

Fabricated Turbine Rotors – Advanced Steam Turbines

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by

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1. **Summary**

An investigation has been made into the possibility of welding together 10%Cr and 3.5%NiCrMoV rotor material in order to produce the next generation steam turbines operating above 570°C.

Following a comprehensive modelling programme and complementary testing and examination by Siemens Power Generation (SPG) and the University of Cambridge, a welding procedure was developed and successful plate and small diameter welds were made between sections of 3.5%NiCrMoV and 10Cr material. Mechanical and metallurgical assessment of these welds showed that the weldment properties matched the requirements of the original parent material.

Following the success of the initial welds, a large-scale weld has been manufactured using the established materials and procedures to fully validate the developed welding procedure. This weld has been subjected to non-destructive examination (NDE) followed by extensive mechanical and metallurgical testing. The results confirm that the large scale weldment properties matched the requirements of the original parent materials and thereby satisfy the objectives of the project.

2. **Introduction**

Turbine manufacturers require the ability to weld high alloy (10Cr) to high toughness low alloy (3.5NiCrMoV) steels in order to produce the next generation of steam turbines operating above 570°C (fig 1). The present project has been carried out to develop and prove a suitable weld procedure.

Financial funding to a level of 46.3% was provided by the UK Department of Trade and Industry (DTI) Cleaner Coal Technology R&D Programme.

A team was set up consisting of members from Siemens Power Generation (SPG) Newcastle, Mülheim and Charlotte supported by the department of Materials Science and Metallurgy, University of Cambridge.

A three-year programme was established and agreed.

3. **Objectives of the Project**

The overall and specific objectives of the project were:-

- To reduce the capital and through-life cost of the next generation of steam turbines generating with clean coal technologies at temperatures above 570°C.
- To develop the materials and welding technology to provide a fabricated steam turbine rotor to operate with elevated steam temperatures in the high temperature part and long, high strength turbine blades in the low temperature part of the rotor.
- To fully characterise the microstructures and properties of such steam turbine rotors to enable the development of lifing methodologies.

4. **Technical Challenges**

The welding of the 10%Cr material to 3.5%NiCrMoV rotor steel presented several potential challenges, namely: -

- The large difference in tempering temperature of the two rotor materials.
- The difference in chemical composition and properties of the two rotor materials.
- The need for a high yield strength weld metal.
- The possibility of carbon migration and segregation due to the large difference in chromium levels.

Two solutions were proposed to address these issues.

Proposed Solution 1

The first proposed solution was to clad the 10%Cr material with a suitable weld metal and subsequently heat-treat the clad layer at a sufficient temperature to adequately temper the heat affected zone (HAZ) of the 10%Cr material. A butt-weld would then be made between the clad material and the 3.5%NiCrMoV steel using a suitable weld metal and finally the composite weldment would be heat treated. This was described as the “two-shot” process.

Proposed Solution 2

The second proposed solution was to weld the 10%Cr direct to the 3.5%NiCrMoV rotor using an appropriate weld metal and post-weld heat treatment (PWHT). This solution, described as the “single-shot” process would generate significant cost and lead time advantages over the previously described two-shot process.

5. Development Procedures

5.1 Constraints

The following constraints were agreed at a preliminary meeting of the team

- The weld metal properties would have to at least meet the relevant design requirements for the weaker of the two parent materials.
- The weld metal would therefore have to have a minimum 0.2% proof strength of 700MPa matching that of both parent materials and a minimum impact energy of 30 Joules at 20°C to match that of the 10%Cr steel.
- Only commercially available welding consumables would be investigated, including consumables developed by, and readily available from, SWPC.

5.2 Weld Metals

The team agreed eight candidate weld metals for consideration within the programme.

5.3 Weld Procedure

The team also agreed the following weld procedure details:

- A narrow gap weld preparation would be adopted.
- The thickness of the buttering weld metal would be kept to the minimum required to retain a 6mm thick layer after machining.
- Only vertical buttering would be employed because of the difficulty of upending the rotors.

6. University of Cambridge Modelling

The University of Cambridge modelled the parent materials and the proposed weld metals for creep and tensile strength at different tempering temperatures and times for the same welding heat input. The heat input was calculated using:

$$\text{Arc Energy (in KJ/mm)} = \frac{VI}{W} \times 10^{-3}$$

where V is the arc voltage (in volts)

I is the welding current (in amps)

W is the welding speed (in mm/s)

Additional parameters used in the model were:-

- preheat temperature
- post weld heat treatment temperature
- post weld heat treatment time

From the initial modelling work information generated by the University of Cambridge the team made the following decisions:-

A comprehensive HAZ simulation programme of the 10%Cr steel and the 3.5%NiCrMoV steel by the University of Cambridge indicated the potential for both single-shot and two-shot processes if a peak hardness of 350HV could be accepted.

Four of the welding consumables were eliminated from further investigation due to a combination of low predicted strength and poor weldability previously experienced. It was decided to exclude a further consumable from the programme because, although the modelling indicated that it could produce acceptable strengths at the PWHT temperatures proposed for the weldment, the actual property data

available at the time did not give enough confidence to justify further work using this consumable.

Following the initial modelling it was agreed that the next phase of work to be completed by Cambridge and Siemens would concentrate on two of the selected alloys

7. Development Welding Trials

7.1 Plate welding

To support the work at Cambridge in assessing HAZ microstructures, response to PWHT and the effects of carbon migration, a number of plate welding trials were made (Fig. 2)

The metallography, hardness surveys and mechanical properties from these test plate welds in various heat-treated conditions showed good correlation with the Cambridge model predictions for the parent metals, HAZ's and the weld metals.

7.2 Small-scale (380mm diameter x 50mm thick) Welding Trials

Following the results from the plate welds the team decided to manufacture three small-scale, 380mm diameter x 50mm thick, test welds between 3.5%NiCrMoV and 10Cr materials (Figs. 3 & 4).

Test data showed that tensile properties were in good agreement with those predicted from the modelling by the University of Cambridge. Weld quality and mechanical properties were considered to be reproducible.

It was therefore decided at this stage to manufacture a 380mm diameter one-shot weld between a 3.5%NiCrMoV forging and a 10%Cr

forging (W5510) using this welding consumable. Welding was completed successfully, the subsequent metallography, hardness surveys and mechanical properties from this weld in the heat-treated condition met the required properties.

The hardness survey revealed a narrow band with lower hardness at the outer edge of the HAZ in the 10%Cr material and a more detailed investigation of this was completed. This examination, together with information received from other European programmes on the welding of 10%Cr alloy steels, revealed that the softening is a typical feature of the HAZ in the new 9-10%Cr type steels. It is thought to be due to the partial dissolution of the carbides at the temperature represented by this HAZ position (about 920°C) followed by the formation of a softer martensite with a lower carbon content. After PWHT the microstructure comprises a mixture of annealed, soft martensite and old and new carbides. It was agreed that this softening is unavoidable when welding the 10%Cr alloy.

The team concluded that the overall results from weld No. W5510 using the selected weld metal were satisfactory. It was also agreed that another weld (W5513) would be completed in Mülheim to determine whether consistent results could be achieved using the same weld metal in conjunction with the same welding procedure.

Following its completion weld No. W5513 was returned to the C.A. Parsons Works of SPG. A section of the weldment was given the chosen PWHT at and subjected to the same testing and examination regimes as the previous four welds (W5498, W5499, W5500 & W5510).

The test results for the Mülheim narrow-gap butt weld W5513 were in close agreement with those previously obtained for the Newcastle weld

W5510 in the same PWHT condition, confirming the reproducibility of weld quality and mechanical properties.

8. Full-Scale Welding Trial

8.1 Description of Weldment

A large-scale weld with a diameter of 840mm and a thickness of 100mm has been manufactured (Figs. 5 & 6) using the selected weld metal and the developed parameters to fully validate the welding procedure.

The weld was stress relieved and then subjected to extensive mechanical and metallurgical testing to compare the properties with those of the previous smaller-scale weld W5513.

8.2 Non Destructive Examination

The weld was subjected to non destructive examination using magnetic particle inspection (MPI) and ultrasonic testing (UT) inspection techniques. The weld was assessed in accordance with BS EN 25817 quality level B (stringent). No defects were recorded.

8.3 Metallography and Hardness Testing

A transverse macro section through the full thickness of the narrow gap TIG weld revealed a very regular bead pattern with smooth sidewall profiles in both parent materials. The weld also had good root fusion and capping bead profile. There were no visible defects in the weld metal (Fig. 7). The welding parameters and bead sequence used for the weld had produced a high degree of refinement both in the weld metal and the heat affected zones (Fig. 8).

Some carbon migration was evident at both sidewalls. At the 3.5%NiCrMoV side, the weld metal showed a carbon enriched zone resulting from the migration of carbon across the fusion line from the lower chromium parent material. Carbon depletion of the 3.5%NiCrMoV had not resulted in the formation of any ferrite grains at the parent material side of the fusion line. At the 10Cr side, the direction of carbon migration was reversed with a carbon enriched zone in the higher alloy 10%Cr parent material and carbon depleted zone in the weld metal but again there had been no ferrite formation as a result of the carbon diffusion (Fig. 9).

Vickers hardness traverses were conducted across the full width of the weldment at three positions near to the top and root of the weld and across the mid-plane. A low load of 5Kg was selected allowing a spacing of only 0.5mm between hardness impressions to establish the hardness profiles across the parent materials, heat affected zones and weld metal. The results obtained at the three positions were very similar and comparison with the hardness results from the previous smaller-scale weld W5513 showed a consistent trend with regard to profile.

8.4 Chemical Composition

Chemical analysis was carried out to confirm the composition of the two parent materials. The weld metal was analysed at the top, middle and root positions to check for any compositional variations. The parent materials were within specification and the weld metal analysis showed consistency throughout the weld apart from some increased dilution effects at the weld root position.

8.5 Tensile Testing

Tensile tests were conducted on both parent materials at 20°C and 300°C. Additionally, tests were carried out on cross-weld specimens and on axial, all-weld-metal specimens from the top, middle and root positions at temperatures in the range 20°C to 450°C.

The tensile properties established for W5522 met the specification and showed good consistency with the previous, smaller-scale weld W5513.

8.6 Impact and Toughness Testing

Impact testing has been carried out on samples of the weldment at top, middle and root positions.

The Charpy impact values obtained were within specification and were comparable with those obtained from the previous, smaller-scale weld W5513.

FATT, fracture crack growth and J_{1C} tests also showed satisfactory behaviour.

8.7 Residual Stress Measurements

Residual stress measurements were made using the centre hole drilling technique with strain gauges located at parent metal, heat affected zone and weld metal positions both before and after post weld heat treatment.

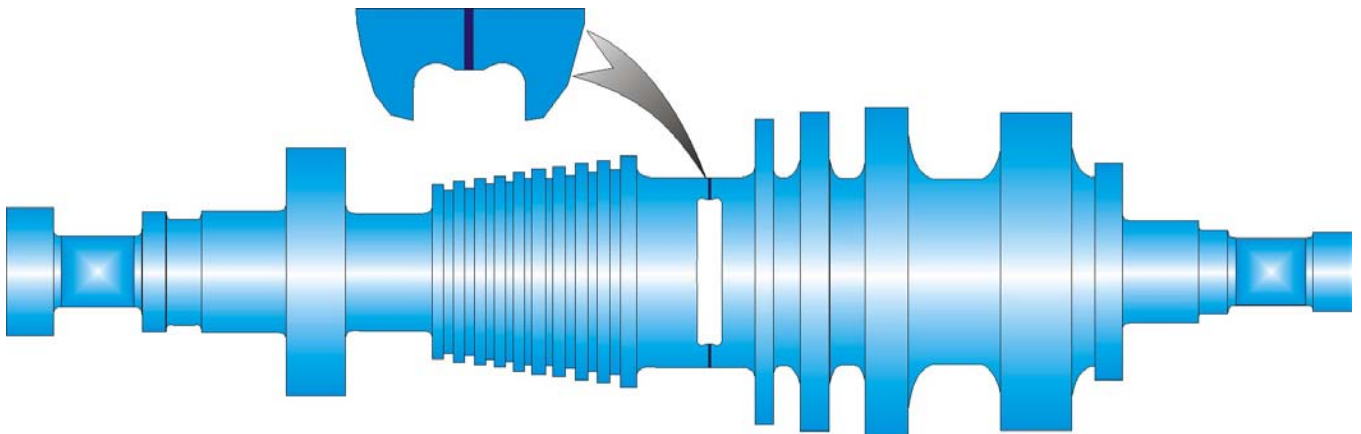
The measurements taken on the outer surface of the weld after PWHT showed that the maximum residual stress was 148MPa in the heat affected zone of the 3.5%NiCrMoV steel.

9. **Conclusions**

1. The modelling undertaken by the University of Cambridge provided accurate predictions of the parent steels and weldment properties.
2. The modelling enabled the short-listing of suitable weld metals.
3. The modelling confirmed the suitability of the selected welding parameters.
4. The modelling established the effects of post weld heat treatment parameters on the weld metals and parent steels.
5. The heat affected zone simulations established the effects of welding and post weld heat treatment parameters.
6. The University of Cambridge models have been enhanced to provide better prediction data for the range of alloys under investigation.
7. Welding trials determined the welding procedures for cladding and butt-welding of the selected materials.
8. The modelling results were confirmed by the test data.
9. The single-shot butt weld made using the selected weld metal (W5413) reported in the interim report, gave adequate strength and toughness and had a satisfactory microstructure.
10. Residual stress measurements after post weld stress relief heat treatment determined that the levels and patterns of stress were acceptable.

11. The welding procedure developed using the selected weld metal and previously proved with the production of the 380mm diameter 50mm thick weld (W5413) has now been successfully used to manufacture the full-scale weld W5522 for the comprehensive programme of testing and metallurgical assessment.

12. The full-scale weld has been shown to be of good quality with a regular, smooth profile and no defects present. The narrow gap TIG process in conjunction with the developed welding parameters resulted in a high degree of microstructural refinement in both heat affected zones and weld metal. These findings are consistent with the results obtained on the smaller-scale weld, W5513, and have demonstrated that the process can be successfully applied to production-size rotor welds between 3.5%NiCrMoV and 10%Cr rotor steels.

Steam Turbine Rotor for Application above 570°C**10%Cr Steel****3.5NiCrMoV Steel****PROJECT 114045**

FUNDED BY: DTI - 46.3%
DURATION: 3.5 YEARS
PARTNERS: University of Cambridge
Siemens Power Generation

ISSUES:

- Weld placement
- Weld metal composition and properties
- Post weld heat treatments
- Welding Techniques and parameters
- Carbon diffusion
- Heat affected zone structure and properties
- Ultrasonic testing

Figure 1

Clad 10% Cr Rotor Forging Plate



Figure 2

**380mm diameter 3.5%NiCrMoV and 10%Cr Forgings with
Machined Weld Preparations**



Figure 3