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Spray formed bearing steel insensitive to distortion

Part I *Material characterization*

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To minimize the distortion of bearing steel components during manufacturing processes, 100Cr6 steel (SAE 52100) has been produced by spray forming as an alternative approach to conventional continuous casting process. Material characteristics and distortion behavior of the spray formed 100Cr6 steel were investigated in comparison with continuous cast material. The investigation showed that the spray formed 100Cr6 steel exhibited less distortion potential than the conventional material due to much better metallurgical homogeneity.

1. Introduction

Distortion of steel components during manufacturing processes such as machining and heat treatment is fairly common, and the compensation for distortion failures is very cost and time consuming [1]. Quenching process typically is regarded as the responsible process for distortion. However, more and more recent investigations have shown that the distortion of a component is not only depending on this single process, actually it is only a release of distortion potential which has been accumulated from the raw material to the final product throughout the entire production chain [2–7]. The metallurgical quality of the raw material may play an important role on the distortion behavior of the component because it has a dominating influence on the phase transformation process and associated volume change during heat treatment.

The conventional manufacturing process of the raw materials for bearing industry is continuous casting. Chemical inhomogeneity of the continuous cast material was found to be responsible for the distortion of the finished components [5]. Improvement of material homogeneity is believed to make a contribution to the reduction of distortion. Spray forming, an advanced rapid solidification and preforming process, is capable to produce homogeneous materials with less distortion potential. From this point of view, this process was adopted in this investigation to make bearing steel 100Cr6 for the production of specimen of ring shape, which is a typical geometry of bearing components. Material characteristics and distortion potential of the spray formed 100Cr6 steel were studied in comparison with continuous cast material. In the first part of this study, the metallurgical quality of the spray formed 100Cr6 throughout the production chain was illustrated and evaluated. In the second part, the investigation focused on the distortion of the spray formed ring specimens.

2. Experimentals

2.1. Raw material

A bearing steel 100Cr6 (SAE52100), consisting of 0.93–1.05 C, 0.15–0.35 Si, 0.25–0.45 Mn, 1.35–1.60 Cr, <0.025 P, <0.015 S (wt%), was used as the raw material for spray forming of billets.

2.2. Production process

2.2.1. Spray forming

The spray forming experiments were performed on a pilot scale spray forming facility at the University of Bremen. This facility was equipped with an inductive melting furnace where the raw material could be heated up to a temperature of 1750°C. To avoid oxidation, the melting procedure was carried out in a separate vessel under protective atmosphere (nitrogen). The melt stream was gas atomized by a scanning free-fall atomizer using nitrogen at a pressure in the range of 0.40–0.45 MPa corresponding to gas flow rates of 0.29–0.32 kg/s. The metal flow rate was adjusted from 0.2 to 0.3 kg/s by the diameter (4 or 5 mm) of the pouring nozzle at the bottom of the tundish. Cylindrical billets were spray formed on a tilted rotating steel disc with a tilting angle of 30° and a withdrawing speed of 0.65–0.85 mm/s. The spray formed billets have a total height of 300–350 mm, diameter about 170 mm and weights of 50–60 kg, depending on the spraying

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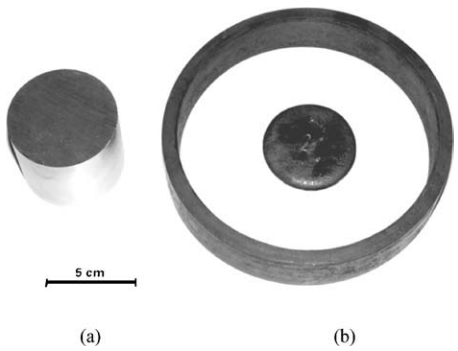


Figure 1 (a) Cylinder machined from the hot rolled 100Cr6 and (b) the forged/rolled ring preform.

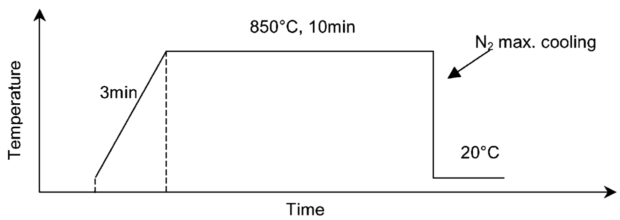


Figure 2 Dilatometer test procedure of spray formed 100Cr6 steel.

parameters. The billets were cross-sectioned at the top (about 60 mm to the top surface) and bottom (about 50 mm to the base) to discs of 10 mm thickness for microstructure examination and density measurement.

2.2.2. Hot rolling

To eliminate the porosity in the deposits, the spray formed 100Cr6 billets were hot rolled at a lab rolling mill to bars around 60 mm in diameter. The porous surface of the billets was removed by peeling to avoid cracking during hot rolling. For the hot rolling procedure, the middle parts of the billets were heated in a furnace at 1250°C for 1.5 h, and hot rolled in 7 passes in the temperature range of 1240–920°C to the final shape and size. The total area reduction ratio is 5 to 6. Small cylinders for ring production were cut and machined from the rolled bars (see the sample on the left side in Fig. 1).

2.2.3. Ring production

To make specimens in the shape of a ring, the small cylinders machined from the hot rolled 100Cr6 bars were forged and ring rolled under the processing condition of heating in a furnace in the temperature range of 1160–1200°C for 20–40 min and forging and ring rolling at 1100–1200°C. The detailed production process of ring preforms is described in [8, 9]. Picture of a ring preform made from the spray formed 100Cr6 steel is shown in Fig. 1. The dimensions of the preform are: 151 mm outside diameter, 130 mm inside diameter, and 32 mm height. The small piece inside the ring preform is the punched-off part from the cylinder on the left side in the hollow forging process.

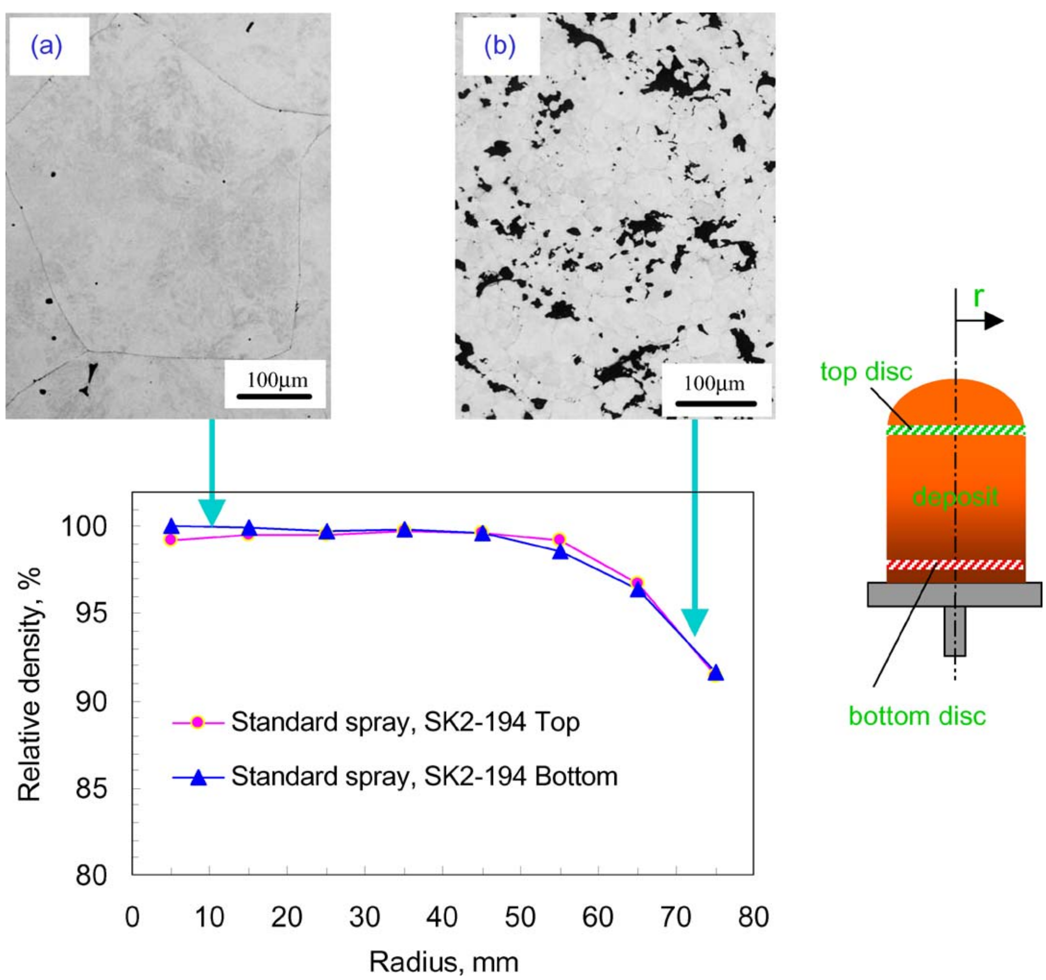


Figure 3 Typical relative density distribution and grain structure of spray formed 100Cr6 billet.

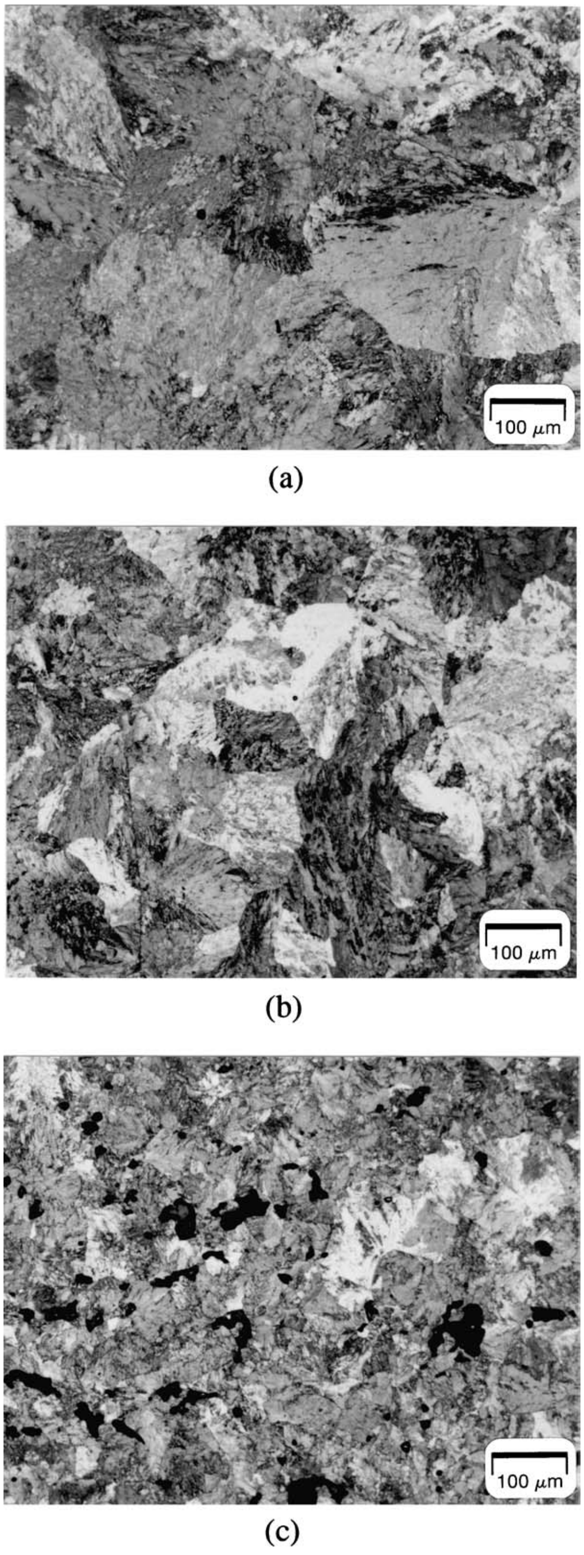


Figure 4 Typical pearlitic structures of spray formed 100Cr6 billet in the areas of (a) center, (b) half radius, and (c) periphery.

2.3. Material analysis

Immersion method based on Archimede's principle was used for density measurement. Optical emission spectrometry (ARL, Typ34000C7B) was used to analyse the distribution of chemical composition in the spray formed 100Cr6 steel. X-ray diffraction techniques were used to detect the texture, residual stress and phases of the spray formed 100Cr6 steel. The measurement instruments, procedures and sample preparation are described in detail in [8]. Optical microscopy (Axiophot,

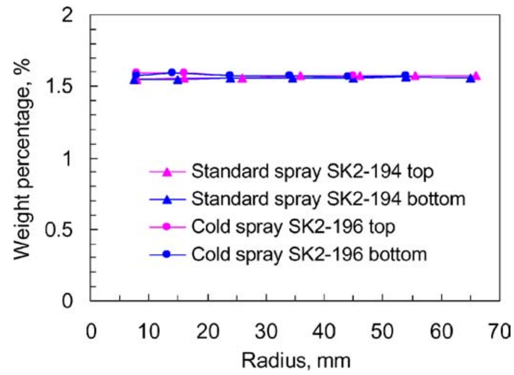


Figure 5 Chromium distributions of spray formed 100Cr6 billets.

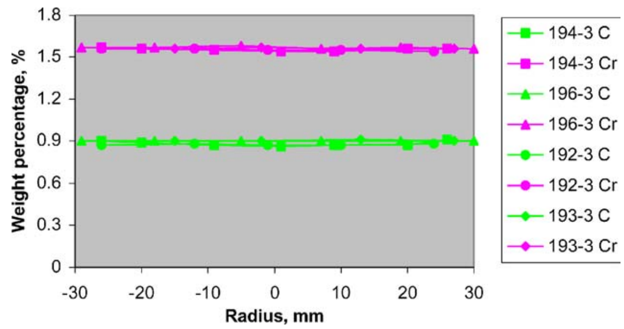


Figure 6 Distribution of C- and Cr-contents in the hot rolled 100Cr6 from spray formed billets.

ZEISS) was conducted on the spray formed billets, hot rolled bars as well as the ring preforms. The etching agent (Nital) was used to reveal the morphology of pearlite phase. Primary austenite grain boundaries in the bearing steel were revealed by etching with picric acid at 50°C for 10 min. Dilatometer test (DIL 805, BAHR Thermo analyze) was carried out to examine the martensite transformation temperature M_s of the spray formed 100Cr6 steel according to the procedure in Fig. 2. Cylindrical specimens of $\phi\, 4 \times 10$ mm were prepared from the center as well as from the periphery of the hot rolled materials after spheroidizing treatment.

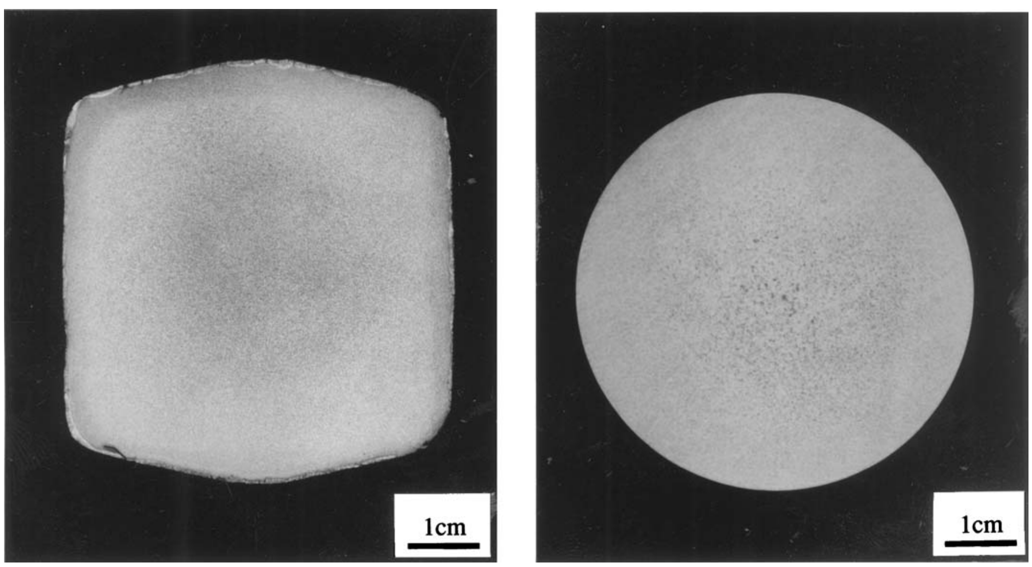
3. Results and discussion

3.1. Material characterization of spray formed 100Cr6 billets

Fig. 3 shows the typical radial density distribution and grain structure of the spray formed billets. Two characteristics can be noticed: A high density level, better than 99% of the theoretical density of 100Cr6, is determined in the core of the billet. The corresponding cross sections show only isolated pores (photo a). In contrast, the peripheral area of the billet is characterized by the appearance of an increasing amount of large and irregular shaped pores (photo b). The radial density distribution of the billet is evidently associated with its cooling and solidification conditions in the spray forming process. It is known from previous work [10–13] that the radial temperature distribution in a billet is nonuniform with a higher temperature in the core and a lower temperature at the periphery in the spraying period. The core of the deposit cools and solidifies very slowly, whereas the periphery undergoes a much faster cooling and solidification process. The cold rim of the deposit apparently has a chilling effect on the new adding layer, like that in the vicinity of substrate, resulting in a large amount of interstitial porosity in that region [14]. On the other hand, sufficient residual liquid in the larger mushy zone in the center of the deposit helps to eliminate such kind of pores, as reported in [15–17]. In addition, the primary austenite grain size shows a similar tendency of distribution as the porosity, i.e., in the center of the billet it is relatively large (in the range of 300–400 μm), whereas at the periphery it decreases to about 100 μm due to high cooling and solidification rate as well as high content of porosity that also acts as barrier of grain growth.

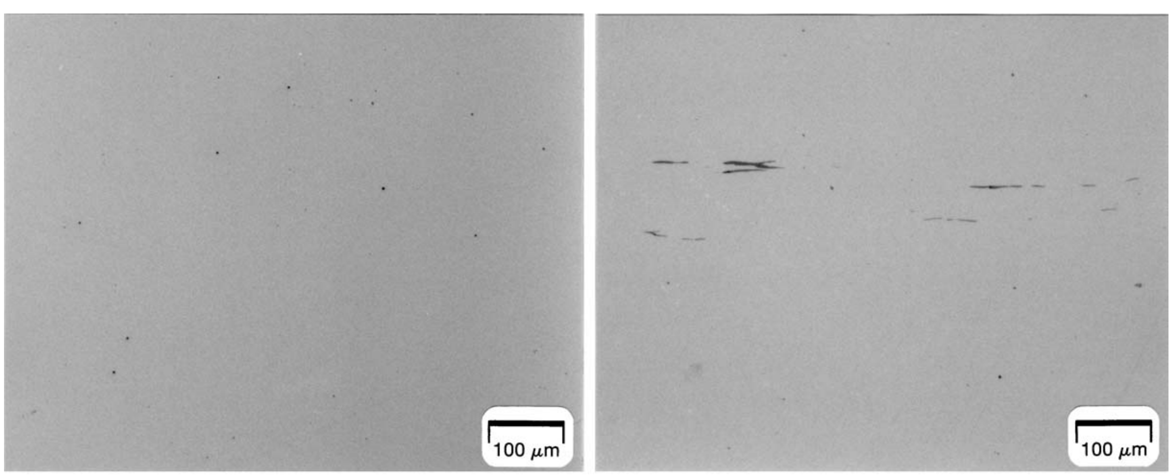
Typical microstructures of the as-deposited 100Cr6 steel in different areas of the billet are shown in Fig. 4. They all show equiaxed pearlitic microstructures with precipitates of fine carbides at the primary austenite grain boundaries. The pearlite blocks are not uniformly distributed along the radius of the deposit, obviously related to the different cooling and solidification conditions of the billet in spray forming. Although the metallographic structure is quite different in different regions of the billet, this is not a severe problem on the homogeneity of material because normally the spray deposited billet must be densified by hot working process like hot rolling. The grain structure will be deformed to a large extent and much more homogeneous and finer grain structures could be obtained finally (see the following section).

Moreover, chemical composition (C, Si, Mn, P, S, Cr) was analyzed on the discs taken from the top and bottom of the spray formed billets, showing that the composition distributions are very homogeneous in the radial direction of billet and also in the height direction. Distributions of chromium in the spray formed billets are shown in Fig. 5. No macro-segregation has been found in the spray formed material, no matter what processing condition it experienced. Because most droplets in the spray are partly solidified before deposition and cool rapidly on impingement, no macro-flow of the residual melt and restrained solute diffusion in the liquid phase occur in the mushy zone of billet. Macro-solute-



(a) (b)

Figure 7 Macro-etching photos of the hot rolled 100Cr6 from (a) spray formed billet and (b) continuous castings.



(a) (b)

Figure 8 Metallurgical integrity of the hot rolled 100Cr6 from (a) spray formed billet and (b) continuous castings.

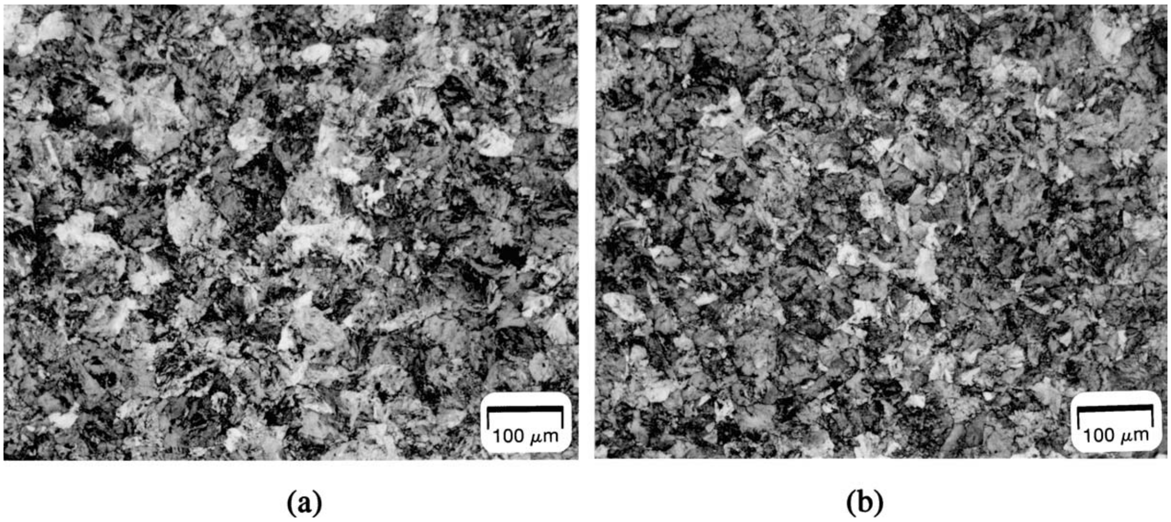


Figure 9 Pearlitic structure of the hot rolled 100Cr6 from spray formed billets: (a) SK2-194 and (b) SK2-196.

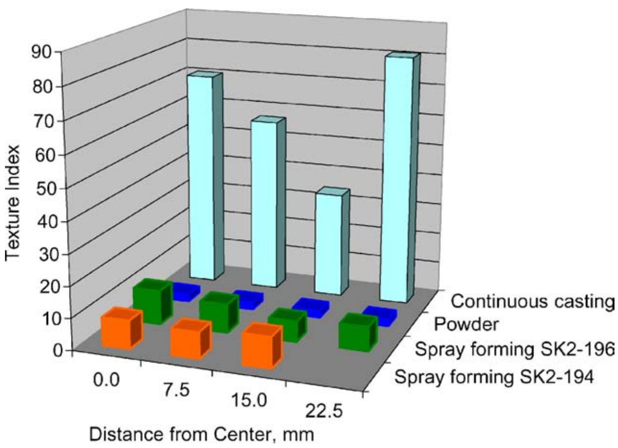


Figure 10 Comparison of texture indices of 100Cr6 steel by different processing.

redistribution that frequently takes place in casting materials is eliminated, and segregation of chemical elements is limited to a narrower micro-section.

3.2. Material characterization of hot rolled 100Cr6 steel

In order to get rid of the porosity in the deposits, hot rolling was applied on the spray formed billets. Density measurement and metallography study demonstrated that the porosity has been eliminated completely by hot rolling. OES measurement (see Fig. 6) and macro-etching (see Fig. 7) on the hot rolled bars from four billets (No: 192, 193, 194, 196) show that the spray formed material is quite homogeneous after hot rolling and no marco-segregation has been detected. On the contrary, nonmetallic inclusions such as MnS are present in the center of continuous cast 100Cr6 bars. Fig. 8 shows the metallographic photos of both spray formed 100Cr6 and continuous cast 100Cr6 in the longitudinal direction of the hot rolled bars at higher magnification, displaying much better metallurgical quality of the spray formed material. It is also noticed that the pearlitic size of the hot rolled materials is greatly reduced due to large degree of deformation and recrystallization in hot rolling, as shown in Fig. 9.

The presence of preferred orientation (texture) can be associated with large anisotropy of mechanical properties [18]. Local textures leading to changes of material properties should be considered to have an effect on distortion. Low level of texture of a material is beneficial for less distortion potential. Fig. 10 shows the texture profile of the spray formed 100Cr6 steel in comparison with the same material processed by continuous casting and powder technology. A term "texture index" is used for determining this profile, which is calculated based

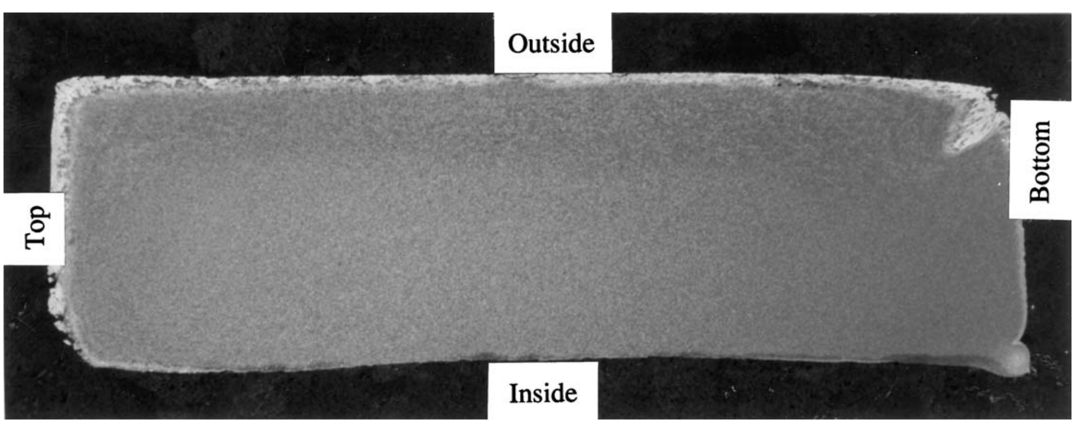


Figure 11 Macrostructures of an as-rolled ring preform made from spray formed 100Cr6.

TABLE I Martensite transformation temperatures of 100Cr6 by different processing

Process	Average value (°C)	Standard deviation (°C)	Maximum value (°C)	Minimum value (°C)
Spray forming	232	3.2	237	228
Continuous casting	231	5.3	240	220

on the Orientation Distribution Function (ODF) analysis (the sum of the squares of the "C" coefficients of the ODF) [8]. For instance, a sample with texture index = 1 is texture free, while a sample with texture index = ∞ is a single crystal. By comparing the texture indices in Fig. 10, it is seen that the spray formed 100Cr6 after hot rolling has a very low degree of texture. The texture index of the spray formed material is normally less than 10, much lower than that of the continuous cast material. Low degree of texture of the spray formed material could be due to the relatively smaller deformation ratio of hot rolling of the billets. For the spray formed 100Cr6, the area reduction ratio is 5–6, while it is as high as 24 for the continuous cast material in this specific example.

The dilatometer test results of specimens taken at different positions of the spray formed 100Cr6 bars after hot rolling and spheroidizing are given in Table I, which shows the M_s point of the spray formed 100Cr6 is about 232°C, independent of the position of sampling. Compared with the continuous cast material, the average value of M_s point of the spray formed 100Cr6 is almost the same, while the standard deviation is smaller. It is well known that the martensite transformation temperature is mainly dependent on the chemical composition of the material, especially on the content of carbon in the matrix, as expressed by an empirical formula [19]:

$$M_s\,(^\circ\mathrm{C}) = 539 - 423\mathrm{C}\text{-}30.4\mathrm{Mn}\text{-}17.4\mathrm{Ni}\text{-}12.1\mathrm{Cr}\text{-}7.5\mathrm{Mo}\ (\mathrm{wt}\%) \qquad (1)$$

If the standard deviation of the measurements is small, the chemical composition (dominantly the carbon element) of the material should be homogeneously distributed. The measurement of M_s point of the spray formed 100Cr6 is consistent with the above OES measurement and with the metallographical results. On the other hand, smaller deviations of M_s values indicates that the phase transformation from austenite to martensite in the same quenching process will be more uniform across the overall quenched parts and result in less distortion.

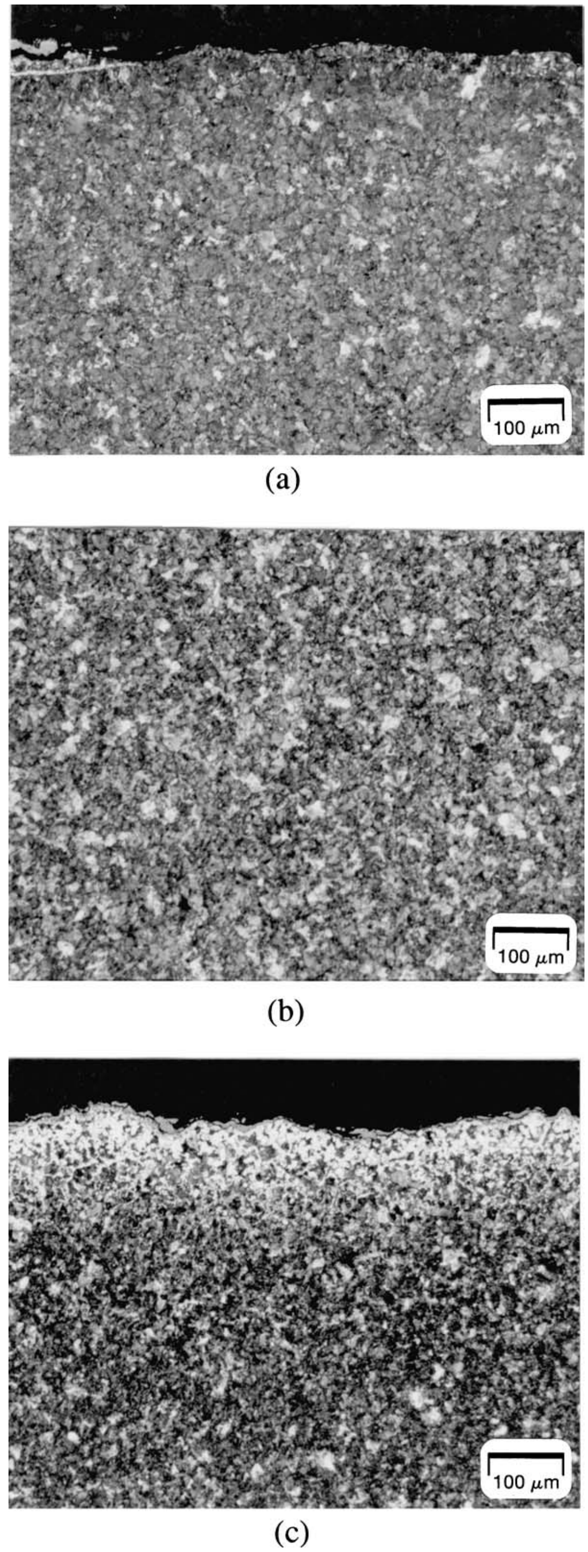


Figure 12 Microstructures of the as-rolled ring preform made from spray formed 100Cr6 at (a) inside surface, (b) middle, and (c) bottom surface.

3.3. Microstructures of 100Cr6 ring preform

Macro- and microstructures of the forged/rolled ring preforms made from the spray formed 100Cr6 were revealed by etching on the cross section of the rings (Figs 11 and 12). It is seen that the microstructures are very homogeneous across nearly all the section, except for the surface area where some zones of oxidation and decarburization exist. These zones will be removed in the subsequent machining process. High degree of material homogeneity is the promising feature of spray formed 100Cr6 steel, indicating this material will be insensitive to distortion.

As reported in the second part of this investigation [20], the ring preforms made from the spray formed 100Cr6 have been machined to the final dimensions and heat-treated in various processes. Distortion behavior of the spray formed rings has been studied compared to continuous cast rings. The residual stress distributions, microstructures and hardness distributions of the ring specimens have been investigated to interpret their distortion behavior.

4. Conclusions

1. Spray formed 100Cr6 billets exhibit macrosegregation free microstructure although the porosity profile and grain structure are not uniformly distributed along the radius of deposit, particularly at the periphery.

2. The hot rolled bars made of spray formed 100Cr6 billets show high metallurgical quality on chemical composition, inclusions, microstructures, texture and martensite transformation temperature.

3. The forged/rolled ring preforms produced from the spray formed 100Cr6 steel show very homogeneous microstructures.

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