbN (W,B) steels of the European R+D-program COST 501 permit an increase of the operating temperatures of about 50-60°C over traditional 1 % CrMoV- and 12 % CrMoV-steels.

Reported are the improvements in manufacturing, chemical compositions and mechanical properties with examples of large rotor forgings.

1 Introduction

Increasing operating temperatures in fossil fuelled steam turbines result in higher efficiency and lower pollution. Reduction of emissions of CO_2, SO_2 and NO_x is a world-wide agreement. 1 % increase in efficiency of an 800 NM power plant lead to a life-time reduction in CO_2 approaching one million tonnes [5].

CASTINGS

Parallel to the ongoing R&D activities within the scope of the European research project COST 501, Voest-Alpine Foundry Linz started the commercial production of steel castings made of 9-10%-Cr steels with and without Tungsten as early as 1992. This paper is reporting on various aspects of the full-scale manufacture of such castings for steam turbines in the weight range from 1 to 60 tons. The report is based on the production experience, which was gained within the last 8 years. During this period the results of the European research work within the frame of COST 501 were introduced into the foundry practice. Some elements of foundry experience within this period are reported [6].

Following items shall be discussed: steel casting metallurgy, , non destructive testing, improvement of foundry technique, microstructure in large castings, heat treatment and mechanical properties, manufacturing- and fabrication welding.

The development of manufacturing processes was done stepwise, and so was the increase of weight per piece. Therefor the knowledge and know how had to be adapted permanently and this learning process has not ended yet, because weight as well as complexity of the deigned castings is still increasing.

Nevertheless, the production of more than 100 steel castings of modified 9-10% Cr-steels in a weight range from 1 to 60 tons demonstrates, that quality performance is as good as for 1% CrMoV steel castings traditionally used for steam turbines.

FORGINGS

Since many years typical steel for HP- and IP-rotors are 1 % CrMoV-steels, for LP-rotors 3 - 3,5 % NiCrMoV-steels. Over the last two decades the characteristics of these steels has been improved substantially [6]. The chemical compositions including the reduction of trace elements have been optimised and results in avoiding temper embrittlement. Improvement of the basic metallurgy coupled with progress in the forging and heat treatment technologies have lead to the production of large homogenous forgings possessing a high degree of purity and less UT-defects [6, 7]. However these advantages in steel quality are limited. New developments were necessary for more significant sucess in efficiency of the turbines.

For the LP-rotors-steels 3 - 3,5 % NiCrMoV super clean version were created to avoid or minimise long term embrittlement. Super clean means further extremely reduction of trace element as Si, Mn, P, S, As, Sb, Sn to very low amounts. (Figure 1) [8]

Super clean quality allows higher operating temperature in the LP-section of the turbines. Saarschmiede has manufactured a lot of forgings, gas turbine parts as well as turbine rotors in super clean version up to dia. 1500 mm and 51 t shipped weight (Figure 2 and Figure 3)

Another contribution of Saarschmiede to the developments was a new 2 % CrMoNiWV-steel used for combined HP/LP- or HP/IP/LP-rotors, where good creep rupture strength in the HP (IP)-sections and good toughness are required in the LP-section [9,10]. As an example Figure 4 shows a combination rotor with 961 mm diameter in the HP-section and 1745 mm diameter in the LP-section manufactured from 134 metric tons ESR-ingot of 2.300 mm diameter. The mechanical properties including stress rupture properties are over the range of 1 % CrMoV-steels (Figure 5).

2 Castings

2.1 The role of the steel foundries within the COST 501 Programme

2.1.1 Casting Programme

After evaluation of the most promising alloy from laboratory melts, and production of cast plates from this alloy, those plates were welded with a matching electrode, to perform a welding procedure qualification, and to start a testing programme for mechanical properties, microstructure and creep rupture strength [1].

Based on these screening programmes, for selection of chemical composition and heat treatment, a pilot valve body was cast, to verify castability, non destructive testability and weldability. The details of this COST 501, round II and III programme are reported in [2].

2.1.2 Welding Programme

As welding is an important cycle in manufacturing process of steel castings, the welding programme within COST 501 and the development of welding consumables is an important issue for the foundry. The investigations and results of the welding group of COST 501 round II are reported in [3] and [4].

2.2 Manufacturing process of heavy steel castings

Figure 6 shows the main sequences in the flow of production of heavy steel castings for power engineering.

After design of casting technology, pattern making and moulding, the existence of the product starts with the melting and pouring process.

As castings in such dimensions must not have defects which result in scrap, the pouring- and solidification-process is simulated on the computer during the design-phase, in order to find out critical sections for shrinkage and avoid them from the very beginning. (see Figure 7).

After the time of solidification (2 to 6 weeks, depending on wall thickness, complexity and material) has passed, the casting is shaken out. The handling of the casting in this condition is absolutely critical, because the as cast microstructure is highly brittle. Therefor an annealing treatment is necessary for the casting, to stand the high thermal stresses during riser burning. The temperature range in which riser burning is performed, is also critical, as the stresses from the different temperature-gradients and the changes in wall thickness in different sections should not be added by the stresses from transformation of microstructure.

The quality heat treatment is the most important sequence besides the chemical composition, to get the required microstructure and mechanical properties, as a basis for creep strength.

After pre machining, the casting is tested by non destructive testing methods (magnetic particle, ultrasonic and radiographic). All indications which do not meet the applied acceptance standard, have to be removed by grinding and arc air burning. After magnetic particle testing of the excavations, these are welded, followed by a stress relief treatment.

A lot of dimension control sequences are performed in between the main production phases, in order to realise suddenly, if the dimensions will become critical for final machining or function.

Final non destructive testing is the last sequence in the foundry, before the casting is shipped for final machining.

2.3 Introduction of new 9-10%Cr steels into the commercial production of heavy steel castings

2.3.1 Reflections about the manufacturing processes

The main points of view to be considered for commercial manufacturing of heavy castings made of newly developed steel cast materials from R&D projects are following:

- *Casting Technology and Solidification Simulation*

  Optimum design of casting and feeding technology is a basic condition for the production of sound castings. The solidification parameters and thermophysical properties of 9-10%Cr cast steel grades are different from those of low alloyed 1CrMo(V) steels, therefor the shrinkage behaviour of the high alloyed 9-10%Cr steels is more complex, especially in heavy sections and mass accumulations..

- *Melting and Pouring*

  Raw materials of high quality, thorough steel making and correct pouring practice are necessary to meet the chemical composition exactly (“Point-Analysis”) and to minimise inclusions. Secondary metallurgy in a ladle-furnace-process is an important basic condition for that.

  Figure 8 shows the melting process which is applied at VOEST ALPINE FOUNDRY LINZ.

  The most important criteria to be considered at melting and pouring of new 9-10%Cr cast steel grades are described in [2].

- *Microstructure*

  Some of the considerations for microstructure, especially in heavy sections of steel castings, namely segregation’s of C and Delta Ferrite, and the necessary adjustments of chemical composition for the new 9-10%Cr steel grades, are described in [2].

- *Heat Treatment and Mechanical Properties*

Figure 9 shows the main production phases in form of a time/temperature diagram, beginning with cooling in the casting mould and ending with final stress relieving.

Due to the fact that severe differences in wall thickness are typical for turbine casings, the temperature distribution in the different sections is highly critical in the temperature range of martensite transformation. Therefore the logistics of handling the casting during production has to be planned, dependent on the conditions of microstructure in the different sections.

Castings in such dimensions usually have a long history of heat treatment cycles with long required holding times for thick sections, due to more cycles of repair and fabrication welds with intermediate stress-relief-treatments for large, critical welds, in order to reduce residual stresses from welding.

In order to show the influence of long holding times and more stress-relief-cycles a special investigation was performed, where we applied several tempering cycles to cast test plates with a wall thickness of 100 mm. Figure 10 shows the heat treatments and holding times applied to these test plates of 9-10%Cr steels with and without tungsten (E911 and P91-type). The results of the mechanical properties show that multiple tempering and long holding times cause a reduction in yield strength. These facts have to be considered in the specification of minimum requirements, especially for heavy castings.

On the basis of the available results, a minimum yield strength of 520 MPa is advised for the tungsten-alloyed G-X 12 CrMoWVNbN 10 1 1. As tungsten has a strengthening effect, it could be proved that the yield and tensile strength was higher than that of 9% Cr cast steel without tungsten at the same tempering temperature of 730 °C. For the G-X 12 CrMoVNbN 9 1 cast steel without tungsten, the minimum yield strength shall be specified within the 480MPa range.

- *NDT and Casting Defects*

One of many advantages of cast steel for complex designed structures such as turbine components is, that defects can be repaired by welding. Fabrication welding is one of the main cycles in the manufacturing plan of a steel casting (see Figure 6). The amount of welding volume related to the casting weight is a matter of costs and is dependent on type and complexity of design and material.

A detailed description of defect types and a comparison of repair volumes between the new 9-10%Cr cast steels and the popular 1%CrMo(V) cast steels is given in [2].

- *Welding*

Due to the high residual stresses of the 9-10% Cr steels, resulting from the martensite micro-structure, major process and construction welds are performed in partial cycles with intermediate stress relieving's. On principle we can confirm that the welding behaviour of the new steel grades is satisfactory, providing that the specific characteristic features and rules for martensite, high Cr alloyed steels are applied and strict quality controls are carried out during the welding process.

- *Cycle Time and Costs*

As against the popular 1% CrMoV cast steel the production period for castings using the new 9-10% Cr steel grades is 2-4 weeks longer, depending on the size and complexity of the casting.

The main aspects which cause the increase in costs and cycle time for 9-10% Cr-steels are:

- Material Costs
- Higher effort in casting technology, resulting in decrease of output (=ratio of liquid steel poured into the mould versus rough casting weight), especially for heavy and complex designed castings from casting technology's point of view. The left chart of Figure 11 shows the difference in output between 1%CrMo(V) steels, 9-10%Cr steels and all produced steels on average. The right chart of Figure 11 shows the increase of the necessary liquid steel for feeding purposes and the appropriate decrease of output for the new 9-10%Cr steels, when the design weight of the castings increases.
- Difficult handling for shake-out, cleaning and riser burning resulting in additional heat treatment cycles and intermediate annealings.
- Complex and longer cycles of heat treatment during foundry production (see Figure 9)
- Intermediate stress-relief cycles for manufacturing welds with high welding volume and fabrication welds with heavy wall thickness
- New formation of well known defect types, resulting in higher volumes of excavations and manufacturing welds.
- High-Cr scrap, alloyed with W, Nb, N is very difficult to sell, even for prices, lower than that of low and unalloyed scrap, therefore the internal costs for circulate material increases.

The presentation of higher costs was done on basis of the experience with the production so far.

At this point of production experience we have to discuss the cost aspect. On the one hand we all profit from the effort to improve power plant efficiency and to participate in the reduction of CO_2 emissions and other important positive effects on the environment. On the other hand we have to accept the higher costs for higher alloyed materials which can resist the elevated temperatures and ultra super critical steam conditions of advanced power plants.

The cost increase from 1 % Cr Mo V steel castings to 10 % Cr Mo W V Nb N material was shown to be 20 to 40 % depending on size and complexity of steel castings. Due to the characteristics of the modified 9-10 % Cr-steels the expenditures for larger steel castings are higher than expected. The experience of the last five years production of modified 9-10 % Cr-steel castings for new power plants in Europe and overseas have shown that the quality of castings made of the new 9-10%Cr cast steels is guaranteed in the same range as for the well known low alloyed cast steels.

2.3.2 Realised projects and examples of manufactured steel castings made of 9-10%Cr steel

The transition of development work into practical casting took place in stages. The increase in weight from 3.5 t (test valve casing) to 14 t (first inner casing for project Schkopau) was coupled with enormous risks for the turbine manufacturers. However, at the end, perfect castings with weights from 1 to 60 t were successfully manufactured using G-X 12 CrMoWVNbN 10 1 1 and G-X 12 CrMoVNbN 9 1.

Detailed information, with an overview of the power stations in which the new tungsten alloyed and tungsten free 9-10% Cr cast steels have been employed up to now, is given in [2].

Some examples should give an impression of such castings.

Figure 12 shows the first projects realised, namely IP inner casings for power plant SCHKOPAU (14 tons) and MERI PORI (19 tons). At this stage, beginning in 1992, we had to define the exact chemical analysis for production castings considering the right heat treatment parameters to provide reliability of production and guarantee freedom from Delta Ferrite and the required mechanical properties in all positions of the castings. The first Welding Procedure Qualifications had to be performed.

The initial increase in weight and complexity was the IP inner casing for SCHWARZE PUMPE (40 tons) with welded-on cast pipes (see Figure 13). The HP/IP inner casing for the Danish power plants SKÆRBÆK and NORJYLLAND was a further challenge especially for casting technology and melting practice (see Figure 14). The problems at this stage of production development were casting technology (solidification parameters and thermophysical properties) and melting (gas content) for heavy wall thickness and severe changes in wall thickness.

The biggest valve casing ever produced of the new steels was for power plant LIPPENDORF (see Figure 15). An absolute performance in all aspects of steel foundry technology were the casings for the project BOXBERG: an IP inner casing weighing 60 tons with 113 tons of liquid steel necessary, which we believe is the biggest casting ever made of 10%CrMoWVNbN steel (see Figure 16). Highest level of difficulty was a VHP casing (31 tons) with welded-on valve casings (18 tons each), connected with a 185 mm welding seam (see Figure 17). New problems appeared: stresses in all sequences of production, starting at solidification, and shake out continuing at heat treatment before riser cutting and quality heat treatment. Martensite transformation is the main initiator for these stresses which are combined from thermal, transformation and residual stresses.

Handling considering the course of temperature in all wall thickness sections during shake out, heat treatment, crane transport and all manipulations on the castings is a main concern.

An Overview over this development in increase of weight on example of IP inner casings for the different projects is given in Figure 18.

These problems together with hot tear behaviour are new fields for application of simulation. Therefor simulation software for shrinkage behaviour have to be extended by mathematical models for stresses and strains during solidification but also during heat treatment.

3 Forgings

Saarschmiede has experience for many years in manufacturing very large forgings also in high alloyed steels. Lot of rotors and discs in 9 to 12 % Chromium steels are manufactured, most of them for high temperature service [12], but also for low temperature service, e.g. geothermal application [15]. These large forgings are made in ESR quality with ingot size up to 2300 mm diameter and weight over 100 mt.

3.1 Advanced 9-12 % Cr-steels

Higher steam temperatures up to 600°C (620°C) or higher need 9-12 % CrMoV-steels with new chemical compositions which are developed in the European COST 501-program. Details are published and reported [11, 12, 13, 14].

For remembering the most successful steels are listed in

Figure 19, which are chosen from a large number of laboratory melts of various chemical compositions. Long term testing was made and is necessary caused by a possible substantial drop after 10.000 h.

Based on these data pilot rotors are manufactured and tested. Long term testing is still running partly now up to 80.000 hours.

3.2 Manufacturing Procedure of a pilot rotor forging in advanced 10 % CrMoV (Nb, N, W, B) steels

Apart from the known structural defects encountered in large conventional ingots such as A- and V-segregations and shrinking cavities, the 9-12 % CrMoV (Nb, N, W, B) steels are very susceptible to oxide inclusion at the bottom of the ingot. These inhomogenities can be avoided by the ESR process, especially for large forgings, respectively big ingots. ESR allows uni-directional solidification over the cross section and the length of the ingots [17]. All of traditional 12 % CrMoV- and the new developed 10 % CrMoV- (Nb, N, W, B) steels are remelted by the ESR-process at Saarschmiede.

As reported for castings a similar development was initiated within the COST 501-program for rotor forgings. Different steel types are made in lab quantities and tested. The best results lab melt were chosen for the production of pilot rotors.

Steel „E“ pilot-rotor was manufactured by Saarschmiede. This rotor was forged from a 42 mt ESR ingot having 1300 mm dia. After double upsetting the ingot was final forged to a diameter of 1250 mm with a 4,9 stretching ratio. The preliminary heat treatment was performed in the pearlite temperature ranges, the quality heat treatment at an austenitizing temperature of 1070°C. After completion of a tempering process at 570°C and 690°C testing was undertaken: mechanical testing (strength, toughness, fracture toughness) creep behaviour at 550°C / 600°C / 650°C up to 100.000

hrs., ISO stress behaviour, long time toughness, overaging, LCF and cycle crack growth. Results are reported in different publications [11, 13, 14, 16] (Figure 20).

3.3 Manufacturing Procedure of industrial rotor forgings in advanced 10 % CrMoWVNbN-steel (COST E-steel)

Up to now 22 turbine rotors in COST E-steel are manufactured in different sizes and weights with maximum diameter of 1280 mm and appr. 45 t delivery weight.

Typical manufacturing procedures of COST E-steel rotors are shown in Figure 21, Figure 22 and Figure 23. The steel is melted in a 125 t electric arc furnace with subsequent secondary metallurgy, that means ladle heating and vacuum degassing procedures, then poured into cylindrical ingots, named electrodes. These electrodes are remelted in an ESR-plant having maximum ingot dia. of 2.300 mm and maximum weight of 165 t (Figure 21). The forging procedure is shown in Figure 22. The subsequent process of preliminary and quality heat treatment is described in Figure 23.

4 Conclusion and Outlook

Figure 24 shows the development of production volume in rough weight and liquid steel since the beginning of production of the new 9-10%Cr steels at VOEST ALPINE FOUNDRY LINZ, in 1992. The proportion has reached 15% of the total production volume since 1997. This fact and the mentioned examples show that the technical introduction of R&D-designed steel grades within COST into commercial production was done most successfully and in the quickest possible way.

The new challenge, with even higher goals and more complex materials in COST 522, will also be a challenge for the steel foundry industry.

From the view of forgings up to 1999 more than 180 forgings are manufactured, rotor shafts for steam turbine as well as discs, shaft ends and hollow shafts for gasturbine application.

Within the COST 501/COST 522-program the boron alloyed melts show the best creep rupture properties. Similar to the first pilot rotors (COST E, COST F) a pilot rotor with body diameter of 1200 mm in an boron alloyed steel FB 4 (Figure 25) was manufactured in the same way which means

- electric arc furnace melting with secondary metallurgy
- remelting ESR, ingot dia. 1300 mm, weight 45 t
- forging on a 60-MN-press with double upsetting
- preliminary heat treated by transformation to martensite
- quality heat treated by austenitizing at 1090°C and double tempered, at least at 700°C

Results of this rotor are shown in Figure 26.

5 Acknowledgements

The difficult, but successful, technical transfer of the R&D work into operational practice was achieved in an excellent co-operation with our customers and the friendly assistance of the COST 501 working group, for which we would like to express our thanks. We also thank the Austrian Research Foundation for their support of the Austrian contribution to COST 501.

6 References

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7 Figures

	Analysis (wt%)	
	Conventional steel (Average of 100 heats)	**Superclean steel (Average of 58 heats)**
Mn	**0.2250**	**0.0220**
Si	**0.0550**	**0.0230**
Al	**0.0065**	**0.0070**
P	**0.0045**	**0.0021**
S	**0.0025**	**0.0007**
Cu	**0.0660**	**0.0250**
As	**0.0090**	**0.0034**
Sb	**0.0010**	**0.0006**
Sn	**0.0050**	**0.0029**

Figure 1: Analysis of superclean and conventional 3-3.5% NiCrMoV steels

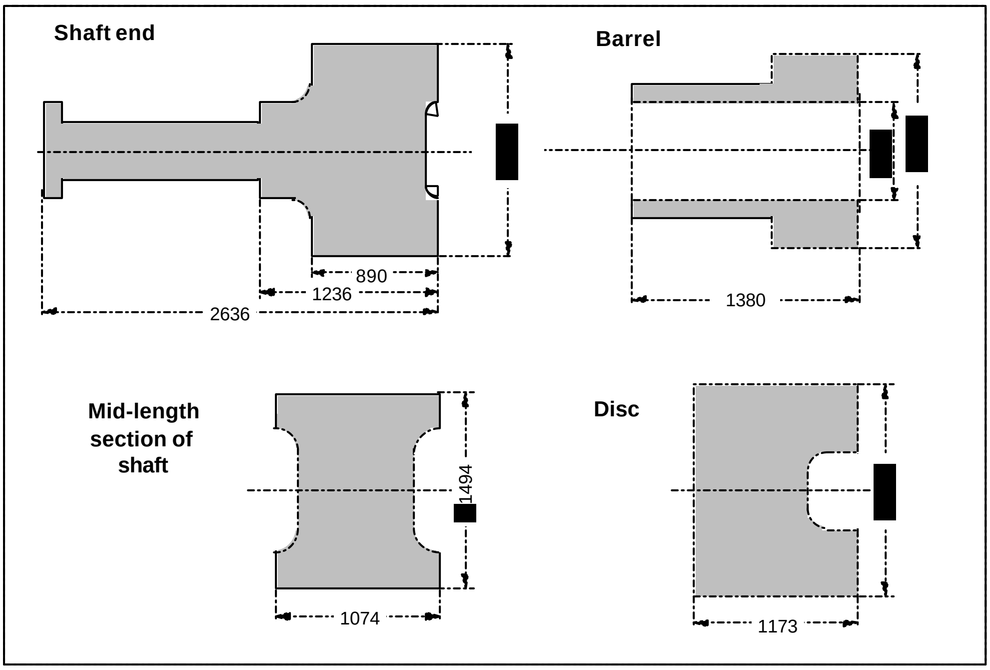


Figure 2: Forged gasturbine parts in super clean 3-3,5% NiCrMoV-steel [4]

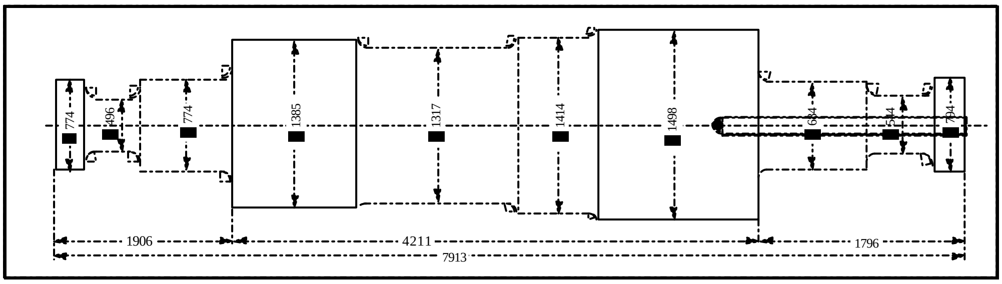


Figure 3: Forged steam turbine rotor in 3.5% NiCrMoV steel

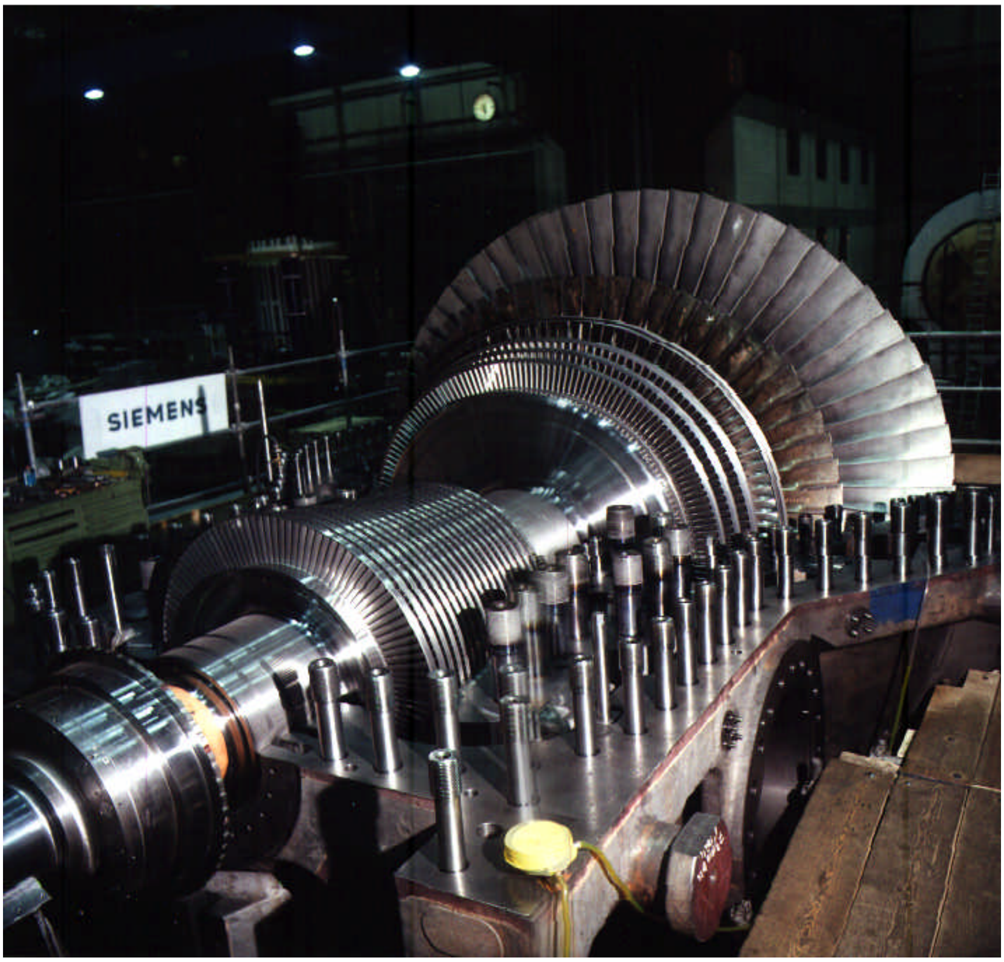
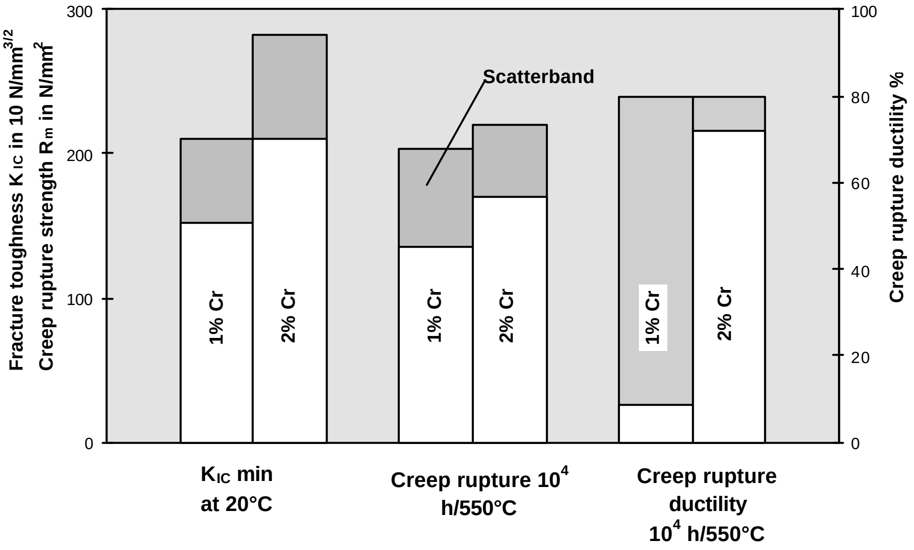


Figure 4: Combination rotor in new 2% CrMoNiWV-steel (Saarschmiede 23 CrMoNiWV 8-8)



	C	Si	Mn	Cr	Mo	Ni	V	W
	%							
1% CrMoNiV	0.28	0.10	0.70	1.30	1.00	0.70	0.30	
2% CrMoNiWV	0.22	0.07	0.70	2.10	0.90	0.75	0.30	0.65

Figure 5: Properties of 1% CrMo(Ni)V and 2% CrMoNiWV rotor steels

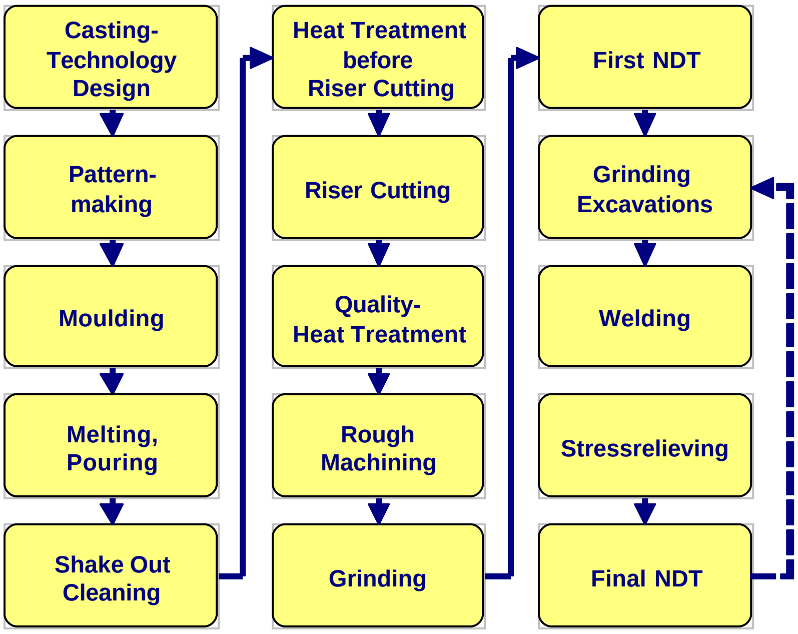
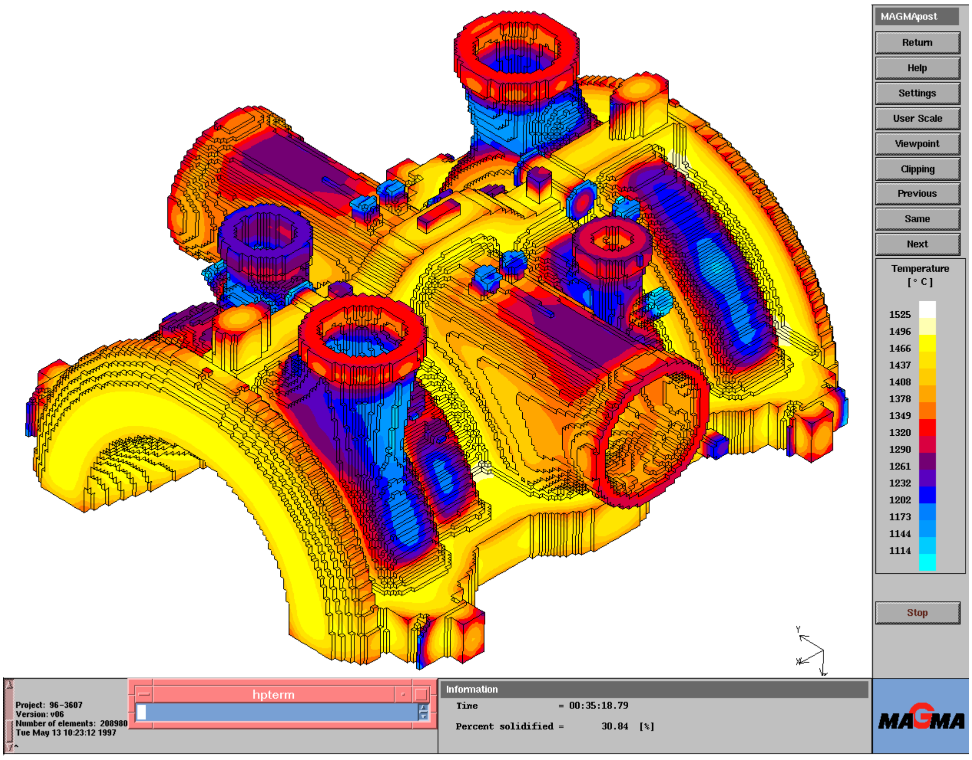


Figure 6: Typical manufacturing plan for heavy steel castings



Project: 96-3607
Version: v06
Number of elements: 208980
Tue May 13 10:23:12 1997

Time = 00:35:18.79

Percent solidified = 30.84 [%]

Figure 7: Simulation of solidification of a IP- inner casing, 60 tons (G-X 12 CrMoWVNbN 10 1 1)

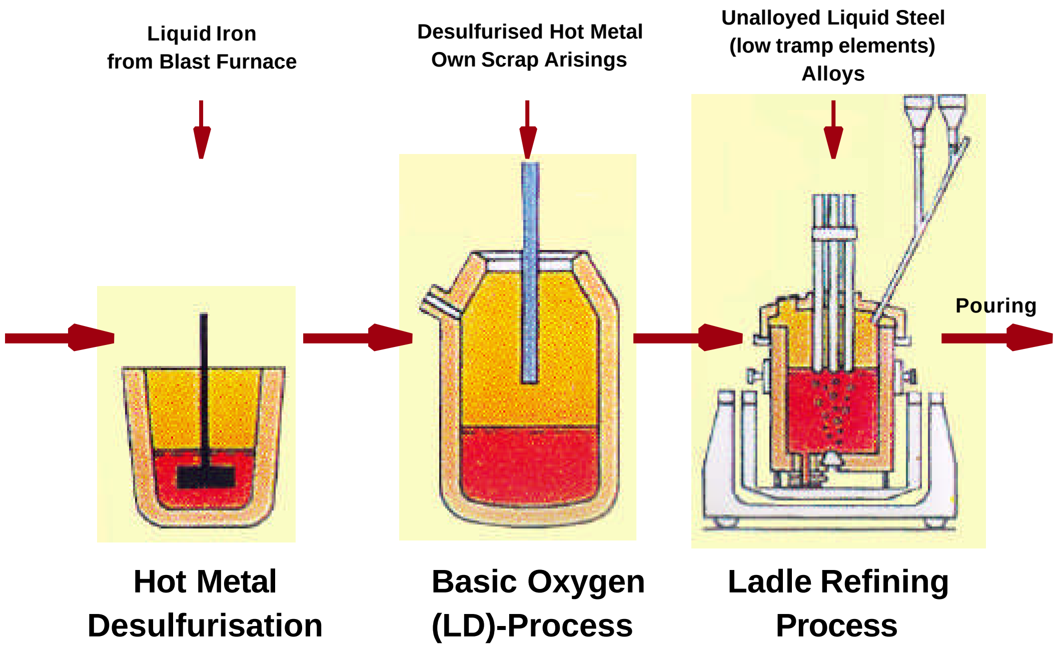


Figure 8: Steel making process at Voest-Alpine Foundry Linz

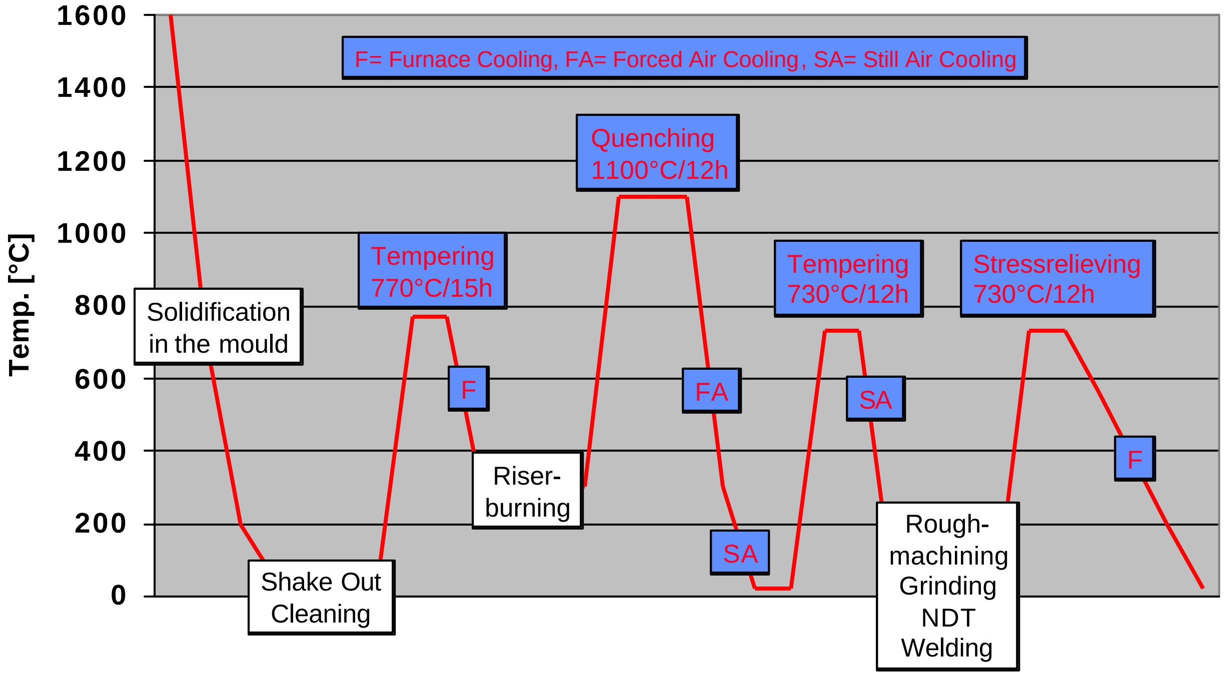


Figure 9: 9-10%Cr steel castings – time/temperature history: minimum cycles of heat treatments during production in the foundry

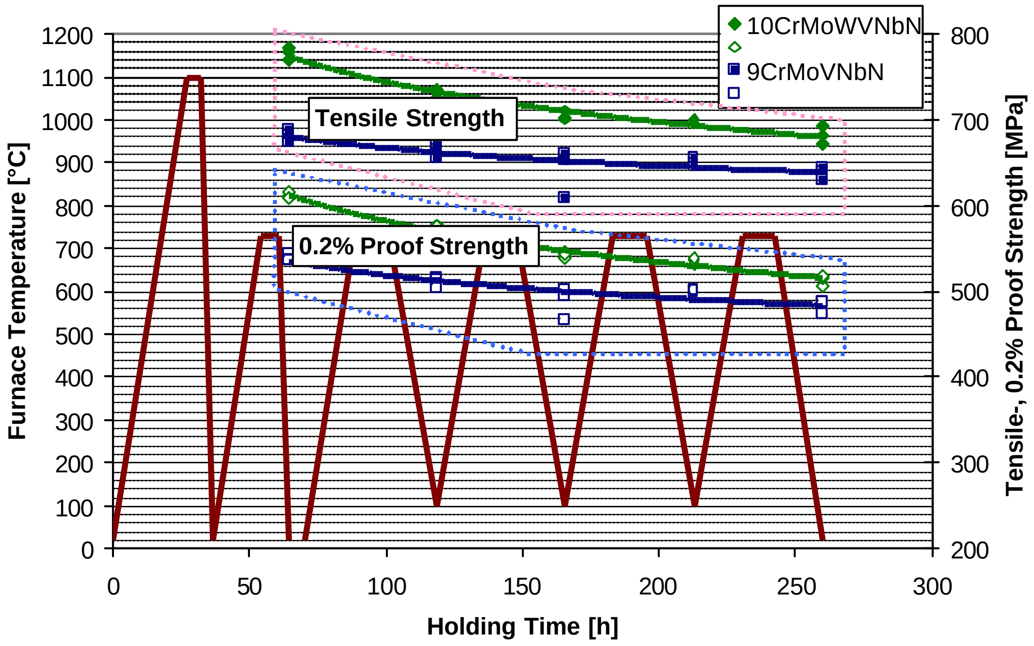


Figure 10: Investigation programme: influence of multiple heat treatments on mechanical properties of new 9-10%Cr cast steels

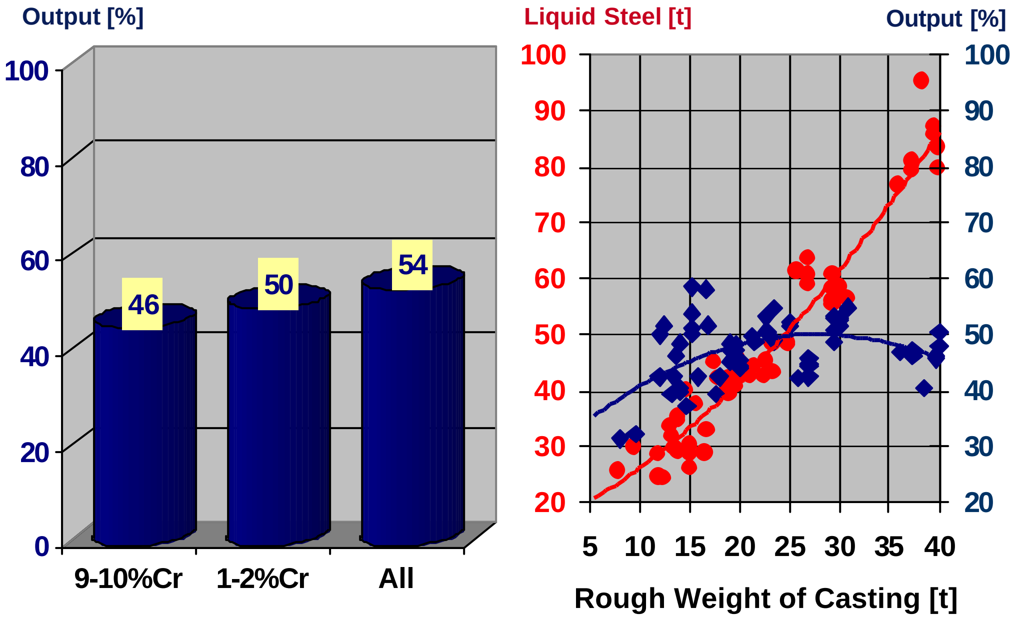


Figure 11: Comparison of output: 9-10%Cr steels, 1-2%Cr steels, all steels in average; Liquid steel and output versus rough weight for 9-10%Cr steel castings

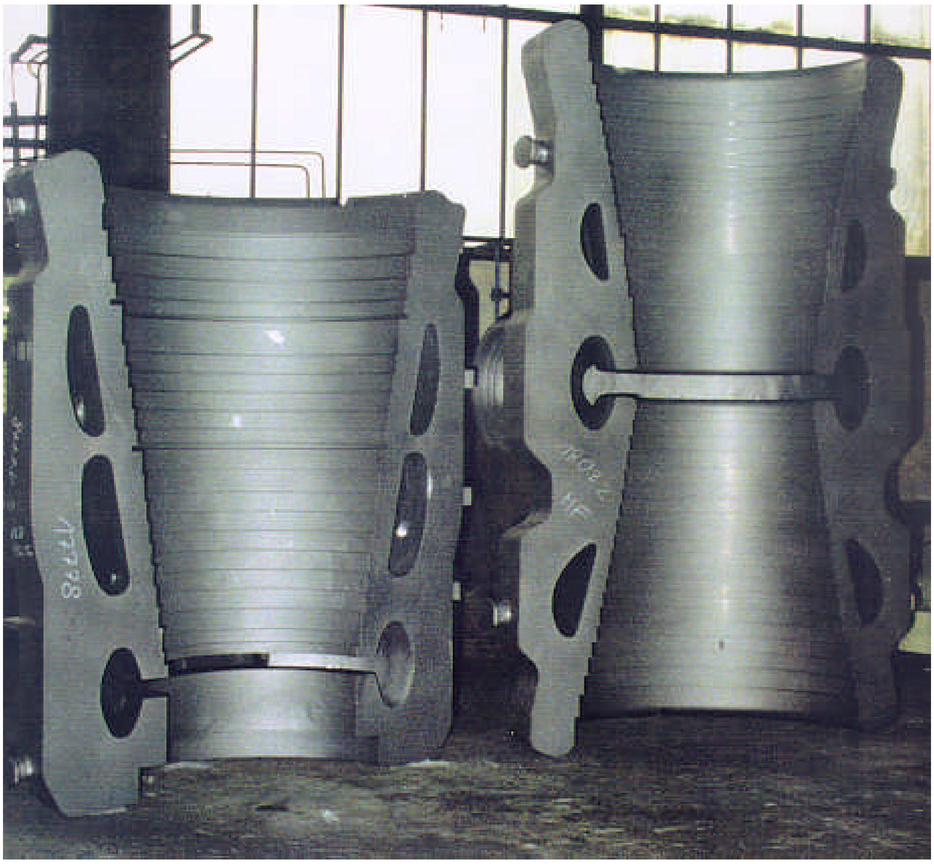


Figure 12: Projects Schkopau and Meri Pori IP Innenr Casing, 14 t and 19 t (G-X 12 CrMoWVNbN 10 1 1)

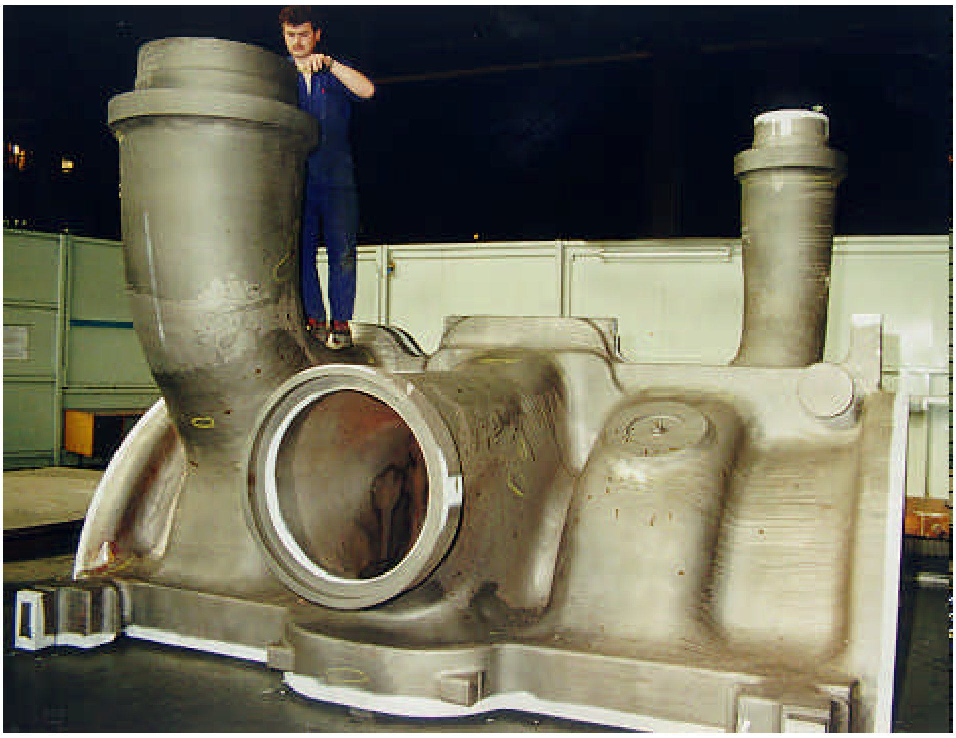


Figure 13: Project Schwarze Pumpe, IP Innenr Casing, 40 t with welded on, cast elbows (G-X 12 CrMoWVNbN 10 1 1)

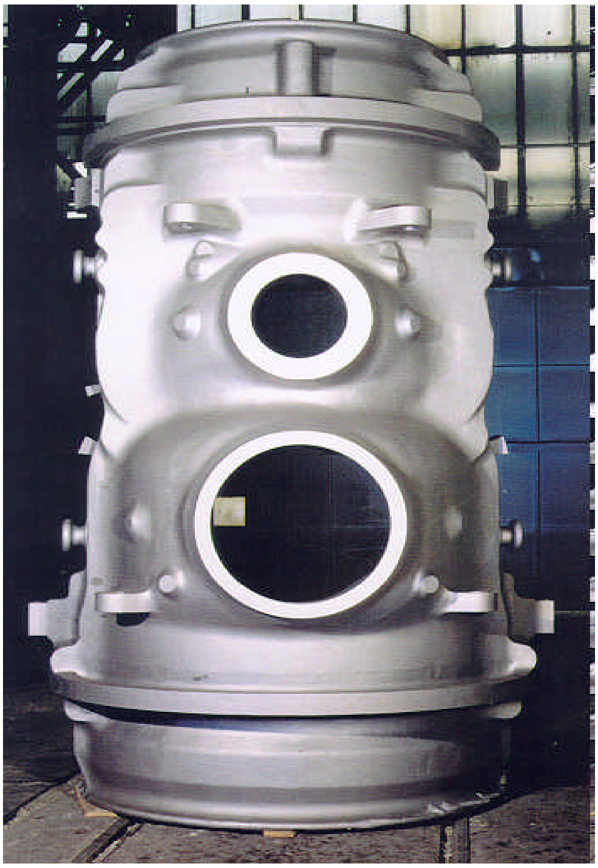


Figure 14: Projects Skærbæk and Nordjylland, HP/ID-Inner Casing
20 t, (G-X 12 CrMoVNbN 9 1)

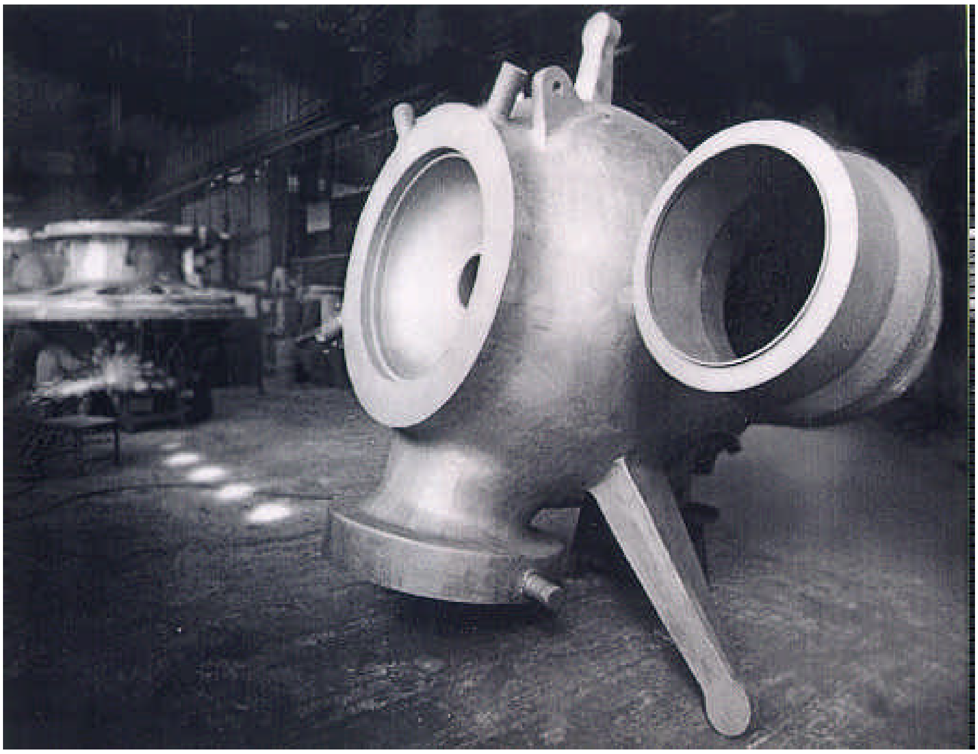


Figure 15: Project Lippendorf, Valve Casing
27 t (G-X 12 CrMoWVNbN 10 1 1)

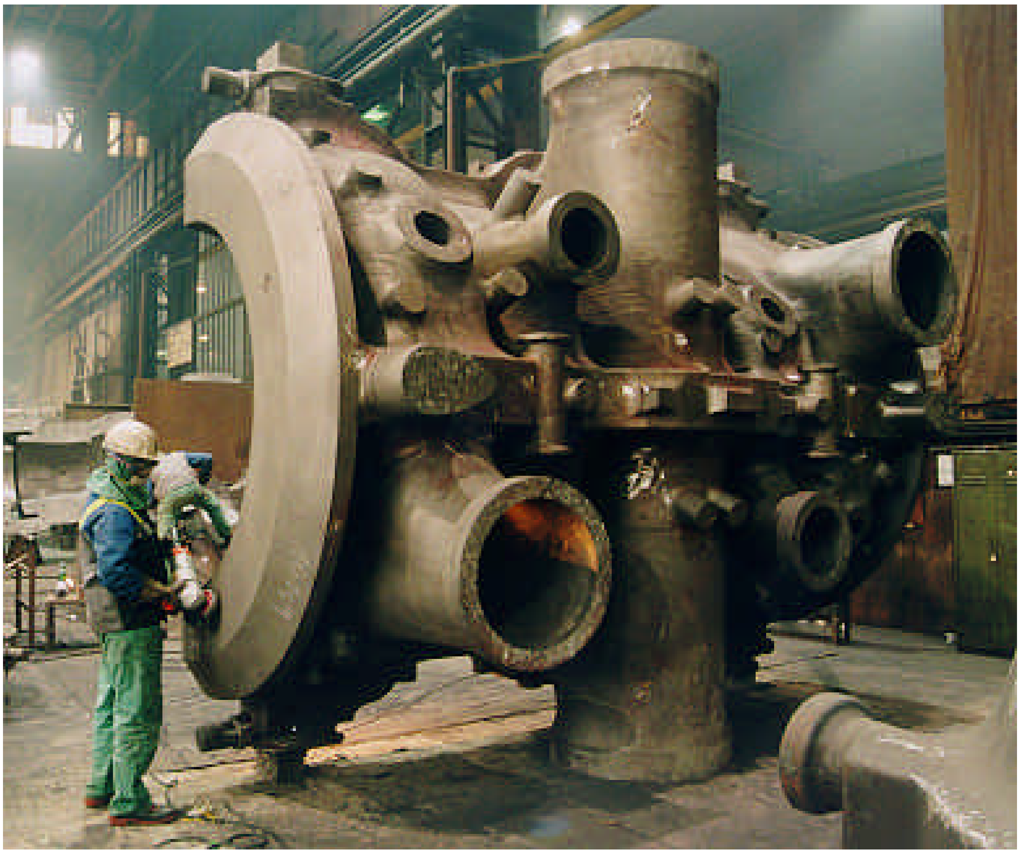


Figure 16: Project Boxberg, IP Inner Casing
60 t (G-X 12 CrMoWVNbN 10 1 1)

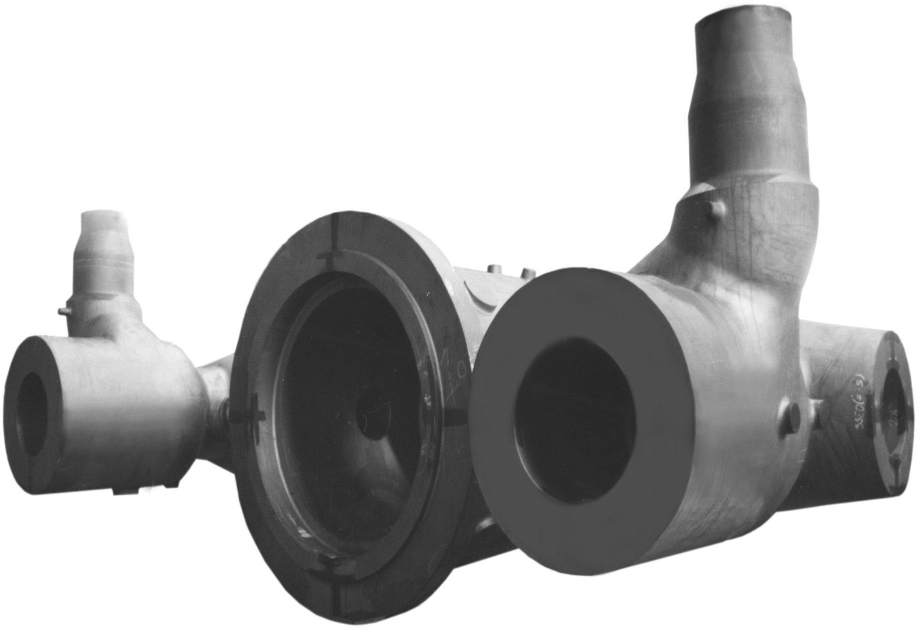


Figure 17: Project Boxberg, VHP casing, 31 t and 2 valve casings, 2x18 t) welded together (G-X 12 CrMoWVNbN 10 1 1)

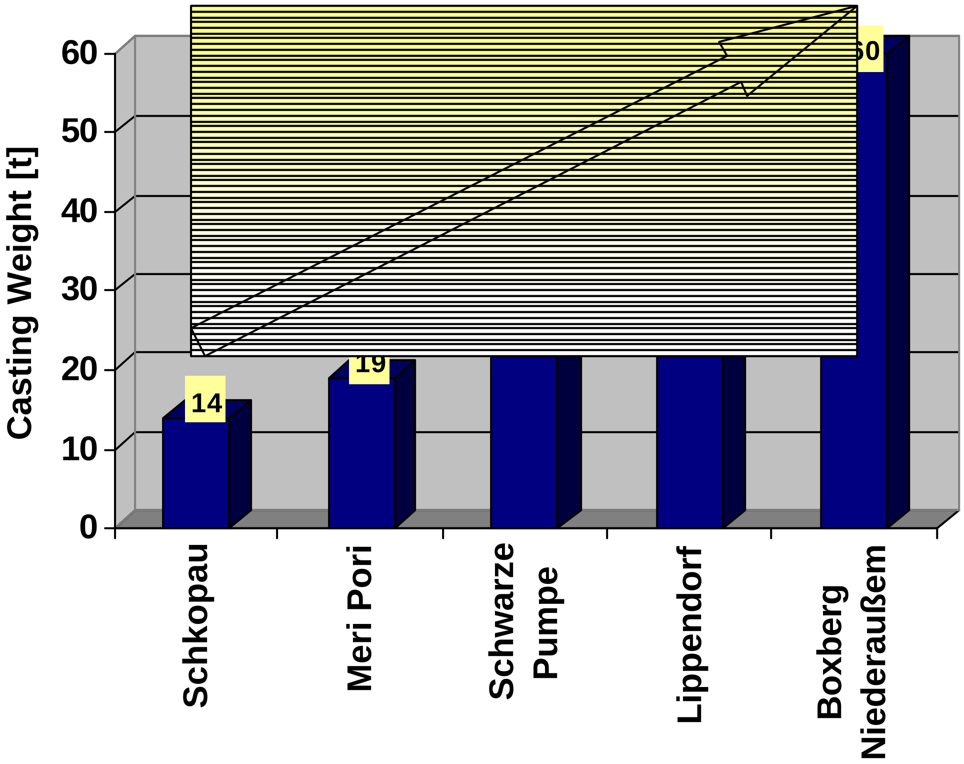


Figure 18: Overview over the development in increase of weight on example of IP inner casings

	type of steel	C	Si	Mn	P	S	Al	Cr	Mo	Ni	V	W	Nb	B	N
trial	melts for forgings														
A	+ nitrogen	0.05-0.08	0.1-0.3	0.2-0.7	< 0.01	< 0.005	< 0.02	9-12.5	1-2	0.5-1.0	~ 0.2		~ 0.6		0.1-0.3
B	+ boron	0.15-0.18	~ 0.1	~ 0.1	< 0.01	< 0.005	< 0.01	9-12.5	~ 1.5	~ 0.1	~ 0.3		~ 0.6	0.005-0.01	
D	+ tungsten	0.10-0.16	~ 0.1	~ 0.5	< 0.01	< 0.005	< 0.01	10-12	< 0.5	0.5-1.0	~ 0.2	~ 2	~ 0.6		< 0.07
E	+ tungsten/molybdenum	0.10-0.18	~ 0.1	~ 0.5	< 0.01	< 0.005	< 0.01	10-12	~ 1	0.5-1.0	~ 0.2	~ 1	~ 0.6		< 0.07
F	+ molybdenum	0.10-0.18	~ 0.1	~ 0.45	< 0.01	< 0.005	< 0.01	9.5-12	1-2	0.5-1.0	~ 0.2		~ 0.6		< 0.07
components			rotors												
	B	0.17	0.07	0.06	0.007	0.001	0.012	9.34	1.58	0.12	0.27		0.059	0.008	0.015
	E	0.12	0.10	0.45	0.006	0.002	0.006	10.39	1.06	0.74	0.18	0.81	0.045	0.0002	0.052
	F	0.11	0.03	0.52	0.010	0.005	0.006	10.22	1.42	0.58	0.18		0.05	0.0012	0.056

Figure 19: Chemical composition of advanced 9-12% Cr-Steels (COST 501 program)

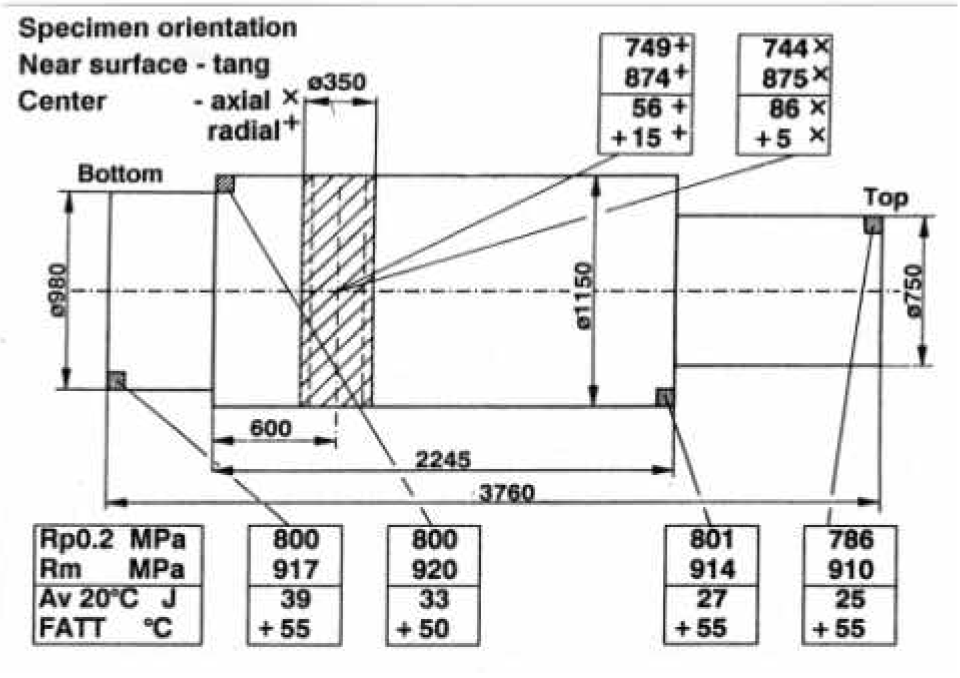


Figure 20: Mechanical properties of trial rotor E, yield strength ~ 750 MPa

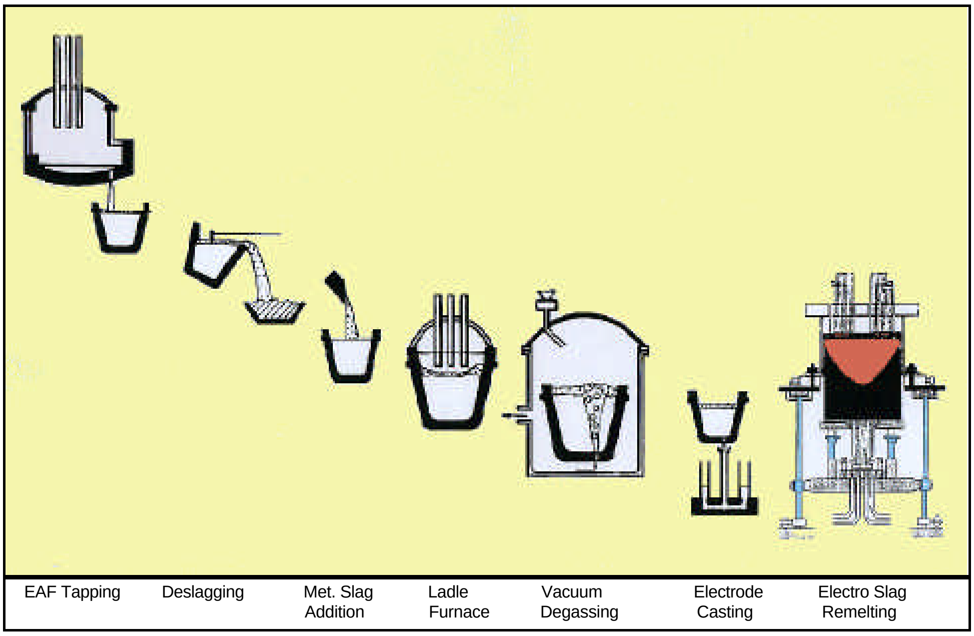


Figure 21: Typical manufacturing procedures of COST E-steel rotors: ESR-Process

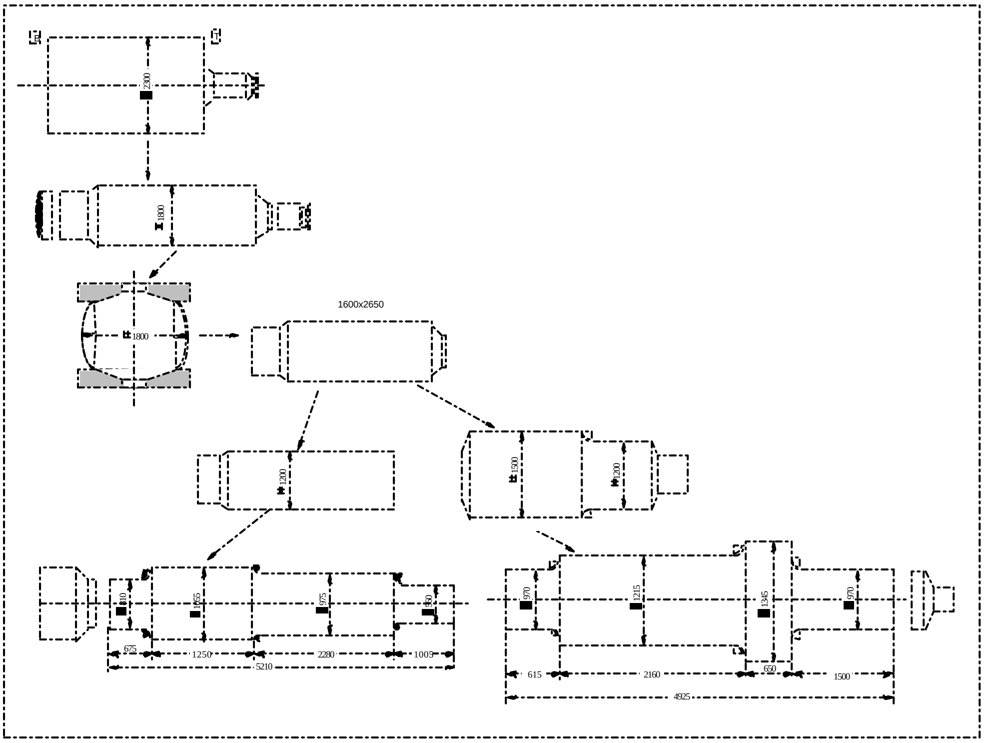


Figure 22: Typical manufacturing procedures of COST E-steel rotors: Forging Procedure

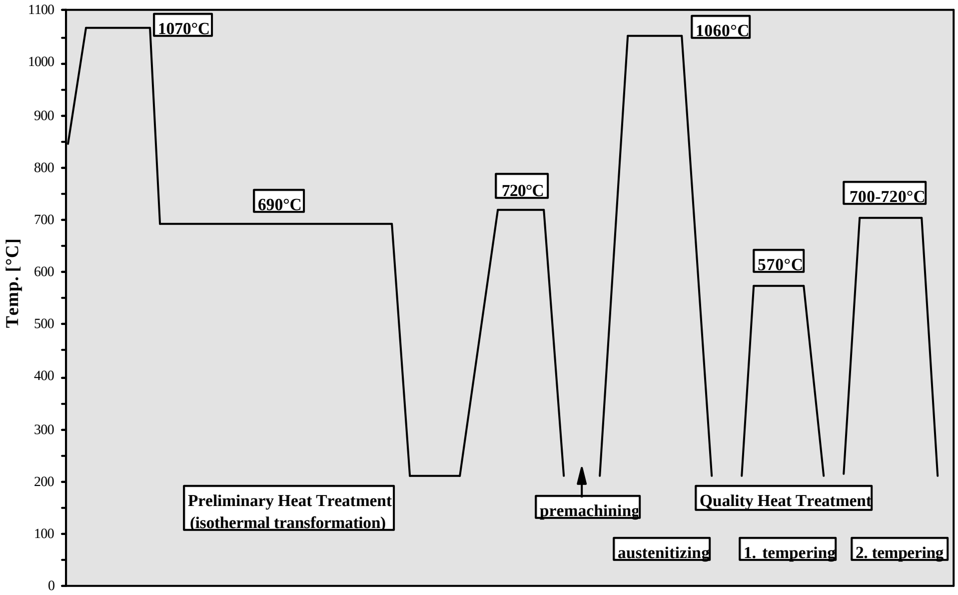
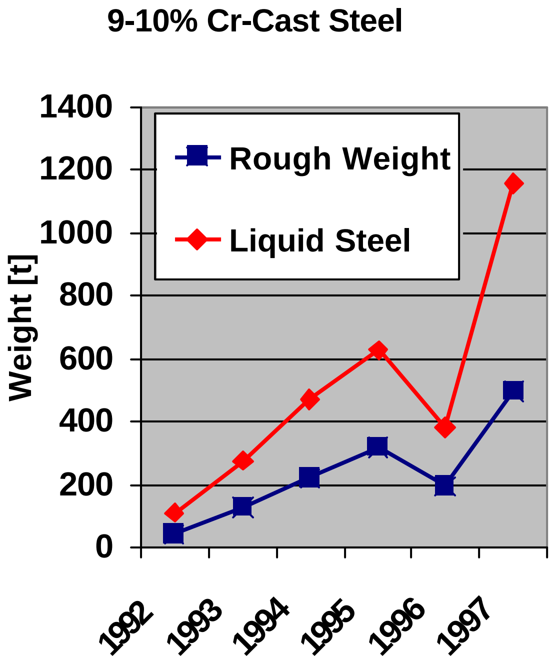


Figure 23: Typical manufacturing procedures of COST E-steel rotors: Heat Treatment Procedure (PHT and QHT)



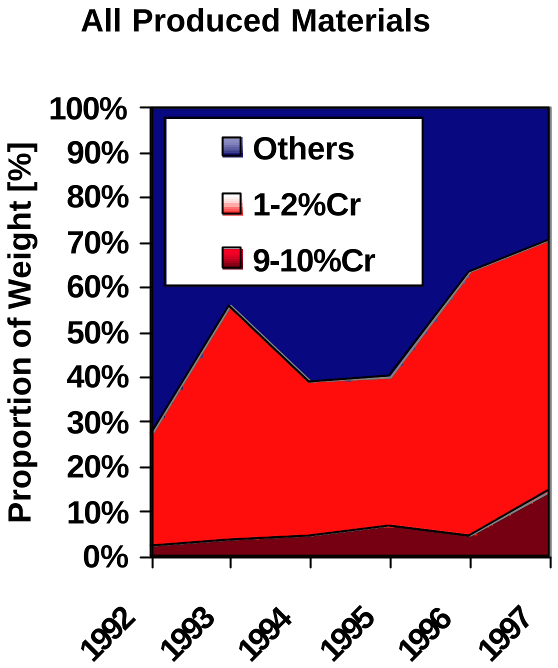
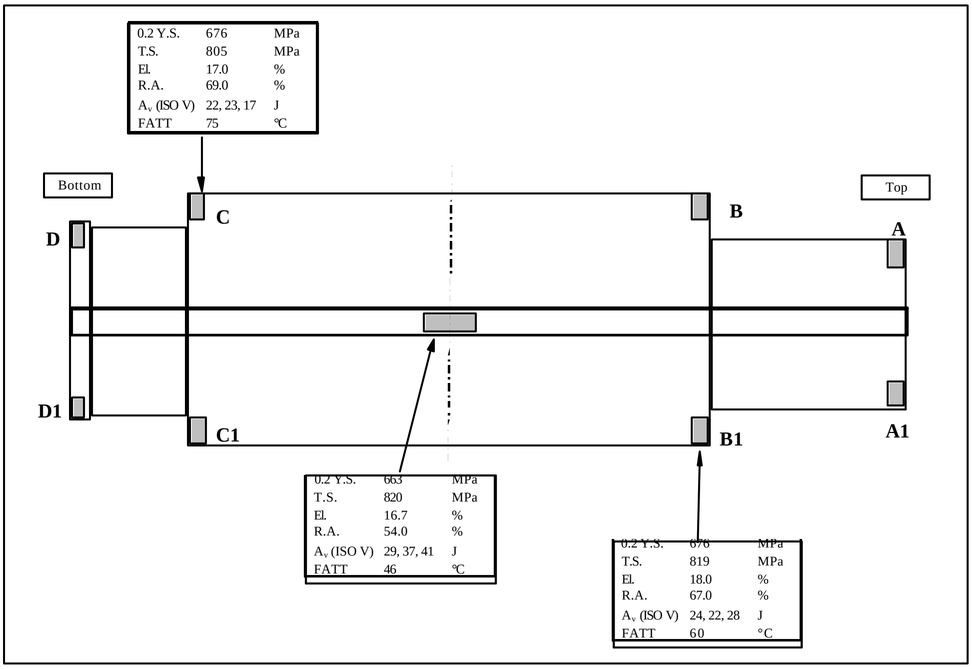


Figure 24: 9-10%Cr-cast steel – development of production in rough weight and liquid steel weight- development of proportionate amount

	Spec.	ESR-melt 930352
C	0.17 - 0.19	0.186
Si	0.05 - 0.10	0.095
Mn	0.75 - 0.85	0.769
P	£ 0.010	0.0070
S	£ 0.005	0.0010
Cr	9.00 - 9.60	9.28
Mo	1.40 - 1.60	1.51
Ni	0.10 - 0.20	0.16
B	0.008 - 0.010	0.0093
N	0.010 - 0.020	0.0113
Nb	0.055 - 0.075	0.065
V	0.24 - 0.29	0.26
Al	£ 0.010	0.006
As	£ 0.008	0.0048
Sb	£ 0.003	0.0007
Sn	£ 0.004	0.004

ESR ingot: dia. 1300 mm
45 mt

Figure 25: Trial shaft made of steel ESR-X18CrMoVNbB10-1 chemical composition ESR-melt



0.2 Y.S.	676	MPa
T.S.	805	MPa
El.	17.0	%
R.A.	69.0	%
A_v (ISO V)	22, 23, 17	J
FATT	75	°C

0.2 Y.S.	663	MPa
T.S.	820	MPa
El.	16.7	%
R.A.	54.0	%
A_v (ISO V)	29, 37, 41	J
FATT	46	°C

0.2 Y.S.	676	MPa
T.S.	819	MPa
El.	18.0	%
R.A.	67.0	%
A_v (ISO V)	24, 22, 28	J
FATT	60	°C

Figure 26: Trial shaft made of steel ESR-X18CrMoVNbB10-1 mechanical properties