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Electroslag refining with liquid metal for composite rotor manufacturing

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ABSTRACT

Purpose: To develop novel ESR based process for composite ingot with shallow transition zone between layers in order to produce efficient heavy-weight rotors for steam turbines.

Design/methodology/approach: The nowadays heavy-weight rotors for steam turbines for power plants are monoblock or two or more layer in length composite part facilitating operation in different zones withstanding various loads and working medium. However, the joining of various steel in composite rotors by welding has low productivity. The ESR now is recognised as the best available technology for the big-diameter and mass forgings for power generating machines, including rotor ones. The ESR affords the most favourable conditions of solidification resulting in homogenous low-segregation ingot with smooth surface and high-quality structure. The step ahead is the ESR for composite.

Findings: The two-layer model ingot had produced from steel grades 12Cr13 and 35NiCrMoV12-5 were manufactured using the electroslag process with the liquid metal (ESR LM) in the CSM of 180 mm in diameter with ingot withdrawing. The transition zone in two-layer ingot had have the shallow shape and low depth with the even macrostructure without defects of the same type as both joined steels. The metal of the transition zone fully satisfies standard requirements for properties of both steel grades in the heat treated and as-cast conditions.

Research limitations/implications: The ESR LM can provide both the monobloc heavy ingots with uniform structure and composites with low-stress connection between metal layers for heavyweight rotors and other critical products manufacturing.

Keywords: ESR LM, Composite ingot, Heavy rotor, Transition zone, Heat treatment, Microstructure, Mechanical properties

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PROPERTIES

1. Introduction

The maximum steam temperature in modern turbines is limited by materials that can operate at these conditions for service lifetimes without failure. The research programmes are going worldwide to create the next generation material for increased steam temperatures and efficiency, known as advanced ultra-supercritical (A-USC) or 700°C technology [1]. There are the European Program AD 700 [2] (Power Plant operating at a range of temperatures of 700°C) and Materials for Advanced Ultra-supercritical Steam Turbines of US (Technology to fabricate and operate an A-USC steam boiler with steam parameters up to 1400°F (760°C)) [3] and recently adjoined projects in China (the National R&D Project of 700°C USC Power Generation Technology)[4] and India (National Mission for the Development of A-USC Technology [5]).

The present requirements for rotor material include high resistance for stress-induced creep and fatigue rupture, hot corrosion damages and oxidation resistance in steam, high strength and toughness simultaneously at elevated temperatures as well as reliability for durable operation, availability on the market with competitive costs. Because of the various and robust requirements, the modern materials for rotors are similar worldwide. The candidate alloys for 700°C application belong to a few materials families, namely - the advanced high chromium steels (with microalloying by boron, nitrogen, etc.) and superalloys (mainly nickel-based, but Co-Re superalloys are under study worldwide as well)[6]. Authors [7] informs that FENIX700 and LTES700R(4) have been used to trial-manufacture a 10-ton class large forged rotor successfully, but for heavy-weight turbines it should be much more.

Thus, rotor shafts for A-USC turbine are quite challenging product for metallurgists, because as the material grade, as the technology of manufacturing and rotor's design are crucial for its service life under high temperature, pressure, corrosion attack and mechanical cyclic loads. There are two main designs in use – welded and monobloc rotors having own merits and demerits.

The manufacturing of monobloc rotor's shafts is also the big challenge. The mass of heavy casts for new rotors' forgings for the high capacity power plants can reach 600 t. Their diameter grows to 3 m that makes mold-chilled ingots segregation-prone. To be competitive the chosen manufacturing way of such forgings have to provide high yield at processing and the uniform chemical composition and microstructure along the length and across the section of ingot/forging: and the ESR/VAR ingot is now the best solution. Having one steel along the whole length, the monobloc rotors are usually much expensive.

The nowadays heavy-weight rotors for steam turbines for power plants consists two or more parts in length, facilitating operation of each part of the rotor under different conditions, both regarding loads and working medium (temperature, corrosive environment, etc.).

Welding of composite rotors from different steels allows providing the best material for each zone, and the inner hole reduces the temperature-induced stresses in compare with monobloc rotor. The advantages of welded rotors are also higher availability and lower price for smaller forgings in compare of big pieces for monobloc rotor, which can be produced by 20-25 companies only in the whole world. However, any welding processes (TIG, GTAW, MIG, MAG, SMAW, GMAW, SAW) have low productivity. The welding technology for the bimetallic rotor has considerable difficulties, primarily due to the deep fusion of the edges and the associated undesirable structures in the weld metal, which leads to a sharp deterioration of its properties. The high-intensive heat affects the structure and causes stresses increasing risk of rupture, especially in dissimilar metal welds from materials with different thermal coefficients of expansion.

World producers of welded composite rotors of steam turbines are considering the possibility of using electroslag technologies for melting composite two-layer ingot to produce the rotor shaft from dissimilar steels and alloys instead of welding. Some results of the trials and researchers made in this direction recently are given below.

Thus, for the heavyweight composite two-layer rotors manufacturing an efficient and productive process is wanted to provide the uniform chemistry and structure in one-metal parts and/or low-stress connections between different metallic materials to guarantee high resistance to creep and fatigue damage in corrosive media.

2. ESR possibilities for two (multiple) layer composite ingot

The methods of steel melting/treatment for sound low segregation ingot largely determine the quality [8,9] of the produced rotor. The complication of composition (amount and variety of alloying elements) in rotor steels/alloys increases the liquation effects at solidification.

Electroslag remelting now is recognised as the best available technology for the big-diameter and mass forgings manufacturing for power generation, including rotor ones. The ESR provides the most favourable conditions of solidification resulting in the smooth surface, high-quality structure, homogenous low-segregation ingot. The advantages of ESR in this field was well-proven while

European COST programs for high alloyed creep resistant steels for high-temperature applications, including FB2 (9%CrMoVNbNB) steel manufacturing, which belongs to MarBN 9-10% Cr, grade E (10%CrMoWVNbN), grade F (10%CrMoVNbN) and analogues [10-13]. It is understandable that the ESR process for heavyweight ingots for rotors should be organised using the state-of-the-art ESR with a protective gas atmosphere (argon) and modern control system realising the minimal immersion of electrode tip into the slag bath due to the swing control.

Early made trials for composite ESR ingots with the consequent horizontal layers made using the ESR with sectional consumable electrode (two rods of different steels welded together) shown that transition zone of mixed composition is too big (more than one diameter usually and up to 2.5 diameters at intensive melting regimes). Serious difficulties exist also at the consequential ESR remelting of consumable electrodes from different steels/metals. The rigid link between the electric modes and the productivity of the ESR process resulting in deep metal bath and extensive transition zone in two(multi)-layer ingot [14].

Recent publications of authors [15] investigated the effect of a current on structure and macrosegregation in dual alloy ingot processed by electroslag remelting of the consumable electrodes were welded from two parts. The results showed that the thickness of the transition zone in 120 mm ingots makes 147 mm, 115 mm and 102 mm with the current increasing from 1500 A to 1800 A and 2100 A, respectively. Thus, in spite of the very small diameter of ingot thickness of transition zone is near diameter of ingots.

In the commercial ingots for rotor were made by Japan Steel Work and General Electric [16] two large integral multiple alloy rotor forgings have been successfully produced. Each single piece forging comprises a CrMoV steel intermediate pressure section and NiCrMoV low pressure section. The multi-alloy electrodes were used for the ESR. The transition zone in described ingot makes 640 mm, but required mechanical properties were achieved, and authors think this technique can be an alternative to welded rotor construction for advanced turbine applications.

It is understandable that whole transition zone can be located in the low-temperature part of the steam turbine. Having more alloyed mixed chemical composition its length has to be minimized for cost cut. The length of forging for rotor shaft increases in compare with the ingot (usually 1.5-3 times) and the width of the transition zone becomes also bigger (in the particular case [16] in forged rotor shaft it reaches 1000 mm).

In the case of manufacturing both the low segregation and composite heavy ingots, the volume and shape of a solidifying liquid metal bath determine the extent of dual-phase area and transition mixed zone, respectively. The bigger are the amount and depth of solidified metal bath; the the probability of segregation defects and the size of the mixed zone with varying chemical composition is more developed. The ESR (VAR) remelting techniques provide the minimum volume of the metal bath of a shallow shape.

The powerful method to reduce and make more shallow the liquid metal bath is to use current supplying mould (CSM) [17] having broad possibilities for various ESR techniques, including the surfacing of composite ingots with coaxial or horizontal layers from different steels and alloys [18] and different metals (steel and copper) [19].

The industrial trials [20] made together with prof. Lev Medovar confirm the current supplying mould and two-circuits ESR diagram allow reducing productivity and depth of the two-phase zone by 25-30%. The experiments were carried out in a CSM of 750 mm in dia using 2CrNiMoV steel that is typical for rotors of steam turbines operating at 650°C. Research of the macro- and microstructure of ingots produced at the regular and reduced rates of remelting confirmed the noticeable weakening of the main types of segregation at the low melting rate. Heating of meniscus by CSM facilitate forming smooth surface in spite of reduced remelting rate. The peripheral electric current supplied by such mould generates the heat release in a slag contacting with CSM, which ensures the smooth formation of the ESR ingot surface independently from consumable electrode remelting rate (productivity) and helps to keep metal bath surface in the liquid state at its small depth under low or even zero productivity. The efficiency of CSM in the lessening of the length of the transition/fusion zone, which formed by mixing of two steel grades while the bonding in two-layer composite at the remelting of a composed consumable electrode or the change of electrodes, was experimentally confirmed at both laboratory and pilot tests. The possibility of heating and remelting the surface of a solid ingot for its surfacing by further remelting of the consumable electrode having different chemistry or a pouring premelted liquid metal was checked in the article.

3. The study of the transition zone in the composite two-layer ingot 12Cr13 and 35NiCrMoV12-5

The model ingots for a composite rotor were manufactured in a current-supplying mould of 180 mm in dia using ESR process with liquid metal (ESR LM) deposition and ingot withdrawing. The pre-melted slag was poured into the current-supplying mould for the preheating and fusion of the top surface of the initial ingot (the first layer – 12Cr13 steel). Molten steel for the second layer was poured a portion by a portion at the predetermined rate from the crucible, which in own turn was filled by the ESR of 35NiCrMoV12-5 consumable electrode. The speed of ingot withdrawing was controlled by an inductive sensor of metal bath level of own design [21]. The appearance of the longitudinal template of the model composite two-layer ingot made by ESR LM [22] is given in Figure 1.

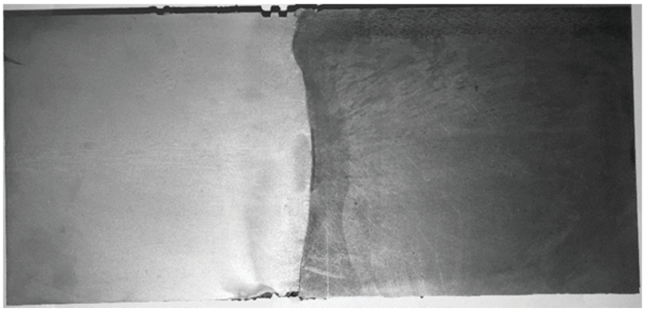


Fig. 1. The macrostructure of the longitudinal template of the two-layer composite ESR LM ingot 180 mm in diameter (initial ingot of 12Cr13 - left part + deposited ESR LM metal of 35NiCrMoV12-5 steel –right part)

The macrostructure of the template from the ingot is uniform and dense without pores, slag inclusions, laminations, cracks and discontinuities. The fusion line is homogeneous without visible defects. The maximum depth of transition zone between two layers is 15-20 mm.

The structure and distribution of the main elements in the transition (fusion) zone we examine using a scanning electron microscope JSM-35CF (JEOL) and an X-ray spectrometer (INCA Energy-350, Oxford Instruments). The structure of the transition zone is plain and have no sufficient difference from the structures of steels of the both grades connected it two-layer composite (Fig. 2).

Going across the transition zone, the chromium content decreases from the 9th point (in compare to spectrums 1-8), which is a characteristic element for 12Cr13. From the same spectrum point the nickel content starts to increase (characteristic element for 35NiCrMoV12-5). The 9th point can be considered as the beginning of the transition zone having a mixed compound (12Cr13 and 35NiCrMoV12-5). In the line of spectrums some misfits of manganese content occur both in the zone belongs to 12Cr13 steel (spectra 3-5) and in the fusion zone (spectrums 17, 20, 21, and 26), which may be due to partial evaporation of Mn.

The Brinell hardness number of metal of the transition zone was measured on the longitudinal template as-cast (no heat treatment). The load 3000 kg and ball of 10 mm in dia were used with 10 mm step between measures.

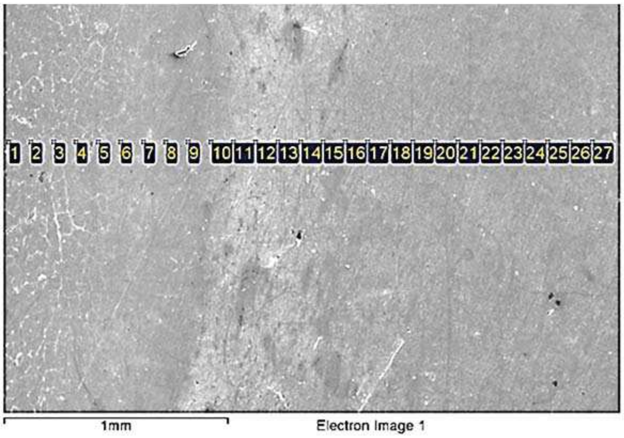


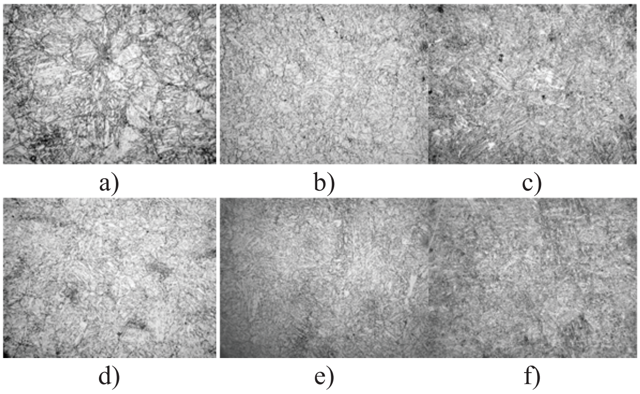
Fig. 2. Spectrum line across transition zone of the two-layer ingot (12Cr13 – left and 35NiCrMoV12-5 – right side)

The strength characteristics of the metal in the transition zone was recalculated using known dependence $\sigma_t = k{\cdot}HB$, where k is the empirical coefficient that makes 3.4 for the steels having hardness HB<175, and 3.6 for HB>175 (as it is in our case). The tensile strength of steel 35NiCrMoV12-5 and 12Cr13 according GOST standards after heat treatment (quenching and tempering) should be not less than 1180 MPa and 539 MPa, respectively, that was fully satisfies even as-cast (Tab. 1).

Table 1.
HB number and recalculated ultimate strength in the transition zone of the two-layer ingot

#	Area belonging to	Brinell hardness number HB, measured on the distance from the ingot surface		Tensile strength σt, MPa, on the distance from the ingot surface	
		15 mm	45 mm	15 mm	45 mm
1	35NiCrMoV 12-5	415	388	1494	1397
2		415	415	1494	1494
3		415	388	1494	1397
4		415	285	1494	918
5	Transition zone	241	255	868	918
6		302	241	1087	868
7		302	207	1087	745
8	12Cr13	170	207	612	587
9		170	170	612	612
10		170	170	612	612

Nevertheless, since the heat treatment procedure is now mandatory in the manufacture of rotors (including composite ones) its effect on the metal of the transition zone was studied. Two standard regimes relevant to each steel grade were realised: HT#1 (35NiCrMoV12-5) – 60 minutes at 850°C and oil-quenching, tempering at 600°C (150 min) and air-cooling; HT# 2 (12Cr13) – 42-56 min at 1000°C and oil-quenching, tempering at 600-700°C (140 min) and air-cooling. After the heat treatment, the metal of all samples from various zones has similar one-type structure of thin-plate tempered martensite (Fig. 3).


a) b) c)

d) e) f)

Fig. 3. The microstructure of the two-layer composite ingot after HT#1(upper raw) and HT#2 (low raw): steel 12Cr13 (a,d), transition zone (b,e), 35NiCrMoV12-5 (c,f), 500x

The structure of the transition zone is thinner than the two joined steels in both cases. The research does not reveal any unfavourable structures that could cause stress concentration that significantly affects its properties.

The efficiency of the two heat treatments was estimated by the size of the grain and the microhardness in the zones related to both steels and transition zone (Tab. 2).

Table 2.
The grain size and microhardness in different zones of two-layer ingot after the heat treatment

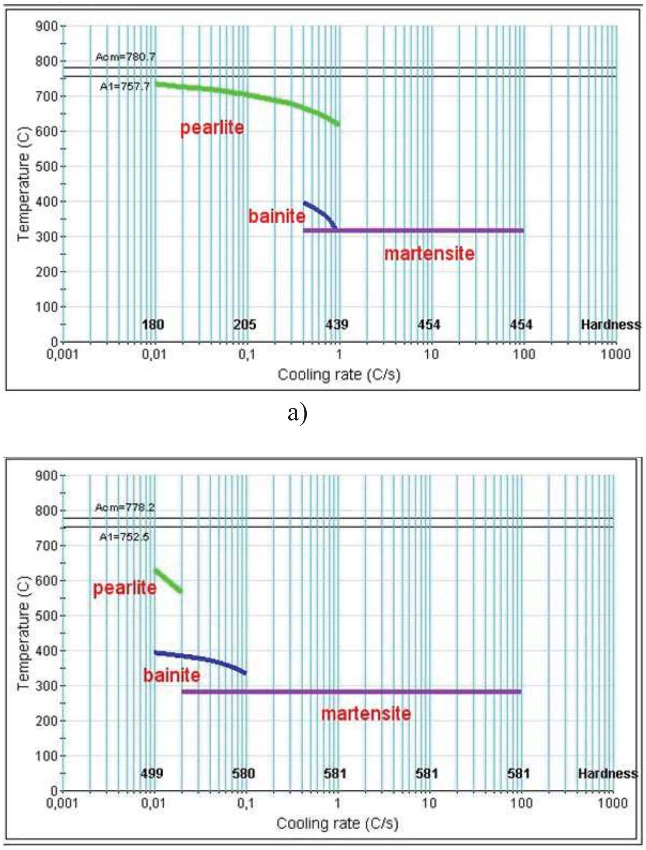
	HT regime	Place of measurement		
		12Cr13	Transition / fusion zone	35NiCrMo V12-5
Grain size, µm	HT#1	28	19	23
	HT#2	18	15	19
Micro-hardness, GPa	HT#1	2.41±05	2.52±05	2.31±05
	HT#2	1.93±05	2.11±05	2.02±05

The microhardness of a metal in the transition zone in the sample from the composite ESR ingot after HT#2 are lower than after HT#1, and spread of values is less. The hardness in the transition zone is somewhat higher than the hardness of the both connected steels. The hardening of martensite due to the alloying of a cementite by chromium and carbon simultaneously due to a internediate composition forming at the both steels mixing may be the possible mechanism for the transition zone hardening at the absence of specific phases precipitation. The precipitation of very fine chromium carbides of complicated chamistry having hardness (16.63 ... 18.82 GPa) higher than cementite (less than 10GPa) is possible, but such carbides were not revealed in our research [23]. The results of the heat treatment by two regimes shown the second one (recommended for steel 12Cr143) provides more elaborate structure of the metal in all zones of the two-layer ingot: the grain size is smaller, primary grain boundaries are less pronounced, dispersion of martensite plates is higher.

4. Forecast of phase transformations in the transition zone at ESR thermal cycle

To assess the influence of a thermal cycle at the ESR for formation and transformations of phases for the steel of mixed composition in the transition zone the CALPHAD method was used. The is analysis of the phase equilibria in a system and thermodynamic properties of phases for plotting the thermo-kinetic diagrams (TKD) of phase transformations. TKD (Fig. 4) were calculated for two middle points of the transition zone with the chemistry belongs to spectrum #10 and #12. An analysis of the TKD for both positions showed that the characteristic temperatures of phase transformation vary insignificantly and makes for the #12 point: T_{ac1} 12 = 752.5°C, T_{ac3} 12 = 778.2°C in comparison with the #10 point having T_{ac1} 10 = 757.7°C, $T_{ac\ 3}$ 10 = 780.7°C. The studied steel can form of perlite, bainite and martensite. For the first composition (#10), the maximum temperature of the beginning of the perlite formation is 740°C, which decreases to 610°C when the cooling rate increases to 1 °C/s. The bainite forms in a rather narrow range of cooling rates – 0.4-0.9°C/s.

The temperature of bainite formation beginning makes 400°C and decreases to 320°C at higher cooling rates. In the range of cooling rates of 0.4-0.9°C/s, the structure consists of perlite and bainite. When cooling rate is above 0.9°C/s, this metal have completely martensitic structure. The temperature of the martensite formation is 300...310°C and its hardness is gradually increases from 4390 MPa to 4540 MPa at the growth of cooling rate.



a)

b)

Fig. 4. Thermokinetic diagrams (TKD) for mixed compositions in two middle points in the transition zone (spectrum #10 and #12)

The structure for spectrum #12 consists of perlite, bainite and martensite also, but the decomposition of austenite starts at much lower temperatures. The perlite formation starts at 630°C, bainite – 400°C and martensite – 280°C. The creation of perlite occurs in a much less range of cooling rates (0.01-0.02°C/s), and bainite forms in the interval between 0.01-0.1°C/s. At cooling rates of 0.01-0.02°C/s a perlite-bainite structure forms and at 0.02-0.1°C/s – bainitic-martensitic one. For spectrum #12 at the cooling rate higher than 0.1°C/s, a purely martensitic structure forms, whose hardness reach 5800 MPa, which is much higher than for the spectrum #10. The steel of #12 is more inclined to hardening structures formation than #10.

The analysis of the obtained results shows that at using of welding for steels 12Cr13 and 35NiCrMoV12-5, the cooling rate in the HAZ should not exceed 0.9°C/s and 0.02°C/s for point #10 and #12, accordingly. That will ensure the formation of perlite or perlite-bainite structure with an acceptable hardness level of 2000... 3000 MPa.

The cooling rate of the ESR ingot formation depends on the diameter but indeed does not exceed the indicated speeds.

5. Conclusions

The transition zone in two-layer ingot had the shallow shape and low depth (near 20 mm) with the uniform macrostructure without any defects of the same type as both joined steels (grades 12Cr13 and 35NiCrMoV12-5). The metal of transition zone is fully satisfied the standard requirements for properties of both steel grades in the heat treated (under two regimes of heat treatment inherent to the steels of connected layers) and as-cast state.

The thermokinetic diagrams for steels of mixed composition additionally prove the favorable conditions at the ESR for manufacturing ingots for a composite rotor.

The ESR LM can provide both the monobloc heavy ingots with uniform chemistry and structure and the composites with low-stress connection between different metallic materials that open the efficient way for new heavyweight rotors and critical products manufacturing.

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