ESRC guide vanes of hydraulic turbine for Three Gorges project

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Abstract: The mechanical properties and internal quality of low carbon martensite Electroslag Remelting Casting (ESRC) stainless steel castings are superior to that of sand casting ones. The key technologies for the equipments and ESRC processes have been resolved during the experimental research period of guide vanes of hydraulic turbines for Three Gorges project. And ESRC guide vanes of hydraulic turbines for Three Gorges project have been produced successfully.

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1. Introduction

ESRC is a special working method gathering refining and casting of molten metal together. With its special process, ESRC can counteract the weakness of common sand castings, thus get high grade castings with good internal quality. In this project, a lot of research has been done about key technologies of material, process and equipment, which are involved in making guide vane of hydraulic turbine by ESRC, and the achievements have been used in practice.

2. Material research

2.1 Trial method

The trial material used is ZG06Crl3Ni4Mo, which is stipulated for the guide vanes of hydraulic turbine for Three Gorges project. First, the molten metal is poured into sand molds to get castings, and then some of the sand castings are used as consumable electrodes to make ESRC castings by ESRC. The two kinds of castings were correctly heat-treated in one furnace in the same time. The sand castings (called No. 1 for short) and the ESRC castings (called No.2 for short) were compared and analyzed about their chemical compositions, nonmetallic inclusions, mechanical properties and ultrasound cavitations.

2.2 Test results and analysis

Table 1 to table 4 shows the chemical compositions, non-metalic inclusions, mechanical properties and ultrasound cavitations of the two kinds of castings.

Table 1 shows that the main alloy elements such as Cr, Ni and Mo etc. in ESRC castings are the same as in sand castings. Because the consumable electrode's terminal immerses completely in the slag pool and isolated from air during melting and solidifying, no second oxidizing occurs. And it's noticeable that the content of impure element P and S in steel lowers greatly in ESRC. So eliminating impure elements from material is one of the main causes to improve the material properties and extend service life. Table 2 shows that nonmetallic inclusions can be reduced a lot by ESRC, which shows the notable effect of ESRC.

Table 1 Chemical compositions of ESRC guide vane castings (%)

Sample No.	C	Si	Mn	S	P	Cr	Ni	Mo
I	0.045	0.56	0.55	0.032	0.020	13.70	4.60	0.68
II	0.040	0.45	0.53	0.015	0.016	13.73	4.60	0.65

Table 2 Nonmetallic inclusions in ESRC guide vane castings(%)

Sample No.	Nonmetallic inclusions
I	0.009~0.014
II	0.0034~0.0040

Table 3 Mechanical properties of ESRC guide vane castings

Sample No.	$R_{P0.2}$ [MPa]	R_m [MPa]	A (%)	Z (%)	A_k [J]	HBS
I	655	820	16	56	82	265
II	750	840	20	65	113	266

Table 4 The experimental results of ultrasonic cavitations [mg]

Accumulative time [h]		1	5	10	15	20
Accumulative weight-losses	(I)	1.70	14.25	27.10	45.00	60.85
	(II)	1.15	11.72	21.98	34.84	45.45

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ZG06Cr13Ni4Mo is a common stainless steel material for passage flowing parts of hydraulic turbine, and most of which were formed by sand mold. The test results in Table 3 indicate that the mechanical properties of castings are improved apparently by ESRC. The causes why ESRC can improve the mechanical properties of castings are as following.

• The impure elements and nonmetallic inclusions are lowered greatly by ESRC.

• Solidifying and forming is completed in water cooling molds, so the strong cooling intensity makes castings' structure densifying.

• ESRC is a progressive solidifying process with the self-feeding function, so it can avoid cast defects such as shrinkage porosity and sand inclusion, etc.

Besides the passage flowing parts of hydraulic turbines are worn by silt in operation, another severe damage is cavitations under water. Cavitations resistance is one of the most important specifications for passage flowing parts. Table 4 shows that cavitations resistance of ESRC sample is about 1.25 times of that of sand sample, which should owe to the good mechanical properties and high dense structure and low nonmetallic inclusions of ESRC castings.

Above test results show that ESRC can enhance general property indexes of castings, further improve the casting quality.

3. Technique research

3.1 Preventing crack

Generally, molds of ESRC guide vanes are made of copper-steel plate. For the large guide vanes of Three Gorges project, gross weight is about 13.5 t. Because its shrinkage is large in the course of ESRC, whilst the transition zones of vane and long shift and of vane and short shift hinder metal from contracting freely, making the vane crack easily. In order to resolve the difficult problem, we develop a new mold with yieldability, as shown in Fig. 1, which is designed in response to the structure feature of guide vane for Three Gorges project, and overcome completely the disadvantage of ESRC molds without yieldability.

Moreover, taking some measures, such as improving the design of consumable electrode and optimizing technology etc., can also enhance the quality of castings and eliminating crack source to a great extent, further prevent crack.

3.2 Determining of slag weight

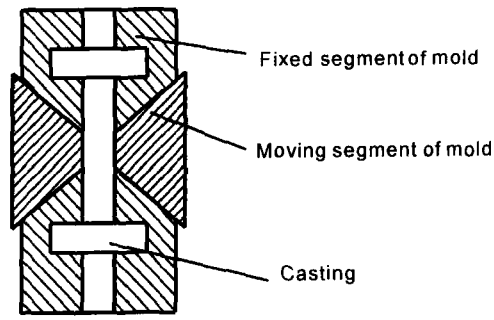

Fig.1 Sketch map of the shape of guide vane casting and mold with yieldability.

The slag weight is calculated by the following formula in common:

$$G = \frac{\pi}{4} D^2 H r \qquad (1)$$

In formula (1), G denotes slag weight and D denotes diameter or equivalent diameter of mold. H, depth of slag pool, and r, density of slag. Obviously, the key to calculate slag weight is to determine correctly the depth of slag pool. Up to now, the H value is determined by experience. Based on the changing regularity of effecting casting's section shape on pool depth, we put forward a new calculation method of pool depth when the guide vane and other complex castings are made.

$$H = \alpha D^n \qquad (2)$$

In formula (2), α is related with the sectional shape of mold, named as shape coefficient, and α=1.5~2.0. *n* is related to the sectional size of mold (equivalent diameter), named as size coefficient and n=0.7~0.8. Formula (2) has following merits.

• Wide scope of application: connecting depth of slag pool with section shape and size of mold is suitable to melt and cast all kinds of complex shaped castings.

• Highlight in theory: after determining sectional shape of mold, the relationship betwen the pool depth and section size of mold is exponential. The value of *n* is only affected by sectional size, and the value of α is only affected by sectional shape.

• High accuracy: by the optimum technologies test to guide Vane, connecting rod, round ingot steel etc., it is verified that calculating results by formula (2) are more accurate.

Generalizing from a large amount of data of tests we have set up a database for α and *n*, which can be used for many kinds of complex castings, including guide vanes for Three Gorges project.

3.3 Expert system and computer simulation of ESRC process design

In order to enhance design level of technique we generalize the test data and achievements in past and have developed knowledge base of process design for guide vanes by ESRC, according to which we have built an expert system of process design for guide vanes by ESRC. This system is divided into twelve modules by function. It can realize auto-draft and generate process files after inputting all sizes marked in guide vane order drawing into computer. The system's operation is simple.

Setting up mathematical model of ESRC process and test boundary conditions, and combining the characteristics of continuous changing of some meshing units in the process of ESRC variable sectional castings, we established calculating software ESRC3D for ESRC process. If inputting technical parameters before drafted ahead, the whole ESRC process under these parameters may be simulated. Based on the temperature gradient and cooling speed simulated at every mesh cell, and then utilizing certain criterion, we can judge whether there are defects such as shrinkage porosity and shrinkage hole etc. or not. After modifying them repeatedly, optimized technology indexes are gained at last and are used in practice. Fig. 2 shows an example of temperature field of guide vanes simulated with ESRC3D software.

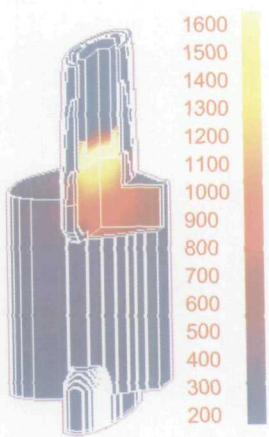

Fig.2 The temperature field at 15 860 s for ESRC guide vane casting

4. Development of equipment

Cooperating with related departments, we have developed a large multiple function electro-slag furnace (ESF) and auxiliary devices to make guide vanes for Three Gorges project.

4.1 Machine system to drive

At present, most of ESF only fit to produce ingot steel with simple shape, and there only are three freedoms of motion of position adjustment between electrode and mold. But the ESF developed by us has five freedoms of motion to adapt to the need of large complex guide vanes, and there is two-speed motion function along *X*, *Y* and *Z*, which can meet the special demands of replacing electrode, superposing mold and micro-adjusting. This equipment fits to melt and cast complex castings.

4.2 Monitor and control system

This equipment has three kinds of controlling system, that is, hand-control, auto-control and computer-control system. Especially for computer-control system, when the technique curve is inputted into computer in advance, the computer may monitor the whole process, and then all data are recorded and saved automatically(Fig.3). For the equipment's failure or exceptional occasion occurred in the course of ESRC, computer can warn automatically and deal with them at once.

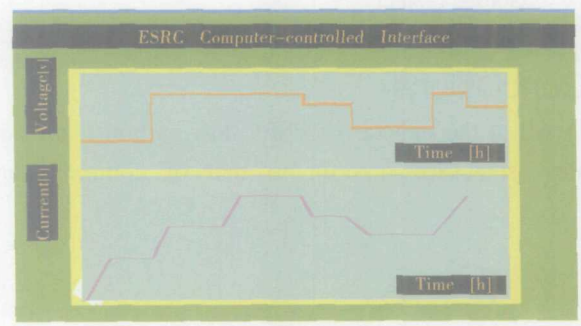

Fig. 3 Computer controlling interface

4.3 Electricity supply system

Under the conditions of meeting the requirements, considering the demands of reliability and equalization of electric net, we choose T type alternate variable transformer being loaded to electricity supply (rated power 3 000 KVA), which is the largest capacity of T type alternate transformer used for electricity supply to ESF. In the design of low voltage short-volt net, applying multiple antimagnetic technology can decrease the loss of short net as much as possible.

5. The trial manufacture of first guide vane for Three Gorges project

The first guide vane for Three Gorges project have been made on the basis of a lot of technique tests, as shown in Fig.4. The gross weight of guide vane is about 13.5 t. Checking results according to specifications show that all indexes completely meet the requirements. And Ultrasonic Examination is up to Class II of American ASTM A609. Magnetic Particle Examination reaches Class II of CCH

70-3. Sulphur content lowers more than 30%. Nonmctallic inclusions of uniform distribution reaches the level of 1~2 grade of GB 10561~89. Now, the guide vane castings have been produced in large number, and the quality of products is steady.

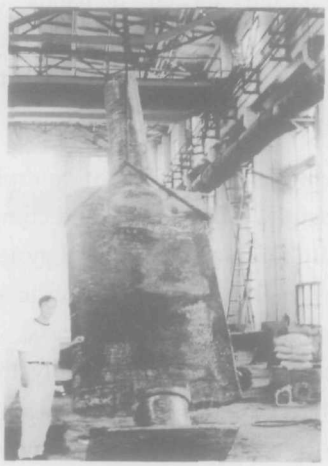

Fig.4 ESRC guide vane of hydraulic turbine for Three Gorges project

6. Conclusions

(1) All of the indexes of ESRC low carbon martensite stainless steel are superior to that of common sand castings apparently.

(2) Mastered the key technologies of large type guide vanes by ESRC and built up a new means to calculate depth of slag pool.

(3) Expert system and numerical simulation software of ESRC guide vanes have been set up and applied in design and practice.

(4) Many advanced technologies are adopted during developing related equipment.

(5) The first batch of guide vanes for Three Gorges project has been made successfully and all indexes has reached the demands of order.

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