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Advances in Compact Manufacturing for Shape and Performance Controllability of Large-scale Components-A Review

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Abstract: Research on compact manufacturing technology for shape and performance controllability of metallic components can realize the simplification and high-reliability of manufacturing process on the premise of satisfying the requirement of macro/micro-structure. It is not only the key paths in improving performance, saving material and energy, and green manufacturing of components used in major equipments, but also the challenging subjects in frontiers of advanced plastic forming. To provide a novel horizon for the manufacturing in the critical components is significant. Focused on the high-performance large-scale components such as bearing rings, flanges, railway wheels, thick-walled pipes, etc, the conventional processes and their developing situations are summarized. The existing problems including multi-pass heating, wasting material and energy, high cost and high-emission are discussed, and the present study unable to meet the manufacturing in high-quality components is also pointed out. Thus, the new techniques related to casting-rolling compound precise forming of rings, compact manufacturing for duplex-metal composite rings, compact manufacturing for railway wheels, and casting-extruding continuous forming of thick-walled pipes are introduced in detail, respectively. The corresponding research contents, such as casting ring blank, hot ring rolling, near solid-state pressure forming, hot extruding, are elaborated. Some findings in through-thickness microstructure evolution and mechanical properties are also presented. The components produced by the new techniques are mainly characterized by fine and homogeneous grains. Moreover, the possible directions for further development of those techniques are suggested. Finally, the key scientific problems are first proposed. All of these results and conclusions have reference value and guiding significance for the integrated control of shape and performance in advanced compact manufacturing.

Keywords: compact manufacturing, shape and performance controllability, high-performance, ring parts, thick-walled pipes

1 Introduction

The high-end equipments used in aerospace, wind power, ships and nuclear power industries develop to high-reliability and long-life served in extremely severe conditions, leading to the large dimension, and complex structure in key components. Moreover, the high performance large-scale components have an increasing demand for advanced manufacturing techniques[1–3]. The macro-dimensional and microstructural state show significant change in the manufacturing process. And the complicated interactions of processing conditions with the changing patterns and results will affect the ultimate properties and qualities of components. However, the geometrical dimensions change and microstructure evolution are not isolated, but are closely connected with each other. For small-scale components, the macro-structural dimension forming is given priority, and how to control the microstructure is become more important for large-scale components.

Over the past few decades, many helpful studies focused on the compact process of shape and performance integrated controllability of metallic components have been conducted. LEE, et al[4], found the mechanical properties of A356 aluminium alloy fabricated by casting-forging integrated technique are superior to that fabricated by squeeze casting or low pressure casting, respectively. JIANG, et al[5–6], also obtained the AM60B motorcycle engine shell and AZ91D motorcycle wheel hub with precise geometrical dimensions and excellent strength and ductility by casting-forging technique. WANG investigated the casting-forging forming process of A356 alloy, and the associated microstructure evolution and mechanical properties were examined[7]. The results show that the high-density microstructure and sound mechanical properties of the parts can be obtained significantly by the forging with large area and large deformation. ZHU, et al[8], revealed the average grain size and its distribution width in as hot-rolled SPHC, SPHD, and SPHE sheets manufactured by compact strip production(CSP) are obviously larger than that by traditional continuous casting and rolling(CCR).

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The initial coarse grain would result in mixed grain size, large distribution width due to the interplay of static recrystallization(SRX) and dynamic recrystallization(DRX) in CSP process. However, an extremely different result was reported by HUANG, et al[9–10], and they found the strength, elongation and hardness of both 30CrMo and 60Mn hot-rolled strips with fine ferrite grains and pearlite interlaminar spacing produced by CSP are superior to those by conventional CCR. REIP, et al[11], also produced C-Mn(VNbTi) and C-Mn(VNb) hot strips with fine-grained ferrite-pearlite microstructure, high strength and excellent low-temperature toughness up to −60 ℃ using CSP technology. In order to fabricate high-performance thin-slab through CSP technology, KANG[12–13] proposed a concept of comprehensive control theory on microstructure, inclusion and precipitate during casting process, and grain refinement in dynamic recrystallization region and non-recrystallization region during hot rolling. Subsequently, ZHAO, et al[14], analyzed the microstructure characteristics and precipitation behavior of automobile beam steels produced by CSP using scanning electron microscopy(SEM), transmission electron microscopy(TEM) and X-ray energy dispersive spectroscopy(EDS). TAN, et al[15], found the excellent microstructure and mechanical properties of hot rolled dual-phase steel are obtained with the finishing rolling at 790–830 ℃, isothermally holding at 680–740 ℃ and coiling below 250 ℃ during CSP. For copper tubes production, the cast-roll integrated method consists of horizontal continuous casting, three roller planetary rolling, and multi-stage stretch forming[16]. The TP2 copper tube produced by cast-roll process exhibits as good microstructure and mechanical properties as those produced by traditional extrusion process, which includes casting bar, heating, hot extrusion, hot rolling and stretch forming[17]. Thus, the cast-roll technology is widely used in air-condition equipments due to its superiorities such as high-efficiency, low cost and high qualification rate of products. However, both the diameter and wall thickness of tube products are small in the cast-roll process, which results in it cannot be applied to the manufacturing for seamless pipes with large diameter and thick-walled. In recent years, to fabricate a large-scale component with a high dimensional accuracy and a uniform surface, additive manufacturing(AM) technology has been attracting much attention[18–20]. The full-density and high-performance complex components are manufactured in a sequential manner through a layer-wise addition of material. The AM has a good processing flexibility in comparison with traditional manufacturing technology[20]. FRAZIER recently provided an excellent review of the subject[21]. So far, important progress related to the processing parameter, microstructure and properties of metal parts including stainless steel[22–23], nickel-base alloy[24–25], heat-resistant steel[26] during AM have been made. For example, ZHONG, et al[27], produced thin-wall complex telescope component with a size of 191 mm in diameter and 305 mm in height. LU, et al[22], investigated on the microstructure evolution of 316L steel during AM, and fabricated a steam turbine blade with precise geometrical dimensions and high surface quality. MA, et al[20], carried out a detailed study on the control of shape and performance of 316L stainless steel part by AM technology. According to the optimum parameters, a component with a size of about 615.3 mm× 216.5 mm×232.5 mm, a homogeneous microstructure and superior strength properties is successfully fabricated.

The above researches almost all concentrated on the shape and performance controllability of metal components with relatively small geometrical size. Although the adopted techniques and methods such as additive manufacturing have been used to produce large-scale parts by some groups, they are immature in high-performance large-scale components. Thus, by focusing on bearing rings, flanges, railway wheels, thick-walled pipes, etc, the conventional manufacturing processes and their developing situations were summarized in this paper. The new techniques related to casting-rolling compound precise forming of rings, compact manufacturing for duplex-metal composite rings, compact manufacturing for railway wheels, and casting-extruding continuous forming of thick-walled pipes were introduced in detail. The corresponding research contents, research findings and development trends were elaborated. Finally, the key scientific problems for macro/micro-structure and high-performance based on the entire process were first proposed. This is an important part of the effort to fabricate the high-performance large-scale components by applying the energy saving, low-carbon and green manufacturing technique.

2 Casting-rolling Compound Precise Forming of Large-scale Rings

Large seamless rings, such as bearing rings and flanges, have been widely used in industries, especially as key components in aerocraft, rocket, ship, wind power, etc. The large-scale rings with a size of over 200 mm in diameter are mainly fabricated by hot ring rolling(HRR), an advanced plastic forming technology characterized by asymmetry rolling, incremental and local deformation, due to its superiorities such as high quality, high efficiency and low noise[28–30]. In HRR, the rotational motion of the driven roll and the feed motion of the idle roll act directly on the ring blank to cause the wall thickness to reduce, the diameter to expand and the axial height to increase or reduce[31]. In addition, the microstructure of the ring undergoes complex changes such as SRX, DRX and grain growth, and meanwhile has an interactive effect on the thermal and mechanical behaviors. The performance and reliability of the ring products have a close relationship with the final microstructure, which depends strongly on the microstructure evolution history and processing parameters in the accumulative and multi-pass processing[30, 32].

Until now, extensive works concern on the macroscopical deformation behaviors and geometric accuracy of ring products in HRR process[33–36] but studies related to microstructure evolution and performance control are insufficient. YADA, et al[37], established a semi-empirical model to describe the recrystallization of C-Mn low carbon steel in HRR, and the model is composed of SRX, DRX and grain growth models. XU, et al[38–39], investigated the average size and distribution of austenite grains through the whole thickness in seven specific sections of low carbon steel during HRR, and also clarified the effect of microstructure on roll force and roll torque. YEOM, et al[40], identified the forming defects of TC4 alloy ring such as local flow deformation, shear band and surface crack through the combination of finite element method(FEM) with experiment. The optimum parameters are obtained by analyzing the data from FEM and microstructure in the specified section of the ring. WANG, et al[30, 41], revealed the fine-grained region transfering from surface-layer to center-layer of TC4 alloy ring in HRR using an empirical microstructure model. Then the effects of both the feed rate of idle roll and initial rolling temperature on β phase distribution and its grain size evolution were investigated, respectively. SUN, et al[42], studied the influences of key rolling parameters including the rotational speed of driven roll, feed rate of idle roll, initial rolling temperature and friction factor on DRX fraction and average grain size of AISI 5140 steel during HRR through the combination of microstructure evolution models with the FEM. SHAO, et al[43–44], found a coordination deformation between lamella pearlite and ferrite of 20 steel during HRR, and a large quantities of lamella pearlites are paralleled to rolling direction in the outer-layer of the final ring product. KIL[45] proposed a quantitative formability index by using processing map to estimate deformation characteristics and microstructure evolution of SAF2205 duplex stainless steel during HRR.

The previous studies on geometric accuracy and microstructure evolution in HRR are mainly focused on the traditional manufacturing technology for ring products. The current process includes pouring ingot, heating, cogging, sawing, heating, upsetting, punching, heating, HRR, and heat treatment, as shown in Fig. 1[46]. Before HRR, the starting material is as-forged state. The process has some disadvantages, such as multi-pass heating, wasting material and energy, and high cost since the huge forming machines are required in cogging, upsetting, and punching. To realize lightweight, security, high-efficiency and long-life of high-end equipments, carrier rockets, petrochemical and wind power industries have an urgently demand for the compact manufacturing in the control of shape and performance of large-scale ring parts. Moreover, an in-depth investigation of the large ring fabrication technology is of important significance in the frontier of the advanced plastic forming field. Thus, a novel compact manufacturing technology for high-performance large-scale ring components, namely casting-rolling compound precise forming(CRCF) process, is proposed by our group[46–48]. The new process consists of casting ring blank, HRR and heat treatment, as presented in Fig. 2. Compared with the traditional process, the CRCF has become a high-end technique with many merits in shorting technological process, reducing times of heating, considerable saving materials(about 25%) and energy (about 60%), low cost and improving productivity. But the initial state of the as-cast ring blank is coarse and inhomogeneous in grain size and microstructure. So it is an important and urgent issue to study the integrated control of geometrical dimensions forming and microstructure modification of as-cast ring blank in HRR, which needs to perform the associated microstructure evolution and models investigations first.

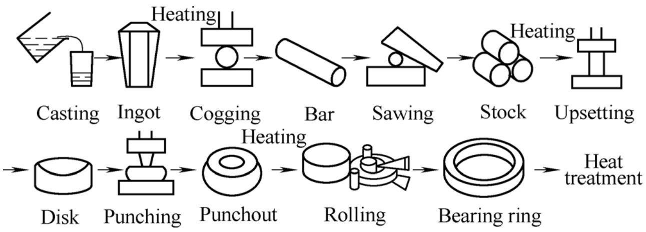


Fig. 1. Current process for producing ring parts

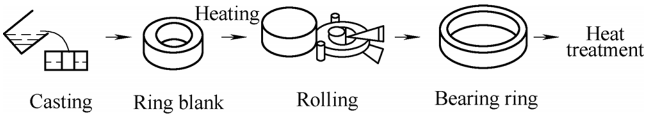
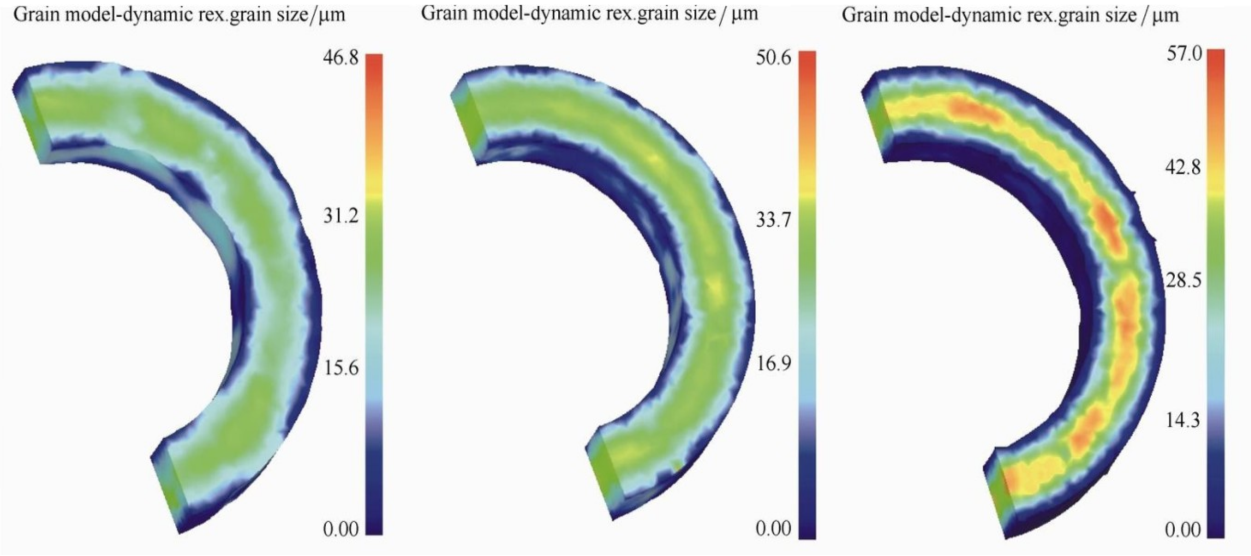


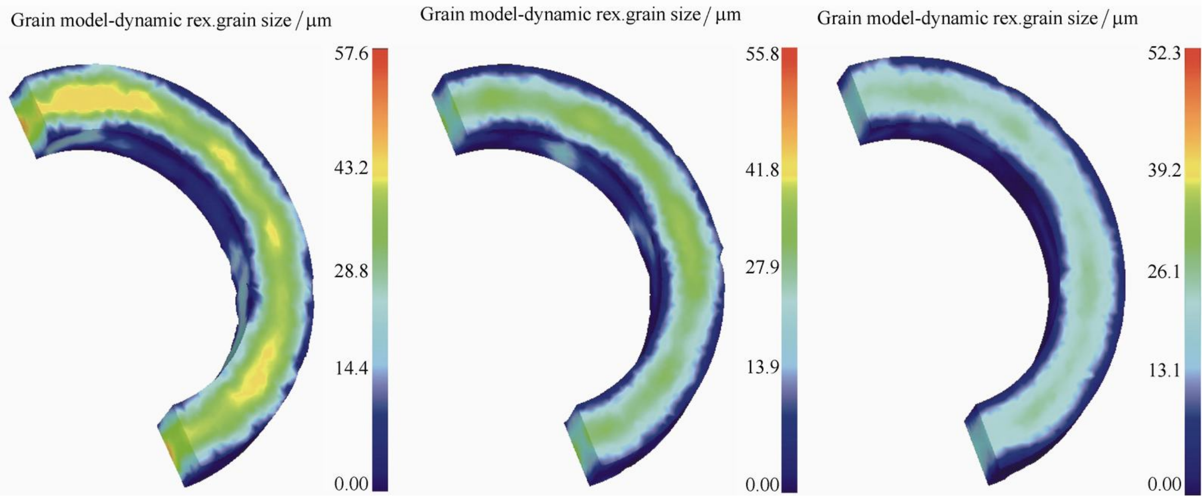
Fig. 2. Casting-rolling compound forming(CRCF) process for producing ring parts

In recent years, our team researches on the CRCF process of large-scale ring components. The hot deformation behavior of as-cast 42CrMo alloy is investigated using continuous and interrupted compression tests, and the corresponding SRX, DRX and metadynamic recrystallization models are established, respectively[49–50]. The effects of main rolling parameters including the feed rate of idle roll, initial rolling temperature, rolling ratio and friction factor on DRX grain size of as-cast 42CrMo alloy ring are analyzed thoroughly through the combination of microstructure evolution models with the FEM, as presented in Figs. 3–4[51–52]. To verify the feasibility of the CRCF process, the industrial HRR experiments of as-cast 42CrMo alloy ring with the size of about Φ840 mm×Φ500 mm×242 mm are carried out on a D53K-4000 radial-axial ring rolling machine, as shown in Fig. 5. The mechanical properties testing and microstructure observations are conducted with the samples cut from as-cast ring blank and rolled rings respectively rolled from as-forged and as-cast ring blank. Samples, marked with 11, 12 and 13(from as-cast ring blank), 21, 22 and 23(from the ring hot-rolled directly from as-forged blank), 31, 32 and 33(from the ring hot-rolled directly from as-cast blank), are all located in the outer-layer and inner-layer(approximately 0.5 mm below the surfaces) as well as in the center-layer through the whole thickness, respectively, as listed in Table 1[46]. The results indicate that the geometrical dimensions(about Φ1358 mm×Φ1175 mm×233 mm) of the final rings fabricated from the as-cast ring blank meet standardized technical demands of production, and the mechanical properties are up to industrial standard. In addition, the refined grains with the sizes of approximately 42 μm, 58 μm and 46 μm along the outer-layer to the inner-layer are obtained, respectively, as shown in Fig. 6. Thus, the CRCF process could provide an effective theoretical guidance for compact manufacturing in the integrated control of shape and performance of large-scale ring components.



(a) $T=1100$ ℃ (b) $T=1150$ ℃ (c) $T=1200$ ℃

Fig. 3. Distribution of dynamic recrystallization grain size at different initial rolling temperature



(a) $v_r=0.6$ mm/s (b) $v_r=1.0$ mm/s (c) $v_r=1.2$ mm/s

Fig. 4. Distribution of dynamic recrystallization grain size at different feed rate of idle roll

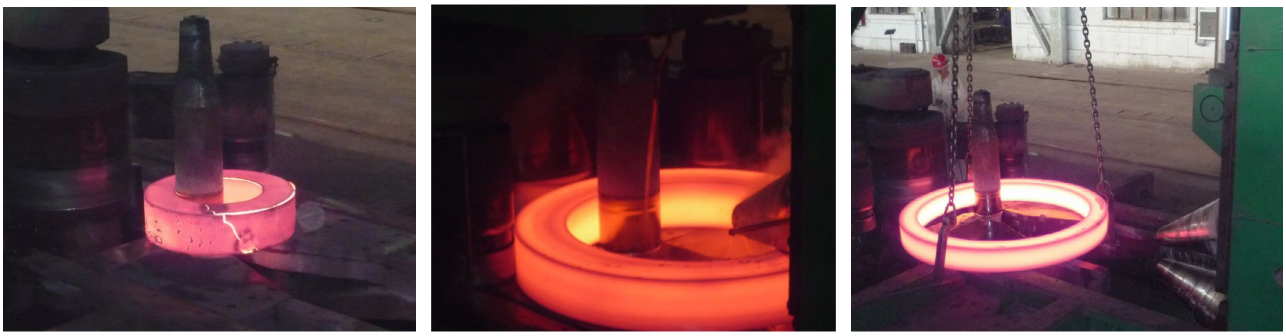
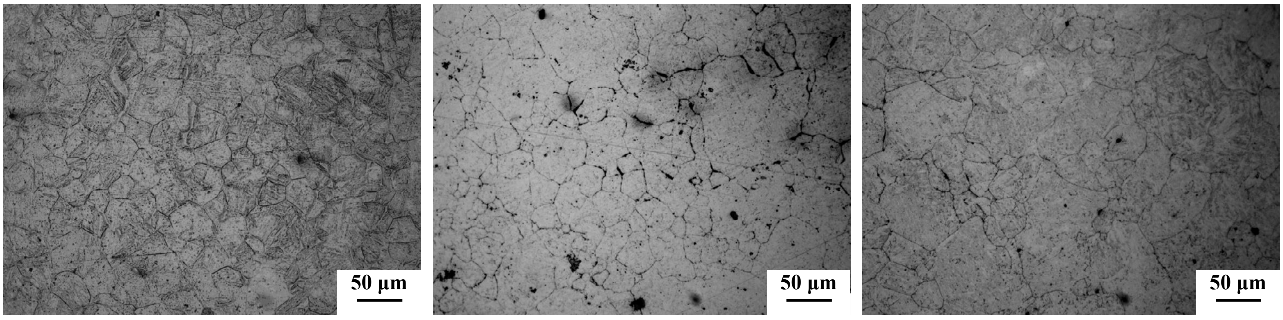


Fig. 5. Hot ring rolling experiments of as-cast 42CrMo steel ring blank

Table 1. Standards and testing data of mechanical properties in CRCF-fabricated 42CrMo bearing ring

Standards and samples number	Tensile strength R_{m}/MPa	Yield strength $R_{\mathrm{p}}0.2$/MPa	Elongation A/%	Reduction of area Z/%	Impact energy at room temperature Akv/J	Hardness HBW	Impact Energy at –40 ℃ Akv/J
JB/T6396–2006	800	550	13	50	35	241–302	—
Q/LYCC(B)0014	800	550	13	50	—	240–280	27
11	1 020	875	9.5	13	—	298	—
12	1 040	930	9.5	19	—	337	—
13	970	830	6.5	9	—	298	—
21	806	635	18	67	—	253	—
22	920	740	19	64	—	258	—
23	875	685	20	64	—	256	—
31	985	840	17	42.5	85.2	317	56.6
32	940	795	17	41	83.7	269	69.2
33	910	770	19.5	54	101.6	288	81.8



(a) Outer-layer (b) Inner-layer (c) Center-layer

Fig. 6. Microstructures in different areas of 42CrMo rolled bearing ring after CRCF

By using the CRCF process, QIAN, et al[53–54], studied the grain evolution rules of as-cast GCr15 bearing steel during HRR, and revealed the effects of the rolling ratio, initial rolling temperature and initial grain size on grain refinement. The derived limit values of through-thickness grain size in final ring could provide guidance for grain refinement controlling of as-cast ring blank during HRR. GUO, et al[55], also established a coupled macro-micro FE model of HRR for as-cast 42CrMo alloy under ABAQUS/Explicit through the user material subroutine VUMAT. It is found that the DRX percentages is high in the outer-layer and inner-layer of the ring resulting in refined grain while relatively low in the center-layer of the ring leading to coarse grain, the DRX percentage increases while the average grain size decreases with the increase of the rotational speed of driven roll, and the rotation speed of driven roll has negligible influence on the uniformity of the average grain size distribution.

Although extensive rewarding findings related to microstructure predicting in HRR have been achieved, most works adopted the microstructure evolution models based on an empirical formula. The complex interaction between microstructure evolution and performance is neglected[56], which results in a low level numerically prediction methods. In addition, the testing verification only focused on the relationships among processing parameters, grain size and performance of the rolled ring. Thus, it is urgently to develop a new method of microstructure predicting and performance controlling during HRR. RYTTBERG, et al[57], analyzed the development of microstructure and texture during cold ring rolling of 100Cr6 steel rings with starting rectangular cross-sections by employing SEM and electron backscatter diffraction(EBSD) techniques. The carbides refinement is most severe near the inner-layer of the ring decreasing towards the region of the outer-layer. The α-fiber texture with intensity of 8.76 near the center-layer and γ-fiber texture with intensity of 8.76 near the outer-layer are mainly depended on the compressive deformation, while {110} texture near the inner-layer is related to shear deformation. By employing industrial experimental techniques, our group studied the grain and texture evolution rules of as-cast 25Mn steel ring blank during HRR process (Fig. 7), and analyzed the mechanical properties in different areas after CRCF. The dimensions of as-cast ring blank and rolled flange product are ϕ670 mm× ϕ326 mm×128 mm and about ϕ1470 mm×ϕ1306 mm× 100 mm, respectively. The microstructure is characterized by refined grains with homogeneous distribution, but a little of irregular grain is also observed in individual area, as shown in Fig. 8[47, 58]. The texture are mainly composed of {111}<112> component distributed along <111>//ND and Goss {110}<001> component with orientation density of 6.0, as presented in Figs. 9–10[47, 59]. It can also be found from Table 2, the strength and hardness of the

CRCF-fabricated 25Mn steel large-scale flange are higher than the standards, while the plasticity and toughness are relatively low, which can be obviously improved through subsequent quenching and tempering(Q&T) process[58].

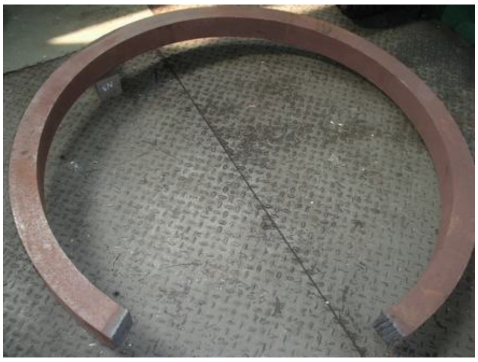


Fig. 7. 25Mn steel large-scale flange after CRCF

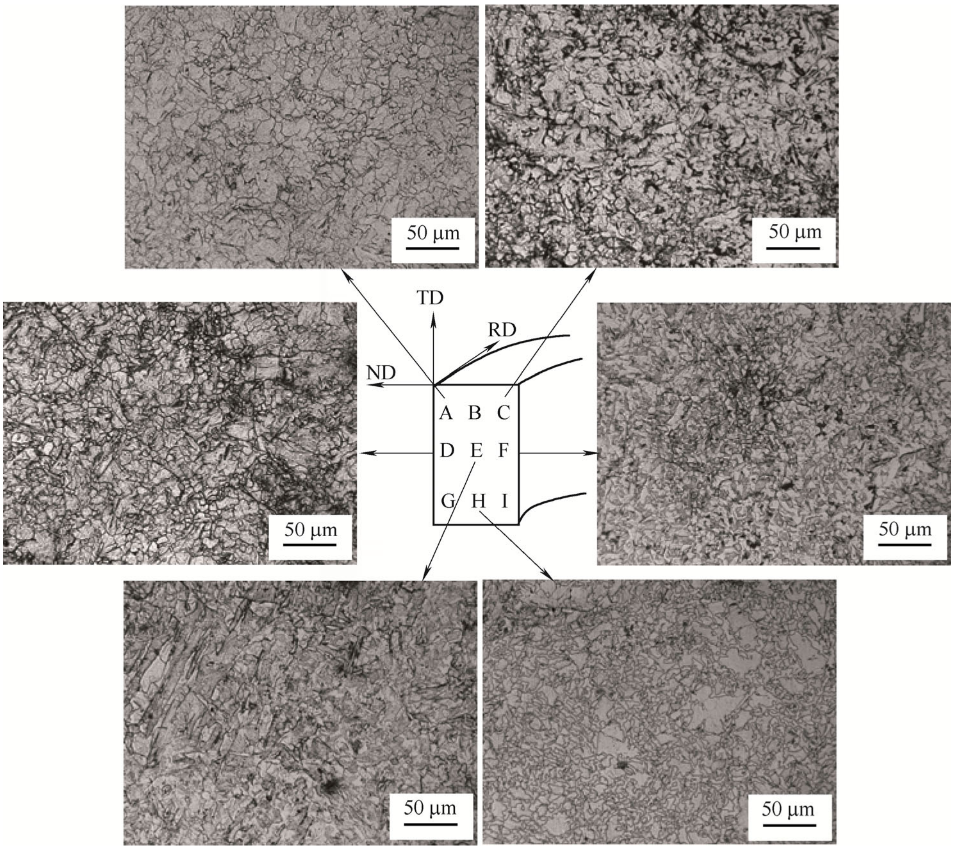
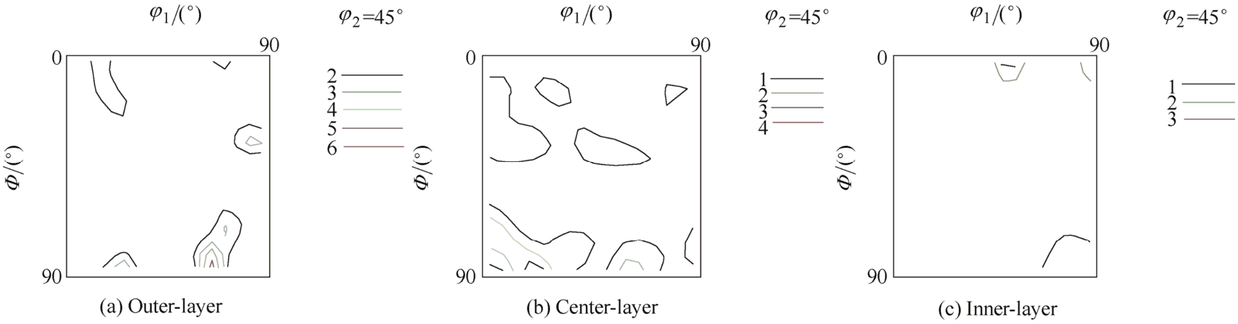


Fig. 8. Microstructures of as-cast 25Mn ring blank in different areas after CRCF (RD, rolling direction; TD, transverse direction; ND, normal direction)



(a) Outer-layer (b) Center-layer (c) Inner-layer

Fig. 9. φ_2=45° sections of ODF of as-cast 25Mn ring blank after CRCF

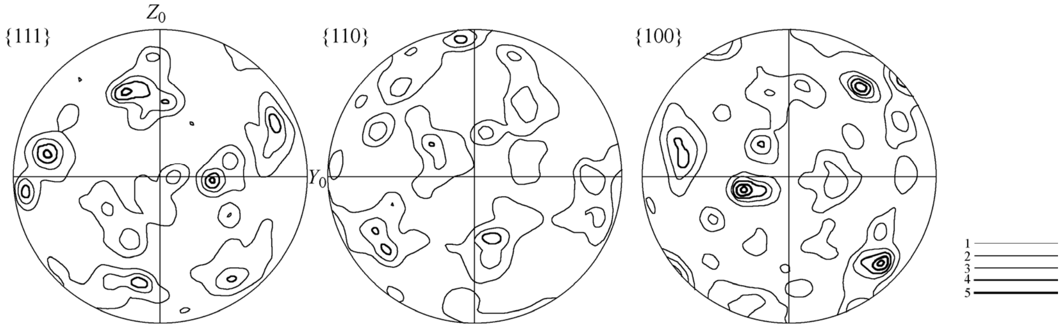


Fig. 10. Pole figures of 25Mn steel large-scale flange after CRCF(1-5 denotes textural orientation densities)

Table 2. Standards and testing data of mechanical properties in CRCF-fabricated 25Mn large-scale flange

Standards and samples		Tensile strength R_m/MPa	Yield strength $R_p0.2$/MPa	Elongation A/%	Reduction of area Z/%	Impact energy at room temperature Akv/J	Hardness HBW
GB/T1222.8–2006		490	295	22	50	71	207
	Inner-layer	551	315	23.4	52.4	43	149
Rolled ring	Center-layer	543	303	23.2	42.7	39	145
	Outer-layer	553	318	25.4	55.4	47	153
Q&T ring		570	387	27.6	65.10	101	182

However, thus far, the effect mechanisms of texture evolution on grain refinement and plasticity and toughness improvements of as-cast ring blank in HRR process are unclear. Additionally, whether the as-forged blank or the as-cast blank before HRR, the complicated strain/stress state in HRR process results in complicated texture evolution, which influences, in turn, the deformation and thus the performance of the rolled ring[60]. Therefore, the key sciencific problems related to the integrated manufacturing for shape and performance controllability of large-scale ring components during HRR need to be addressed in the further investigation, as follows:

(1) To clarify the effect mechanisms of key rolling parameters especially feed rate of idle roll, initial and finishing rolling temperatures on the microstructure evolution and grain orientation of as-cast ring blank.

(2) To establish the microstructure evolution models by performing complex multi-pass compression tests, which are suited to HRR with characteritics such as multi-pass and accumulative deformation. And the deformation mechanism in HRR through the whole thickness of the final rings should be revealed.

(3) To improve the methods of testing and characterization in performance of the final rings by means of SEM, TEM, EBSD and situ-EBSD techniques, and to develop the relationships among processing parameters, microstructure, texture and mechanical properties.

3 Compact Manufacturing for Duplex-metal Composite Rings

The rapidly growing areas of high-tech equipments such as petrochemical, ship and automobile results in single-metal ring components are difficult to meet the served performance in extremely conditions. For example, under the environment of high wear or corrosion, the ring components not only concern the properties of base material itself in ring part, but also adopt alloy materials with characteristics such as wear-resistance and resistance to corrosion. Thus, it is urgently needs to study the manufacturing theory and technology of duplex-metal composite rings with different properties.

The duplex-metal composite rings are commonly fabricated by base and clad materials through mechanical connection or metallurgy reflection. Comparing to single-metal ring components, the bonding properties including physics, chemical and mechanical properties are superior leading to replace the precious single-metal ring. The current manufacturing process for duplex-metal composite rings is as follows[61]:

(1) To produce two single-metal rings respectively by cogging, upsetting, punching.

(2) To assemble concentrically two single-metal as-forged rings.

(3) To obtain the duplex-metal composite ring by cold ring rolling.

The poor stability of ring rolling exists resulting in the end face warping in axial direction of the composite ring during the current process. In the cold ring rolling, the bonding strength of interface is low due to completely mechanical connection, which can not meet the manufacturing requirements for high-performance duplex-metal composite rings. In addition, the process is complex with characteristics such as difficult to preform, huge cost and considerable wasting material and energy. However, an increasing attention has been attracted firstly by the roll-bonding of the duplex-metal composite plates including carbon steel/stainless steel composite plate[62–63], carbon steel/Al composite plate[64–66] and Mg/Al composite plate[67–68]. The influences of processing parameters such as rolling temperature and reduction on bonding strength, microstructure and elements diffusion are analyzed in detail, and the interface bonding mechanisms are revealed[66, 68–69].

To overcome the above disadvantages, a novel compact manufacturing technology of high-performance duplex-metal composite ring components is proposed by our team[70]. Taking Q345B as base material and 40Cr as clad material for example, the key steps are as follows:

(1) To smelt Q345B steel and 40Cr steel respectively, and control the tapping temperature of 1650–1680 ℃ for Q345B and 1600–1630 ℃ for 40Cr.

(2) Preheat the casting mould at 150–180 ℃, pouring gate and pouring ladle at 250–300 ℃.

(3) Casting 40Cr clad layer: pouring at 1520–1530 ℃, control the rotate speed of casting mould at 204–250 r/min and pouring speed at 24.5–26.5 kg/s, then casting base layer with 27–30 s interval time.

(4) Casting Q345B base layer: pouring at 1550–1570 ℃, control the rotate speed of casting mould at 220–299 r/min and pouring speed from equal or higher than 25.7 kg/s reducing to 20 kg/s, control the rotate speed of casting mould at 170–220 r/min after pouring.

(5) Depanning at the surface temperature of the composite ring blank cooled to 1000–1050 ℃.

(6) Temperature-compensation: at the temperature of 1230–1250 ℃ with 2.5–3 h holding time.

(7) HRR: the initial rolling temperature and finishing rolling temperature are 1150±10 ℃ and 900±10 ℃, respectively.

Thus, the problems, such as the low interface bonding strength, poor qualities, low-efficiency, wasting material and energy, existing in the current process can be efficiently addressed. And the critical scientific problems based on this entire new process consist of the centrifugal casting of duplex-metal composite ring blank, and the HRR of as-cast duplex-metal composite ring blank. So it is important to research on the following issues in the further development:

(1) To reveal the interface diffusion and bonding mechanisms during casting, the relationship of solidification parameters with diffusion state and composition homogenization should be clarified. And the pouring temperature, pouring speed and interval time of base and clad layers during centrifugal casting also should be optimized.

(2) To reveal the interface grain refinement mechanisms of as-cast duplex-metal composite ring blank during hot compression, the effect of deformation parameters on recrystallization should be analyzed in-depth. And then the recrystallization and grain growth models in the interface are established.

(3) To study the mechanisms of microstructure evolution and performance controlling of as-cast duplex- metal composite ring blank during HRR, the rules of solid-state diffusion and grain refinement should be clarified, and then to realize a close bonding between base and clad layers.

Finally, the technique of HRR for centrifugal casting duplex-metal composite ring blank and its quality controlling can be developed, and the purpose of compact manufacturing for shape and performance controllability can be achieved.

4 Compact Manufacturing for Railway Wheels

Railway wheels are a critical component to railway system, and mainly as the function of supporting, traction, guiding and braking. The railway wheels usually are huge in mass(mass: 330–450 kg, and diameter: Φ500–Φ1300 mm). To meet the high speed and heavy haul, the railway wheels have an increasing demand for safety simultaneously, high-performance and high-quality during the operation[71].

In the current, the railway wheels are composed of cast steel wheels and rolled wheels. The process of cast steel wheels with high carbon content is given by: smelting, pouring in graphite casting mould, heat treatment, and machining. The process is mainly adopted by Abex and Griffin manufacturers. The plasticity and toughness are poor in spite of its superiorities in simplicity, low energy consumption and precise geometrical dimensions of cast steel wheels. Thus, the cast steel wheels are applied only to freight trains, instead of high speed and heavy hual trains. The process of rolled wheels with low carbon content and alloying elements is as follows: smelting, continous casting round blank, heating, upsetting, punching, heating, hot rolling, bending, and heat treatment, as presented in Fig. 11. The process of rolled wheels is widely used in many wheel manufacturers such as Sumitomo, Valdunes, Lucchini, Standard Steel and Masteel in China, etc. WARD, et al[72], determined the influences of material allocation and die structure on geometrical dimensions and mechanical properties of railway rolled wheel in the entire manufacturing process. SHEN, et al[73–74], proposed an axisymmetric model for the wheel rolling process to predict the metal flow in radial direction, and then investigated the microstructure evolution of CL50D railway wheel during hot forming process. Under the current railway wheel forging process, the distribution in grain size is inhomogeneous, and a narrow coarse grain zone between the external part and center of the hub is caused by SRX[74]. ROBLES, et al[75], analyzed the effects of initial pearlite and bainite microstructures on high-performance rolled wheels, and carried out the verification tests in heavy hual lines. For the purpose of developing a railway wheel steel with a good combination of strength and toughness, an improved wheel steel containing high contents of Si and Mn and a low content of Cr is developed[71]. The results show that the improved steel is hardened by solid solution strengthening and refinement of pearlite interlamellar spacing, while the impact absorbed energy is raised by increasing the proeutectoid ferrite fraction. In addition, extensive researches on the fracture toughness, rolling contact fatigue, thermal cracks and residual stress of rolled railway wheels have been done[76–79]. Although the rolled wheels with characteristics such as dense microstructure and sound mechanical properties, the disadvantages including long-period, huge cost, considerable wasting material (about 20%) and energy are obvious. Thus, it has become a challenging research direction how to develop the combination merits in the manufacturing technologies for the cast wheels and rolled wheels.

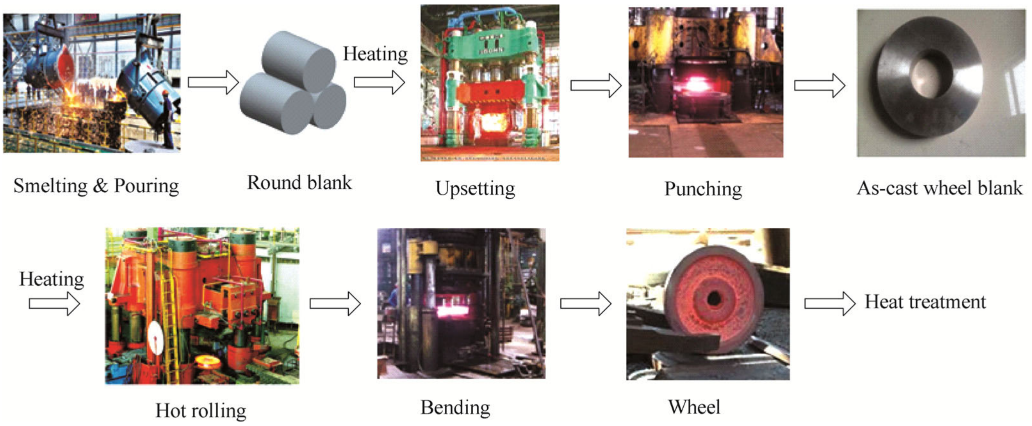


Fig. 11. Traditional manufacturing process of rolled railway wheels

Lately, a compact manufacturing technology, namely near solid-state pressure forming of railway wheels, is proposed by our team, as shown in Fig. 12[80]. The process contents are described as below:

(1) Melting: the raw material with a small amount of microalloyed element is smelt by 50tUHP-type electric-arc furance.

(2) Casting wheel blank with metal mold at the temperature of 1540–1560 ℃, and real-time monitor the volume fraction in solid phase.

(3) Near solid-state pressure forming through 80MN-type hydraulic machine with the pressure of 65–70 MPa and the ram speed of 35–40 mm/s when the volume fraction in solid phase reaches to 60%–70%.

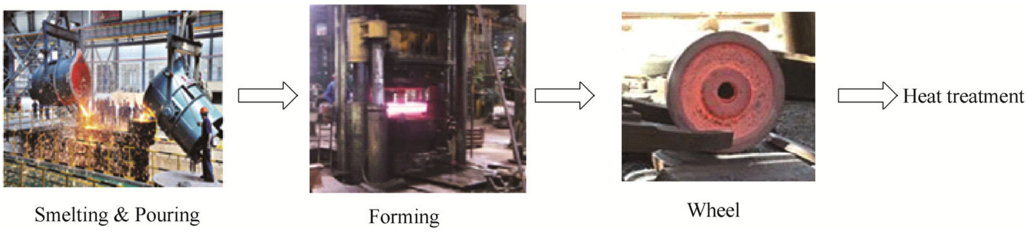


Fig. 12. Near solid-state pressure forming process of railway wheels

The following key issues for macro/micro-structure and high-performance based on the entire manufacturing process need to be solved in the further development of this technique:

(1) To control the crystallization velocity of railway wheel blank during pouring in metal mold.

(2) By controlling precisely the volume fraction in solid phase, the low-density defects due to insufficient feeding can be avoided.

(3) To clarify the mechanism of grain refinement in the rim and disk areas of railway wheel during pressure forming.

5 Casting-extruding Continuous Forming of Large-diameter Thick-walled Pipes

Large-diameter thick-walled pipes with the sizes of over 300 mm in outer-diameter and 20 mm in wall thickness based on alloy steels, stainless steels and difficult-to-deform alloys are a critical component to nuclear power and petrochemical industries. The manufacturing technique commonly used in large-diameter thick-walled pipes is mainly vertical extrusion process. The traditional process consists of melting, casting ingot, cutting, heating, pre-upsetting, heating, upsetting, punching, heating, hot extruding, and machining, as shown in Fig. 13. Considerable studies on hot extrusion deformation behavior of large-diameter thick-walled pipes have been conducted. ZAIKA examined the mechanical properties and defects of 08X18H10T corrosion-resistant steel thick-walled pipe fabricated by centrifugal casting[81]. SU, et al[82], found the mehanical properties of HR3C stainless steel pipe are improved through three-dimensional compressive stress during hot extrusion. DANG, et al[83], analyzed the effects of extrusion speed V, initial blank temperature T_b and friction coefficient on the average grain size and grain uniformity of Inconel 625 pipe based on a thermal-mechanical and macro-micro coupled FE model. The influence sequences of T_b, V and extrusion ratio λ to the average grain size and grain uniformity were also clarified through hot extrusion process of large-scale thick-walled 304 stainless steel pipe, namely $T_b>\lambda>V$ and $T_b>V>\lambda$[84]. GUO, et al[85], identified suitable extrusion processing windows for Inconel 625 pipe, and disclosed the coupled effects of key extrusion parameters on the temperature rise and peak temperature. In addition, the extrusion force, lubrication condition and die structure are also investigated in detail[86–88].

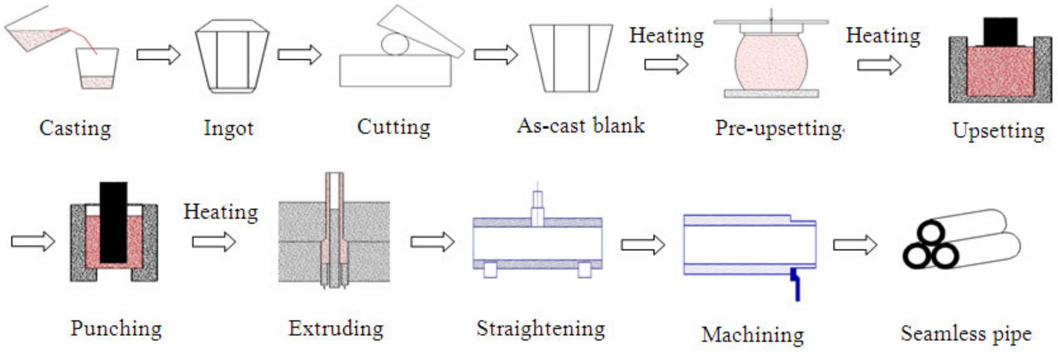


Fig. 13. Traditional process for producing large-diameter thick-walled pipe

However, the as-forged blank is adopted before hot extrusion in the all above studies, which results in multi-pass heating, low-efficiency, high cost and high-emission. Thus, a casting-extruding continuous forming of large-diameter thick-walled pipes is developed by our group, as presented in Fig. 14[89–90]. The key steps and research contents are as follows:

(1) Melting: the raw material is smelt by medium-frequency induction furance.

(2) Casting pipe blank: pouring at the temperature of 1590–1610 ℃ with the neck riser, depanning at the surface temperature of the pipe cooled to 1280–1330 ℃.

(3) Hot extruding in vertical extrusion machine with the remained heat of 1200–1250 ℃ in the surface of casting pipe blank, and control the extrusion speed of 300–400 mm/s and extrusion ratio of 10–12.

(4) Machining.

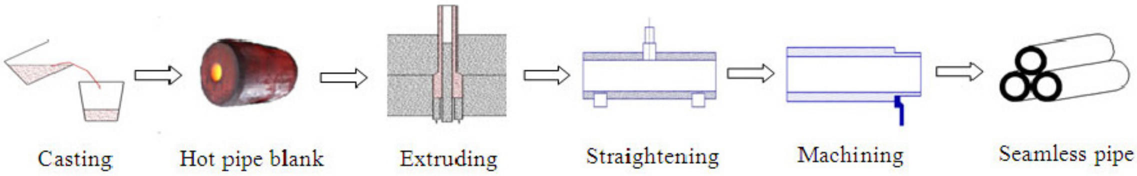


Fig. 14. Casting-extruding continuous forming process for producing large-scale thick-walled pipe

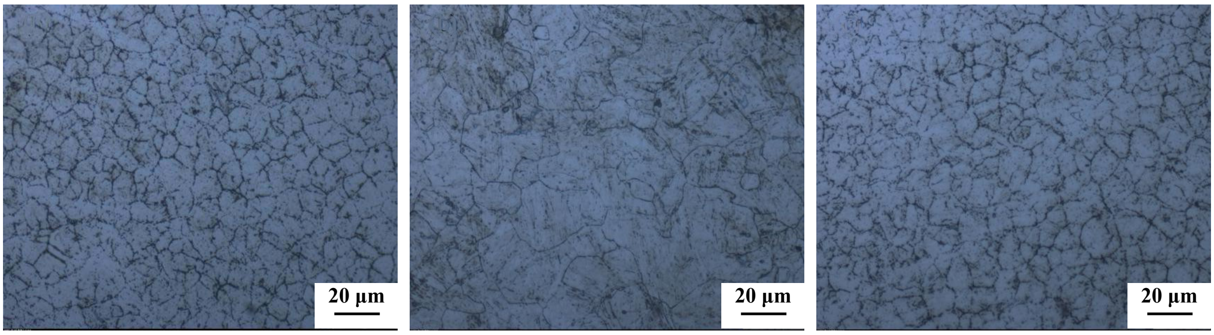
In recent years, our team studies on the compact manufacturing process of large-diameter wall-thickness pipes based on the as-cast hollow blank. The constitutive equations and recrystallization models of as-cast P91 steel are derived by analyzing its microstructure evolution at different temperatures and strain rates during hot compression, as presented in Fig. 15[91–92]. The hot extrusion behavior and extrusion force of large-diameter thick-walled P91 pipe with a size of Φ720 mm×Φ520 mm×12000 mm are analyzed by the principal stress method. Then the effects of initial extrusion temperature and extrusion speed on the stress/strain distribution and the average grain size are numerically clarified using FEM. From Figs. 16 and 17, it can be seen that the average grain size decreases with the increase of extrusion temperature and extrusion speed[93]. This is mainly due to the fact that the DRX occurs in those conditions. And the relatively homogeneous distribution of average grain size is shown in the initial extrusion temperature of 1150 ℃ and extrusion speed of 26 mm/s. However, the obtained results are insufficient to reveal the mechanism of shape and performance controllability of large-diameter thick-walled pipes. Thus, the following main problems for macro/micro-structure and high performance based on the entire manufacturing process should be solved in further development:

(1) To obtain the thermodynamic conditions related to as-cast coarse microstructure transfering to as-forged fine and homogeneous microstructure during isothermal and non-isothermal hot compression.

(2) To realize integrated manufacturing of macro/ micro-structure and performance for as-cast hollow pipe blank during hot extrusion through the combination of metal flow with microstructure evolution rule in the deformation regions.

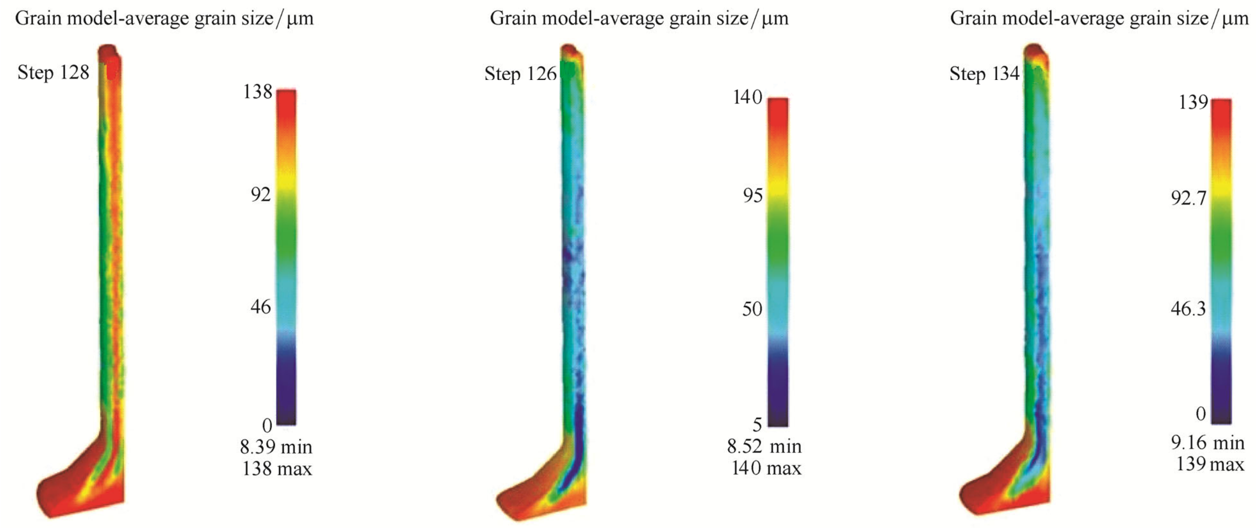
(3) The influence mechanisms of key processing parameters and die structure on the qualities of extruded pipe should be clarified by industrial experiments, and then

to derive the optimum processing parameters.



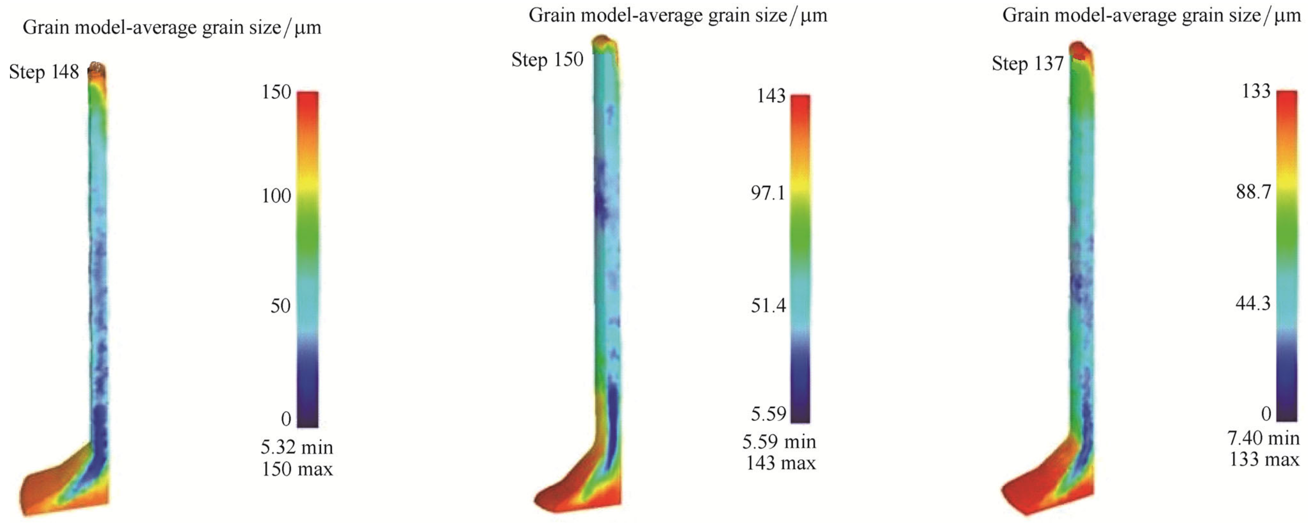
(a) 1100 ℃/0.05 s^{-1} (b) 1150 ℃/0.05 s^{-1} (c) 1100 ℃/0.1 s^{-1}

Fig. 15. Microstructures of as-cast P91 pipe blank at different compression conditions



(a) T=1100℃ (b) T=1150℃ (c) T=1200℃

Fig. 16. Average grain size of as-cast P91 steel pipe blank at different initial extrusion temperatures



(a) v=16 mm/s (b) v=26 mm/s (c) v=36 mm/s

Fig. 17. Average grain size of as-cast P91 steel pipe blank at different extrusion speed

6 Conclusions

To realize the high-performance and high-reliability of large-scale components and the simplification in fabrication process, the compact manufacturing in the integrated control of shape and performance for components were studied. The conclusions can be drawn as follows:

(1) Focused on the high-performance large-scale components such as bearing rings, flanges, railway wheels, thick-walled pipes, etc, the conventional manufacturing processes and their developing situations are summarized. The existing problems including long production period, multi-pass heating, wasting material and energy, high cost, low-efficiency, and high-emission are identified, and the present study unable to meet the green manufacturing in high-quality components is also pointed out.

(2) The new techniques related to casting-rolling compound precise forming of rings, compact manufacturing for duplex-metal composite rings, compact manufacturing for railway wheels and casting-extruding continuous forming of thick-walled pipes are introduced in detail, respectively. The corresponding research contents, such as casting ring blank, hot ring rolling, near solid-state pressure forming, hot extruding, are emphatically elaborated. Some research findings in through-thickness microstructure evolution and mechanical properties are also presented. The components produced by the new techniques are mainly characterized by fine and homogeneous grains.

(3) The introduced manufacturing processes have become a high-end plastic forming technique with many advantanges over the traditional one in reducing times of heating, considerable saving material and energy, high-efficiency, low-emission, low cost, etc. And the fabricated large-scale components possess precise geometrical dimensions (shape) and excellent mechanical properties (performance). In addition, the possible directions for further development of those techniques are suggested.

(4) The key scientific problems for macro/micro-structure and high-performance based on the entire manufacturing process are first proposed. The challenging issues related to correlate the mechanical properties with the through-thickness microstructures urgently need to be solved in the future. All of these results and conclusions have reference value and guiding significance for the integrated control of shape and performance of large-scale components in advanced compact manufacturing.

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