DESIGN AND MANUFACTURE OF A VERY LARGE HOT-GAS EXPANDER IMPELLER IN ALLOY 718 FOR HIGHLY CORROSIVE OFF-GAS

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Abstract

This paper focuses on metallurgical issues and manufacturing of impellers for an integrally geared 2-stage expander for a corrosive hot-gas application. The design employs the largest single piece forging in Alloy 718 material for use in the low pressure stage impeller. Alloy 718 was chosen due to the combination of best corrosion resistance and mechanical properties. With this single piece forging it is possible to manufacture very large impellers in a "non-weld-design". Information about development of the disc production, the manufacturing process and mechanical properties are presented.

Introduction

Since the development of the first MAN TURBO radial expander in the early 1960's, the trend of increasing energy recovery has lead to more efficient expander systems with higher power outputs. Increased power outputs have been achieved through higher gas flow temperatures, bigger mass flows and increased expander sizes. These higher operating temperatures and the large size of the components used in the radial expanders have created new, more difficult demands on the materials and processes employed to make these off-gas expanders. The impeller wheels for the radial expanders have provided a particularly difficult challenge because the class of materials (steel) used to build the radial expanders at the end of the last century, was already stressed to the limits of its temperature, strength and corrosion resistance capabilities.

MAN TURBO develops , designs and manufactures radial expanders (Type ER) according to individual customer specifications to operate up to temperatures of 500°C and to be subjected to highly corrosive off-gases. These radial expanders are mainly used in PTA (Purified Terephtalic Acid) processes. The design had to comply with the requirement of avoiding condensation of the off-gas under any operating conditions. **Figure 1** shows the 2 Impellers for the High and for the Low Pressure Stage during assembly of the hot-gas expander .These Impellers were made from one single piece forging each and then machined to their intricate aerodynamic design without welding.

The leading edge MAN TURBO design of the expander rotor requires a single piece impeller with a forged rod on the back-side of the Impeller wheel as shown in the **Figure 2**. With this special but simple design no welding of the blades to the wheel is necessary to make an Impeller. The problems of reduced corrosion resistance and other serious mechanical properties in the welding joint are completely eliminated.



Figure 1: Assembly of 2-stage integrally geared hot-gas expander

In order to avoid condensation it had to be ensured that the expander is always hot when subjected to the hot off-gas. This will be ensured by a warm-up procedure using heated compressor air. The so-called cold-start had to be implemented into the control scheme. A completely buffered labyrinth sealing system has been designed using buffer air from the machinery trains compressor. A CFD calculation of the secondary air system at the impeller back-side has been performed to verify that off-gas is kept out of the critical areas. A detailed transient finite element analysis (FEA) accounting for start-up, upset and run-down conditions, determining the hot and cold clearances of the impeller has been performed to ensure maximum safety and mechanical integrity for this very large hot-gas expander.

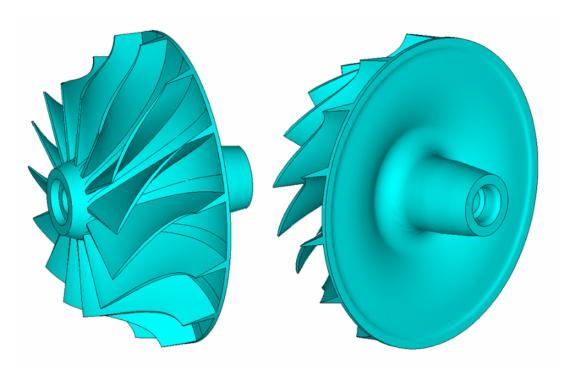


Figure 2: 3D-plots of the single piece impeller in the non-weld-design

Material Selection

The selection of the materials for the parts of this hot gas-expander is governed by the required mechanical properties defined by the design at the temperature of 500°C, the gas constituent with traces of halogens and some corrosive halides beside traces of acetic acid.

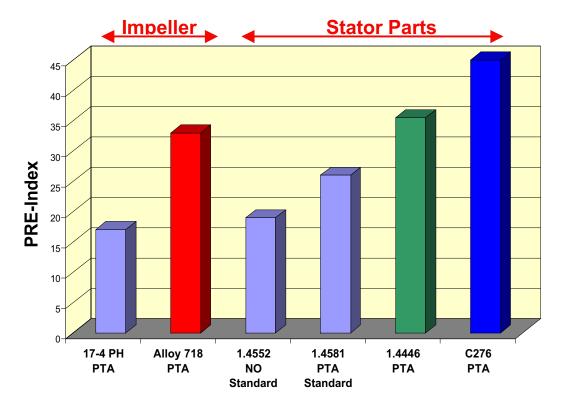


Figure 3: Calculated PRE-Index of some corrosion resistant material.

The best way to define the corrosion resistance in case of halogen attack is given by the Pitting Resistance Equivalent Index called "PRE" [1].

This Index is shown in **Figure 3** as calculated with:

$$PRE = \% Cr + 3.3 X \% Mo + 30 X \% N$$
 (DIN 81249)

for the materials used in the main parts of the expander. Where as austenitic casting (Material Nr.1.4552, 1.4581, 1.4446 according to DIN EN 10027) [2] and Alloy C263 can be used only for low stressed static parts because of low strength, the choice for the impeller was Alloy 718, which has much higher corrosion resistance than a stainless steel 17-4 PH used usually as impeller and the necessary mechanical properties at the high temperature to sustain the substantial stresses at room temperature as well at the service conditions.

Impeller

The material for the impeller and a number of other parts was chosen to be Alloy 718 because this guarantees best corrosion resistance in conjunction with best mechanical properties at high temperatures.

Alloy 718 is a nickel based super alloy used in a wide range of applications such as high temperature material for aircraft engines parts or high strength material in land based turbines, but also as high corrosion resistance material in the off-shore industry.

The requirement for this very special application was at a temperature of 450°C:

- Yield strength of $R_{P\,0,\,2} = 1000 \text{ MPa}$ minimum
- Tensile strength of $R_M = 1200 \text{ MPa}$ minimum
- Elongation of $A_5 = 17 \%$ minimum
- Reduction of area Z = 25%. Minimum

The component size of these impeller became a critical issue.

Since the low pressure impeller has a diameter of 1120 mm and a height of 610 mm, it became the largest forging ever produced in Alloy 718 used by MAN TURBO. Due to the requirement that only a single piece forging of good homogenous quality was to be used, the largest ever produced free-form forging in Alloy 718 resulted as far as known to us. The contour of Ø1130/630 forging with the rod to be produced in a closed die requires a set of pre-and finishforging tools. Moreover as these expanders are all tailor made, so the repetition of the same size is less probable and the very high forces required of the forging press led to the conclusion to produce these in free-form forging, as the alternatives were prohibitively costly. The heaviest 718 free-form forging made previously, as far as known to us for rotating components was about 4000 kgs. The production of the low pressure impeller with a machined diameter of 1120 mm and height of 610 mm, weighs over 6000 kgs as a pancake in the rough forged machined condition. These impellers were manufactured at SAARSCHMIEDE which is a major supplier of open-die forgings from high alloyed material. For more than 40 years nickel and cobalt based alloys have been manufactured, for aircraft engines, land based turbines, compressors, for application in the off-shore and medical industry as well as for tooling in the drop forging industry. Based on the state of the art facilities like a new 16 t-vacuum-induction-furnace (VIM) electroslag remelting (ESR), vacuum arc remelting (VAR) as well as a new 8.500 mt-press SAARSCHMIEDE has made a lot of different products in alloy 718, but these large impeller and the necessary ingots were a big challenge.

Melting

Alloy 718 is very well known from the aircraft engine parts. But these are made usually from small ingots with a diameter of 500 mm. Alloy 718 is very sensitive to segregations such as freckles, centre segregations or dirty white spots and this tendency increases with larger ingots. The high niobium content of more than 5 % and additional elements like Titanium, Aluminium and Chromium as well as trace elements of Carbon and Nitrogen initiate a lot of phases like carbides, carbonitrides which can result in macro segregations during the solidification in the remelting process.

The melting practise was specified to be VIM-ESR-VAR a triple melting process to minimise all the remelting related defects in the big VAR ingot. After melting an ingot by a vacuum induction process (VIM), a first remelting is done by electroslag remelting process (ESR) followed by the second remelting by vacuum arc remelting process (VAR). The metal was primary melted in a 16 mtonnes vacuum induction furnace (VIM). The chemical composition of the VIM-melt and the check analysis is shown in **Figure 4**.

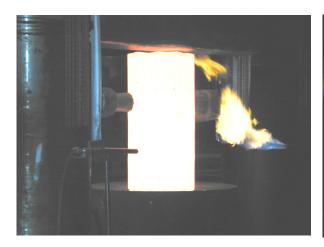
		С	Si	Mn	P	S	Cr	Mo	Al	В	Nb	Ti	Fe	Ni
ppm ppm ppm														
Melt 1	heat	0,018	0,06	0,02	10	14	18,32	2,84	0,44	44	4,98	0,98	18,3	bal.
	check	0,018	0,06	0,02	15	7	18,25	2,83	0,40	42	5,03	1,02	18,3	bal.
Melt 2	heat	0,021	0,07	0,03	20	10	18,12	2,84	0,52	42	4,99	0,99	18,0	bal.
	check	0,019	0,06	0,03	25	5	18,21	2,83	0,48	42	5,05	1,00	18,1	bal.

Figure 4: Chemical Analysis of the VIM Ingots in wt% except otherwise stated

The poured VIM electrodes were electro slag remelted (ESR) to an ingot diameter of 750 mm. The intermediate step of ESR avoids shrinkage cavities and cracks in the ESR-electrodes for the VAR process. This results in a stable VAR process. Further advantage of the intermediate electro slag remelting is an additional removing of oxide and other inclusions. This ESR ingot was forged and cleaned to an electrode suitable for vacuum arc remelting (VAR) in a diameter of 655 mm crucible. Important factor for avoiding or minimizing the mentioned segregations is to minimize the solidification time in the VAR-process and the optimised variation of the solidification rate. It is well known in the industry that VAR Ingots with acceptable segregation have upper limit in their diameter [3]. Our experience says this limit to be nearly 655 mm.

Forging

Prior to the billetizing a homogenisation treatment is necessary for solving laves- phases, a niobium rich phase, which is formed during solidification. These laves phase reduces the ductility of the material significantly. These as cast ingots are homogenized at about 1200°C prior to forging. The billetizing was undertaken on an 85 MN- open die press, newly installed at SAARSCHMIEDE in 2002. It was done by multiple upsetting (**Figure 5**) and drawing operations.



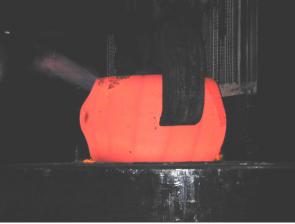


Figure 5: Billetizing and upsetting

The billet diameter was 780 mm. After cutting the top and bottom scrap a forging length of nearly 1.550 mm was achieved. Prior to final forging the billet was conditioned. The disc forging was performed similar to the process with alloy 706 disc forging [4]. The billet was upset approximately 2:1 in one stroke. This was followed by a series of passes consisting of multiple strokes to step across the face of the disc, which was also rotated between the passes to eliminate structural gradients.

The finished forging dimensions were diameter 1.200 x 670 mm which resulted in a forging weight of approximately 6,1 mtonnes. It was difficult to maintain low forging temperatures to achieve a fine grain size in the final product. The high flow stress of alloy 718 at low temperatures challenges the capability of a large force press for an open die forging.

Heat Treatment

The so forged disc was heat treated, at first the typical solutioning at 960°C. The two step aging was performed after near finish machining of the impellers. After the solution heat treatment the forged disc was premachined contour for ultrasonic testing. The test rings were taken at outside and inside positions for mechanical and micro structural, then treated in a simulation aged conditions and the testing was done.

The shape of the as forged, as premachined and as machined disc for delivery is shown in **Figure 6**.

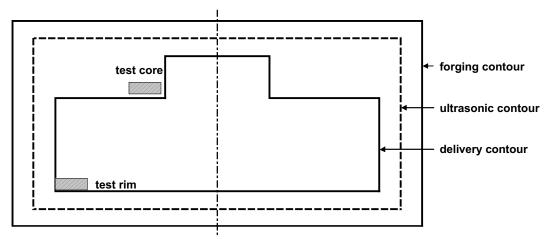


Figure 6: Contours of the forging at different stages and test location

Testing

1. <u>Ultrasonic Testing</u>

The full size forging in the solution treated and premachined condition was inspected by an automated system using a 2 MHz transducer. No reportable indications were found. The minimum detectable defect size (MDDS) was determined to 1.5 mm for the axial and 1.9 mm for the radial direction.

2. Mechanical Properties

Mechanical properties were determined from the described test rings at room temperature (**Figures 7+8**) and at 450°C (**Figures 9+10**).

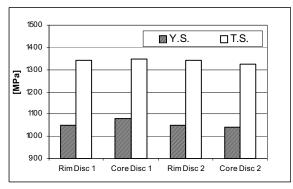


Figure 7: Yield strength and Tensile strength at room temperature

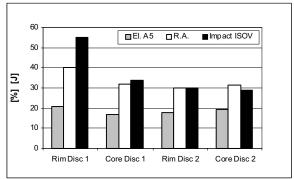
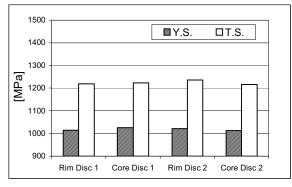


Figure 8: Elongation, R.A. and impact at room temperature



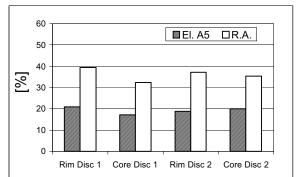


Figure 9: Yield and Tensile strength at 450°C Figure 10: Elongation and R.A. at 450°C

3. Microstructure

The grain size was determined according ASTM Standard E112. At both test locations, rim and core, the grain size is 4-5.5 with occasionally larger grain of 3 as shown in **Figure 11**.

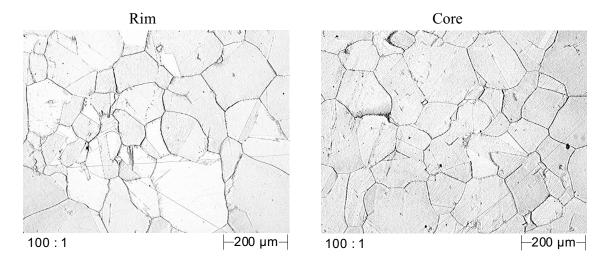


Figure 11: Microstructures at rim and core

Summary

The production of low pressure impellers open die forged from triple melt 718 ingots with a diameter of 655 mm and more than 6.000 kgs has been successful. The melting and forging techniques are evaluated in such a manner that the mechanical properties, the microstructure and the soundness of the forgings are within the specified requirements. There is no significant difference in measured properties between rim and core position.

The above results have shown that with proper control of the melting, forging and heat treatment processes it is possible to achieve a uniform grain structure and mechanical properties in large open die alloy 718 forgings.

References:

[1]: DIN 81 249 (1997), Part 1-4 Corrosion of metals in sea water and sea atmosphere, DIN Deutsche Institute für Normung e.V. 10722 Berlin.

[2]: DIN EN 10027 (1992) as in [1].

[3]: Thamboo,S.V., R.C.Schwant, L.Yang, L.A.Jackman, B.J.Bond, R.L.Kennedy: "Large Diameter 718 Ingots for Land-Based Gas Turbines", <u>Superalloys 718,625,706 and various Derivates</u>, (Edited by E.A. Loria, 2001) p 57-70

[4]: Schoenfeld, K.H., B.Donth, M.G.Cambi, S.V. Thamboo, M.P.Manning: "Manufacturing and Properties of a large Alloy 706 Disc made by the Open Die Forging Process", <u>Superalloys</u> 718,625,706 and various Derivates, (Edited by E.A. Loria, 2001) p 185-192