Review of production status of heavy steel castings and key technologies for their manufacture in China

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Abstract: This paper expatiates on domestic status of heavy steel casting production, with a special focus on hydraulic turbine castings for Three Gorges Project. In China, there is magnificent demand for heavy castings with the rapid growth of the national economy in recent years and the expected high growth in the coming 10 to 20 years. Some heavy and large castings such as mill housing and hydraulic turbine runner crown, blade and band for Three Gorges Project have been successfully made. However, the domestic production capability is still far from meeting the gigantic requirements. The domestic capability still lags behind the world class level, and a lot of heavy castings still depend on import. The paper also gives a particular introduction of the key technologies in the manufacturing of heavy steel castings like metal melting, foundry technology, heat treatment technology and numerical simulation technique, etc. In addition, several case studies on the application of numerical simulation in the production of heavy steel castings are presented.

Key words: heavy steel casting; numerical simulation; foundry technology

Heavy castings are widely used in the equipment for metallurgy, shipbuilding, petrochemical, power and other industries, such as mill housing, hydraulic turbine runner, runner crown, band and blade, steam turbine casing, pump casing for nuclear power station and etc. Therefore, the manufacturing of heavy castings is very important to a nation’s economy, and it symbolizes the capability level of industry. The castings are also factor influencing the construction schedule and safety of the national key projects.

1 The status of the domestic production of heavy castings

1.1 Strong domestic requirements

Due to the fast growing China’s economy, there are more and more big projects in metallurgy, power, shipbuilding and equipment manufacturing industries. In the hydro power station sector, the hydro power capacity will increase from 117 MkWh in 2005 to 190 MkWh in 2010 and to 300 MkWh in 2020. The ongoing Three Gorges project totally needs thirty two 700 MW power generation units with twenty one units installed up to date, ranking the biggest power plant in the world. More large power stations are in planning in the upper stream of Yangtze River and Yellow River which will need more 700—1,000 MW power generator units, such as the under-construction Xiluodu and Xiangjiaba hydro power stations which will install eighteen and eight 700 MW power generator units, respectively. In total, for the next 20 years, about one hundred and fifty 700—1,000 MW hydro-power generation units will be installed. Meanwhile, the pumping storage power generation units also come to be a soaring market. Currently, ten pumping storage power stations are under construction, and by the end of 2020, its power capability will increase from current 6.4 GW to 50 GW. The hydraulic turbine runner, one of the critical components for power generation unit, is made of a single casting or weld structure by crown, band and blade castings. For the 700 MW unit in the Three Gorges Project, the runner is a welded structure with a band (weight 104 t, diameter 10.3 m and height 2.59 m), a crown (weight 130 t, diameter 8.5 m and height 1.6 m) and 13 or 15 blades (size 5.2 m × 3.6 m × 1.28 m and weight 16 t for each). This makes the runner with its own diameter at 9.85 m and maximum diameter at 10.3 m, height at 5.7 m, and weighing 430 t, as illustrated in Fig. 1.

With the development of hydro power stations, steam and gas turbine power stations and nuclear power stations are also in design and construction. The supercritical and ultra-supercritical steam and gas power generation stations are the trend of coal-fired power industry. The first station with four 1,000 MW ultra-supercritical power generator units is under construction in Yuhuan County, Zhejiang Province. Inner and outer casing and shell castings are necessary for the steam and gas turbine power stations.

In metallurgical industry, there are still rigorous requirements for hot, cold and continuous milling machines with the upgrading
and expansion of iron and steel industry. The first five meter wide steel slab milling machine has been installed at Baosteel. The milling machine needs mill housing, roll and roll carriage castings. The startup of commercial airplane project needs heavy forging machines. Recently, the manufacturing plan of 800 MN hydraulic die forging press has just been approved by the government. The heavy frame and beam castings are the most important structural components for both oil press and hydraulic press.

All these ambitious projects proposed huge requirements for heavy castings. However, the domestic manufacturing industry is far away to satisfy the huge requirements. For example, the Three Gorges requires thirty two 700 MW power generators, and up to now only three blades, one crown and one band were made in China, while most of the castings were imported.

The heavy castings usually serve under high stress, high temperature and/or high pressure. So the internal quality, soundness, mechanical properties should be well controlled. On the other hand, the technology and experience for small and medium size castings can not be directly copied to the production of large castings because of their specific features, heavy and large. Consequently, they need more time to solidify and bigger risers to compensate the shrinkage along with control of thermal stress for the bigger temperature gradient across the heavy section, inverse deformation design or ribs for the deformation tendency, and control of hot and cold cracks.

1.2 Recent progress of domestic production

In China, there are about thirty foundries with the capability to make heavy castings, most of which are captain foundries [3], affiliated to the former state owned enterprises, such as the foundries affiliated to the China National Erzhong Heavy Machinery Group Co., China First Heavy Industries, and Shenyang Heavy Machinery Group Co. Ltd. However, only a few have the capability to make the heavy castings weighing more than 100 tons. The production of the heavy castings is mainly for the domestic need, rarely for export.

Up to now, the domestic foundries have made great progress to meet the requirements from melting to heat treatment. Several foundries have updated their melting equipment by installation of LF (Ladle Furnace, the largest one at 100 t), VOD (Vacuum Oxide Decarburization) or AOD (Argon Oxide Decarburization), shifted from traditional sodium silicate bonded sand to self-hardened resin bonded sand, and improved the heat treatment equipment for large size casting such as 11 m × 13 m × 5 m furnace. For quality control, many foundries have equipped with various surface measurement systems, such as laser measurement systems and etc. The Foundry Division of China Erzhong has made two 380 tons mill housing castings (as illustrated in Fig. 2) with 706 tons of liquid steel for each, the heaviest carbon steel castings in China, used for a five-meter wide slab milling machine. A year later, in 2006, the record was broken by the 480 tons mill housing with consumption of 743 tons liquid steel by the China First Heavy Industries [4].

Erzhong produced a 180 t stainless steel runner crown casting for Three Gorges Project, the heaviest stainless steel casting in China. Erzhong has also successfully produced a blade and a crown for Three Gorges hydro turbine. The China First Heavy Industries also successfully made a blade for Three Gorges Project [5].

To meet the urgent requirement of castings for Three Gorges Project in past two years, Ansteel Heavy Machinery Co. Ltd., Dalian Heavy Industry Huarui Steel Co., Ltd., Kocel Steel Foundry Co., Ltd. and Harbin Electric Machinery Co. Ltd. joined in the family to produce these hydraulic turbine castings. Ansteel Heavy Machinery Company has made four runner bands and two blades, and will establish the capability to produce castings for ten sets of Three Gorges turbines per year [6]. Kocel Steel Foundry has also successfully cast a blade. Dalian Heavy Industry Huarui Steel Co., Ltd has cast one blade. This symbolizes the progress of heavy castings propelled by the urgent and huge domestic demands.

ESRC (Electro-Slag Remelting Casting) has been very successfully used to produce all the guide vanes for Three Gorges Project (as illustrated in Fig. 3) by Shenyang Research Institute of Foundry [7]. Its advantages include low sulfur content (0.007%—0.015%), good casting soundness (with Magnetic Particle Examination reaching Class II of CCH 70—3 standard and Ultrasonic Examination being up to Class II of ASTM A609 standard, and the experiment results of ultrasonic cavitations showing 30% increase compared to sand casting), and reduced machining allowance. Its disadvantage is the low efficiency. For larger scale of castings, there are still a lot of obstacles facing the production of large and heavy steel castings in the future.
1.3 The requirements cannot be satisfied only by domestic or overseas capability or even by both in future

Although Chinese heavy steel casting foundries have made great progress in recent years and have produced some important heavy castings for Three Gorges Project, the available capacity is far away to meet the domestic demand, even with the importation from overseas. Hence, almost all of runner bands, crowns and blades for the 21 installed Three Gorges turbines were imported from South Korea, France, Romania and Slovenia. Even by doing so, the delivery could not be well guaranteed and resulted in the delay of the delivery of power generation unit. Also, it has been proven that the quality of imported heavy castings can also be questionable sometimes. At the end of 2007 two blades imported from Slovenia were discarded due to cracking occurred after welding to the band and crown. Hot crack also ruined the first runner crown made in South Korea and the first runner band made in China. Although the crown and two blades were successful, very large machining allowance was usually given to guarantee the final dimension, which resulted in long machining period.

Nevertheless, compared to the developed countries, the domestic production technology still lags behind in terms of technology, quality control and equipment. For the Three Gorges Project more than half the hydraulic turbine runner castings are still dependant on import.

The design of 700 MW hydraulic turbine unit has been mastered by Dongfang and Harbin Electric Machinery Co. Ltd. using imported technology. As a result, each of these two companies has won the bid of four units of the right bank of Three Gorges Project in the competition with foreign rivals. However, the manufacturing of heavy steel castings is beyond the technology transferred. Even the order of heavy castings placed at overseas is not guaranteed for various reasons and excuses sometimes. Therefore, to improve the domestic manufacturing capability is one of the top priorities.

2 Key technologies in the production of heavy castings

2.1 Melting control

Melting, the first step to make castings is of essential importance for casting quality. It is mainly to control the required alloy elements and especially the detrimental elements such as sulphur and phosphorus. Hence, advanced melting technology and equipment have to be applied, such as the refining equipment, VOD, LF and AOD for obtaining super low carbon stainless steel. Loose control of melting process is very susceptible to the result of hot cracks and segregation. In addition, the control of oxygen, nitrogen and hydrogen is very important to guarantee the final properties.

2.2 Deformation and cracking control

There are also several cases of hot cracking occurrence in heavy castings, such as runner band and crown and the mill housings. For the hydraulic turbine blades the deformation principle has not been clear, so usually large machining allowance is given to assure the final shape and dimension, resulting in excessive machining. For instance, the domestically produced blade casting need to be machined for 15 days each, and its utility is just 28%. The deformation is related to melting, casting design and quality control as well as the heat treatment. The determination of inverse deformation is critical to the final shape. Therefore, the distortion in casting and heat treatment process should be controlled and measured for further deducing the deformation principles. There is still lack of systematic measurement of the deformation during each process; and the deformation principle has not yet been obtained.

2.3 Heat treatment and control of properties

The heat treatment is necessary to acquire the desired microstructure and properties, including quenching and tempering or normalizing and stress relief annealing. How to optimize the thermal program during heat treatment, containing the heating and cooling rate, soaking temperature and time, is very critical to the final properties. The final mechanical properties include hardness, yielding strength and tensile strength. Meanwhile, the control of microstructure is the guarantee of the mechanical properties. The residual stress and deformation are also important factors in quality control.

2.4 Standards study and the control of alloying elements

Many of the current standards for heavy castings are borrowed from overseas. In the standards there are usually critical requirements of final properties, for example, the FATT (the transformation temperature from ductility to brittleness). To meet this requirement, the carbon content has to be controlled at very low level, leading to high cost, while this requirement of FATT is doubtable. Hence, it is necessary to establish national standards based on experimental results.
2.5 Numerical simulation

For the production of heavy castings, the numerical simulation method shows great importance and necessity. It is going to replace the traditional trial and error method to save cost, time and guarantee the quality. During the ninth five-year period, the quality control of heavy castings by numerical simulation method had been carried out [9-13]. Currently most Chinese foundries for heavy casting production have purchased the domestic software packages such as FT-STAR, CAE/Intecast or the imported software such as Magmasoft, Procast, Novacast, or even both. The heat transfer and prediction of shrinkage defects have been widely applied [14-17]. Prof. Liu Baicheng’s group at Tsinghua University developed FT-STAR software package which includes filling process, heat transfer, and thermal stress analysis and can predict shrinkage porosity, hot tearing, deformation and stress.

The numerical simulation has been applied in the production of many heavy castings [15, 16, 18-20]. Under the condition of insufficient melting capability, the simulation results tell when and how much liquid steel should be poured again, for example, a steam turbine casing for Dongfang Steam Turbine Works (as illustrated in Fig. 4) [15], and a 218 tons mill housing for Magang Machinery Company (as illustrated in Fig. 5) [16]. The thermal stress analysis for many heavy castings, such as the hydraulic turbine blade, mill housing, runner band (as illustrated in Fig. 6), has been conducted to predict the deformation, stress and hot tearing tendency by the FDM/FEM integrated method [16, 18-20]. The microstructure is another area in numerical simulation, for instance the grain size prediction [21]. Furthermore, the segregation of large steel ingot is modeled and simulated [22-23], as shown in Fig. 7.

![Solidified region just after the first compensation](image1)
![Solidified region just before the second compensation](image2)
![Solidified region just before the third compensation](image3)
![Temperature filed after the third compensation](image4)

**Fig. 4** A mill housing casting with a total weight of 218 t, while the melting capability only at 190 t once a time. Therefore, the compensation pouring is simulated by FT-STAR to determine the right time and right liquid steel mass for obtaining sound casting. Cut view for the sight of inside solidification status.

![Equivalent stress during solidification process](image5)
![Residual equivalent stress](image6)
(c) Deformation (magnification 15)

Fig. 5 The stress analysis of a mill housing casting

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<th>b</th>
<th>c</th>
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<td>The original size, mm</td>
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<td>Calculated shrinkage, %</td>
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Fig. 6 Prediction of hot tearing tendency by the distribution of semi-solid region, tensile stress and shrinkage tendency for the Three Gorges turbine runner band

3 Summaries

There are rigorous requirements for heavy steel castings for the next 10—20 years in the Chinese market, which provides domestic foundry industry great opportunities as well as challenges. Therefore, these foundries have to enhance melting, foundry technology, heat treatment quality control and upgrading of equipment so as to grasp the opportunities. Numerical simulation software is a powerful and helpful tool to understand the physical phenomena in casting process, to predict shrinkage, stress and deformation, hot tearing, segregation defects, and finally to improve the domestic production capability of heavy castings. In foundry industry, the enterprise-institute-university alliance should be formed to facilitate the progress in the production of heavy castings.

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References


