Spray formed bearing steel insensitive to distortion

Part II *Distortion behavior*

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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 behaviour of the spray formed 100Cr6 steel were investigated in comparison with continuous cast material. The investigation showed that the spray formed 100Cr6 steel exhibited lower distortion potential than the conventional material due to much better metallurgical homogeneity.

1. Introduction

In the first part of this investigation [1], the material characteristics of spray formed 100Cr6 steel have been studied and evaluated compared with conventional continuous cast material. Metallurgical homogeneity has been identified as an outstanding advantage of the advanced spray forming process. This feature of spray formed material is expected to lead to lower distortion potential since chemical homogeneity of a material was found to have influence on distortion [2]. In the second part of this investigation, the forged/rolled ring preforms produced from spray formed 100Cr6 steel were machined and heat-treated. Distortion behavior of the spray formed 100Cr6 rings has been examined and interpreted based on the investigation of microstructures and residual stresses.

2. Experimentals

2.1. Machining

The forged/rolled ring preforms were prepared by soft annealing and sand blasting for subsequent machining. The dimensions of finished rings are: outer diameter 145 mm, inner diameter 133 mm, height 26 mm. The detailed machining process and parameters are described elsewhere [3, 4]. A special design of clamping system was used for the machining process with 6 contacting points on the outer circumference of the rings for reduction of elastic deformation due to clamping. The configuration of the clamping apparatus is illustrated in Fig. 1. Pictures of the rings made from the spray formed 100Cr6 steel are shown in Fig. 2.

2.2. Heat treatment

The machined rings were heat treated in three separate processes: hardening (850°C, 25 min) using oil quenchant, hardening (850°C, 25 min) using gas quenchant and stress relieving (650°C, 2 h). For the quenched rings, two rings were tempered (200°C, 2 h) additionally to examine the influence of tempering on their distortion behaviour. The heat treatment furnace used for oil quenching and stress relieving is a vacuum furnace (IPSEN, Type RVAFOQ 220-R). The device used for gas quenching was developed at the Institute for Materials Science, University of Bremen [4]. The schematic drawing of gas quenching process is shown in Fig. 3. Three layers of gas nozzles are positioned towards different height of the ring specimen, with 12 nozzles in each layer both at the outside and inside of the ring. The distance from the nozzles to the ring surface is 20 mm. The diameter of gas nozzles is 4 mm, and the distance between two neighbouring nozzles is 30 mm. The distance between two layers of gas nozzles is 8 mm. In the gas quenching process, the gas velocity at the exit of nozzles reaches 100 m/s.

2.3. Distortion measurement

Distortion of the spray formed 100Cr6 steel rings was measured on a 3D-coordinate measuring machine (Leitz PMM654). The inside diameters and outside diameters of the rings were measured at three height positions: 3 mm to the top surface, 3 mm to the bottom surface and the middle height ($z = 13$ mm).

2.4. Material analysis

X-ray diffraction techniques were used to detect the residual stress and the amount of retained austenite of the spray formed 100Cr6 steel [4]. Optical microscopy was conducted on the rings after heat treatment. The etching agent (3% Nital) was used to

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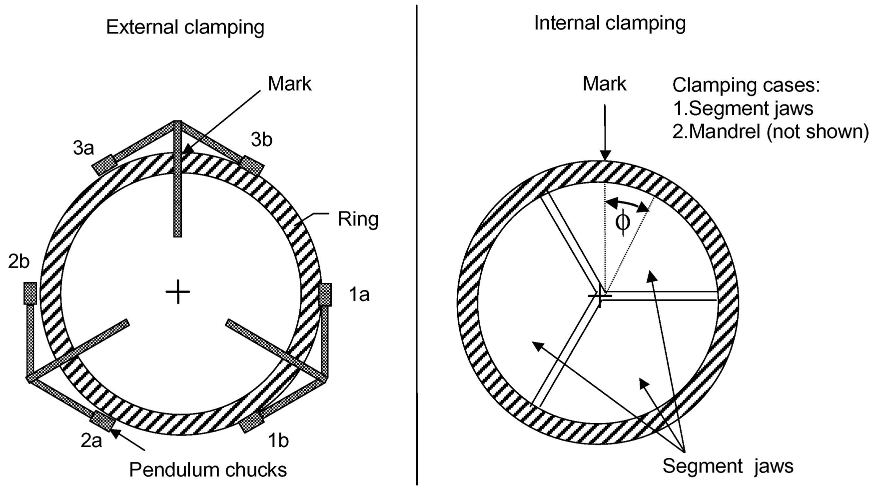


Figure 1 Illustration of the clamping apparatus for machining of rings [3].

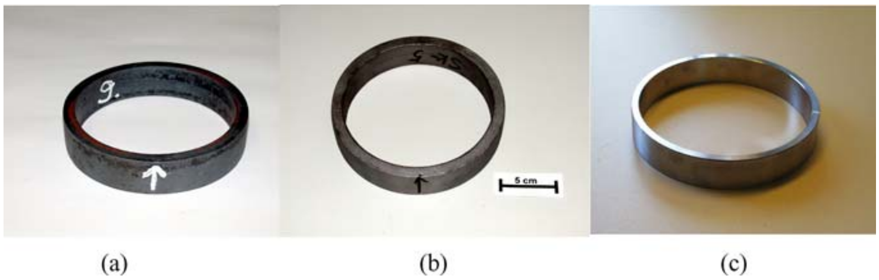


Figure 2 Rings made from spray formed 100Cr6 steel after (a) annealing, (b) sand blasting and (c) machining.

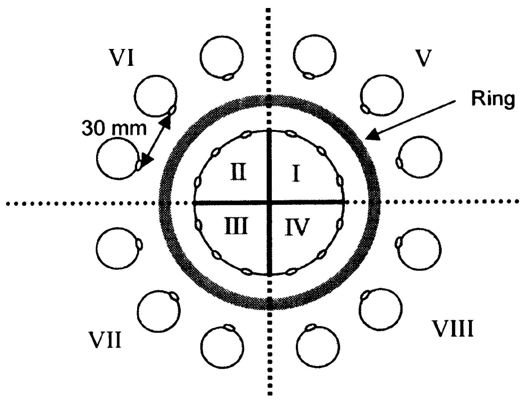


Figure 3 Schematic of gas quenching process of spray formed 100Cr6 rings [4].

reveal the morphology of martensite phase and carbides. Hardness distributions at three height positions of the heat-treated rings were examined by Vickers indentation measurement.

3. Results and discussion

3.1. Distortion behaviour of spray formed 100Cr6 steel rings

3.1.1. Distortion after machining

The typical three-coordinates measurement result of a spray formed 100Cr6 steel ring after machining is shown in Fig. 4a (SK01, measured on the outer circumference of the ring at the middle height $z = 13$ mm). The dashed circle is the ideal shape of the ring of average radius, the solid curve presents the real ring shape after machining. The radial difference between the solid curve and the dashed circle is the distortion of the ring. Herein, the radius difference is magnified by 500 times. Roundness, defined as the difference between the maximum radius and the minimum radius of the ring specimen, is used to evaluate the distortion of 100Cr6 rings. The roundness values of spray formed 100Cr6 rings after machining are plotted in Fig. 4b, in comparison with continuous cast rings. Mean values of the inside roundness and outside roundness of the spray formed rings are 33 μm (Standard deviation 5 μm) and 38 μm (Standard deviation 8 μm), respectively. These values are similar to those of standard rings of continuous cast material, indicating that appropriate machining process produces rings of nearly the same roundness independent of material homogeneity.

3.1.2. Distortion after stress relieving

The rings after stress relieving have very small distortion too (see Fig. 5), indicating no significant change of distortion from the machining state to the stress relieving state. Only a roundness difference of approximately 6 microns between the machined ring and the stress-relieved ring is found, which means the machining of the rings doesn't generate significantly inhomogeneous residual stresses inside the rings and results in very small amount of distortion in stress relieving.

3.1.3. Distortion after oil quenching

Oil quenching has been found to play a dominant role on the distortion of the spray formed 100Cr6 rings, as

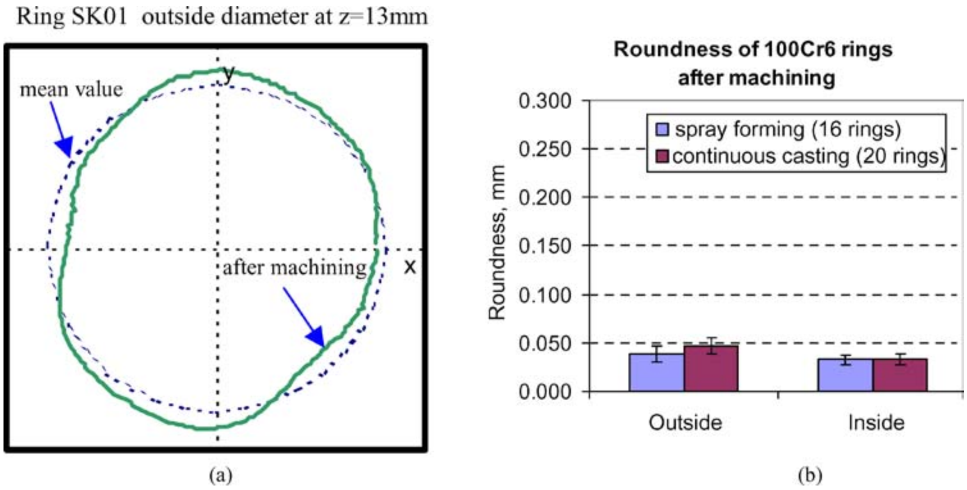


Figure 4 Distortion of the spray formed 100Cr6 rings after machining compared with continuous cast rings.

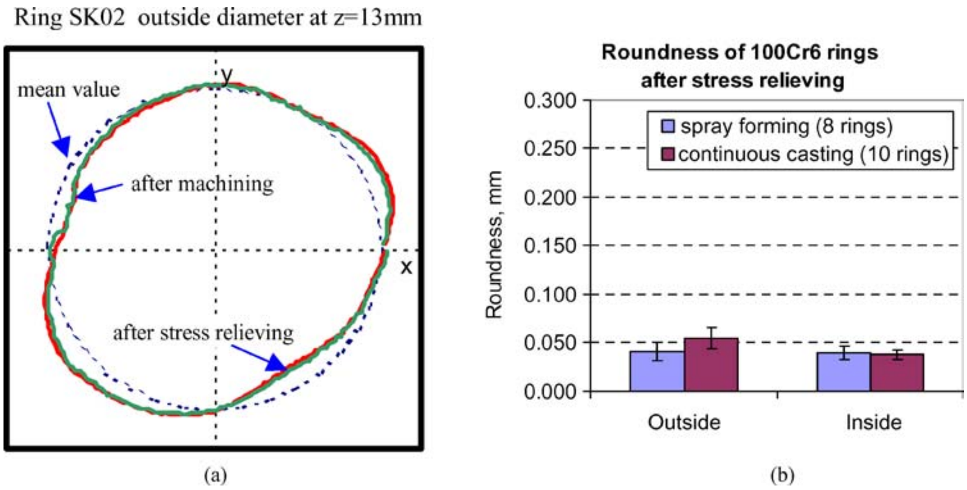


Figure 5 Distortion of the spray formed 100Cr6 rings after stress relieving compared with continuous cast rings.

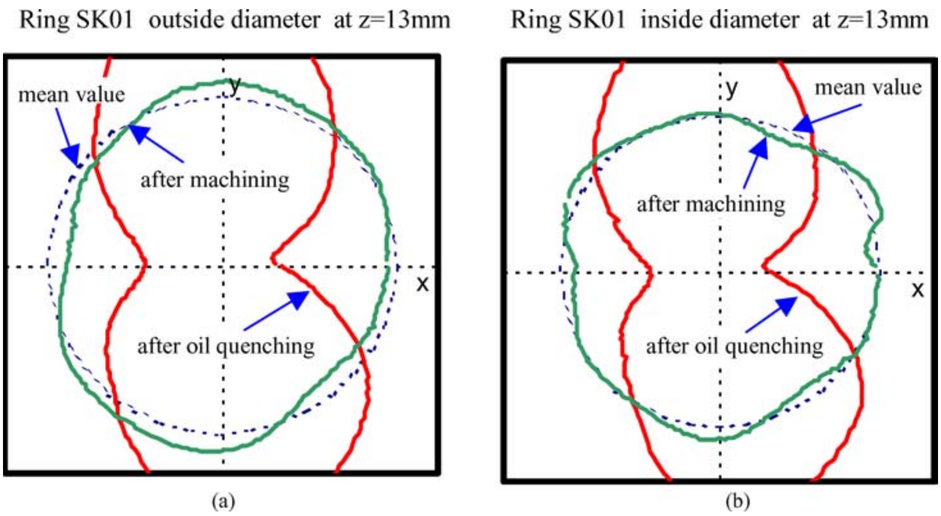


Figure 6 Distortion behaviour of the spray formed 100Cr6 rings after oil quenching.

shown in Figs 6 and 7. Large differences of roundness, both for the outside diameter and the inside diameter, are found as the rings are oil quenched. A mean roundness value about 155 μm with a standard deviation of 63 μm is presented for the inside diameter of these rings. For the outside diameter, the mean roundness is 163 μm with a standard deviation of 70 μm. Compared with continuous cast rings (Fig. 7a), the distortion of the spray formed 100Cr6 rings is improved to some extent, yet with a large standard deviation. The large distortion and scattering of the data are probably caused by the inhomogeneous quenching of rings in the oil bath, which is mainly due to nonuniform heat transfer process and unbalanced cooling behaviour. It is well known that the

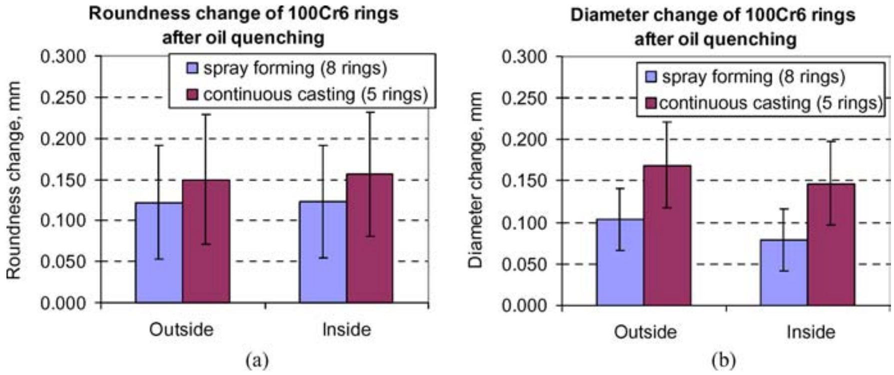


Figure 7 (a) Roundness and (b) diameter changes of the spray formed 100Cr6 rings after oil quenching compared with continuous cast rings.

problem with oil based media is the transient vapor film that forms on the surface of the hot part; depending on the circulation of the quench media and the geometry of the specimen it tends to break down at different times in different locations. Since the resulting boiling phase is removing heat at considerably higher rates this leads to nonuniform cooling and corresponding thermal stresses [5, 6]. As a consequence, distortion of the specimen occurs.

In addition to the roundness, the diameter changes of the rings were also seen in Fig. 7b. Increase of ring size is apparently generated by the martensite transformation. The diameter change of the spray formed rings is smaller than that of the cast rings due to more retained austenite in the spray formed rings. Since spray forming is a rapid solidification process, the spray formed rings have refined microstructures compared to the cast rings. The fine carbides in the spray formed material may dissolve more rapidly and completely during austenization. Higher content of carbon in the matrix leads to lower martensite transformation temperature and more retained austenite after hardening [7]. Another cause may come from the higher pickup of nitrogen (about 200 ppm) in the spray formed material (in cast material normally below 100 ppm). Since the spray forming process of 100Cr6 steel were carried out in nitrogen atmosphere, the melt at high melting temperature is liable to pick up more nitrogen, which has been found to make austenite more stable [8–10]. From X-ray diffraction measurement of samples after oil quenching and tempering, the content of retained austenite is found to be about 12% in the spray formed 100Cr6 and 8% in the cast material.

3.1.4. Distortion after gas quenching

The distortion of the spray formed 100Cr6 rings after gas quenching is much smaller than that of oil quenched rings. The 3D coordinates measurement results are given in Figs 8 and 9, respectively. A mean value of roundness change about 19 μm with a standard deviation of 8 μm is presented for the inside diameter of the spray formed rings. For the outside diameter, the mean roundness change is 10 μm with a standard deviation of 7 μm. The great improvement of distortion behaviour of gas quenched rings is obviously due to the much more uniform gas cooling of the hot specimen in the quenching process. Compared with continuous cast rings, the distortion of the spray formed 100Cr6 rings is improved to a small extent as seen in Fig. 9a.

The diameter changes of the rings after gas quenching are shown in Fig. 9b. Increase of ring size is also seen due to martensite transformation. The diameter change of the spray formed rings is still smaller than

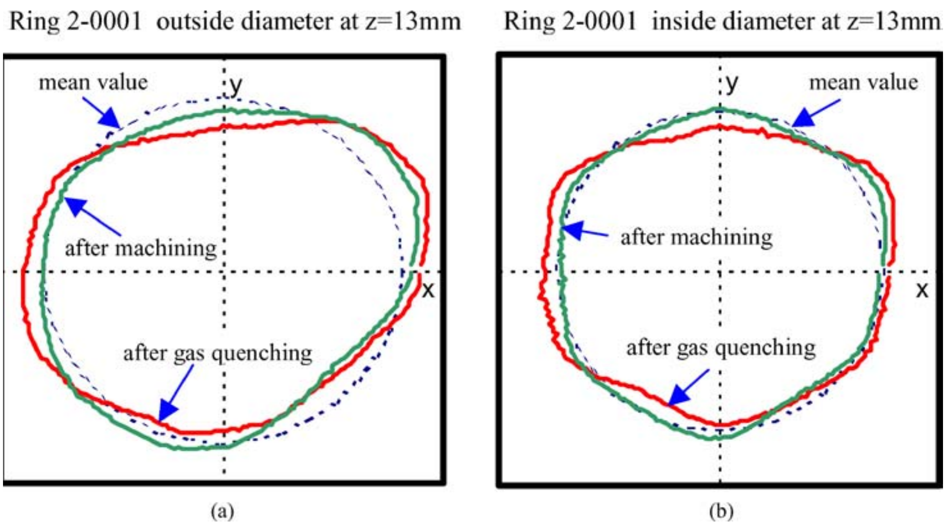


Figure 8 Distortion behaviour of the spray formed 100Cr6 rings after gas quenching.

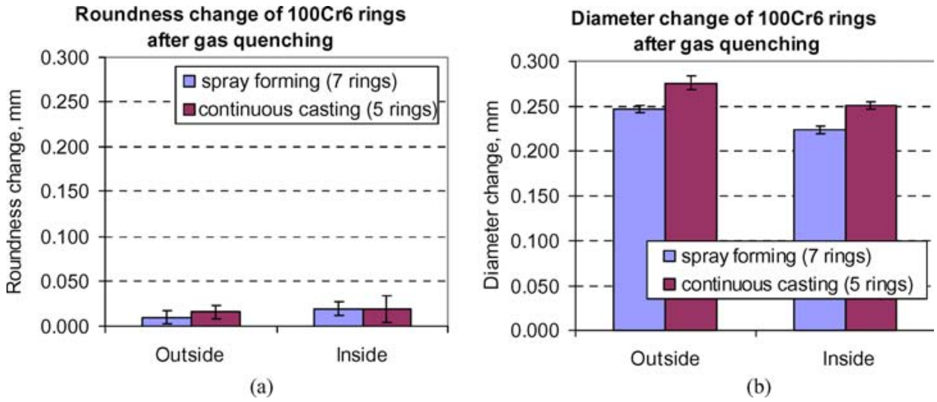


Figure 9 (a) Roundness and (b) diameter changes of the spray formed 100Cr6 rings after gas quenching compared with continuous cast rings.

that of the continuous cast rings due to more retained austenite. Comparing Fig. 9b with Fig. 7b, it is found that the diameter change after gas quenching is larger than after oil quenching. This result can be explained by the deep quenching ability of gas quenching process [4, 5]. Higher heat transfer coefficient of gas quenching in the low temperature range near martensite transformation point promotes the transformation from austenite to martensite, resulting in larger volume expansion.

3.1.5. Distortion after oil hardening plus tempering

Tempering was applied on two oil quenched, spray formed rings to study whether further distortion is caused by tempering. The measurement results show that no distinct roundness change occurs after tempering (Fig. 10). Size reduction of about 50 μm for both inside diameter and outer diameter of the rings is detected due to carbide precipitation.

3.1.6. Fourier analysis of roundness

The *Fourier transform*, in essence, decomposes or separates a waveform or function into sinusoids of different frequency which sum to the original waveform. It identifies or distinguishes the different frequency sinusoids and their respective amplitudes. Based on Fourier transform, the actual circle of a ring can be separated into a series of sinusoids of different frequency. This gives more detailed information on the geometric characteristics of the ring. Fast-Fourier-Transformation (FFT) of the roundness of rings has been frequently used to analyse the distortion behaviour of the rings and the influencing factors [2, 4, 11–13]. In this study Fourier analysis of roundness of the spray formed 100Cr6 rings after machining and quenching was also performed. Fig. 11 shows the Fourier analysis results of the measurement data for the middle position of the outer circumference of the rings, in which Frequency 0 denotes the mean value of the outer diameter of the rings; Frequency 1 denotes the shift of the center point of the ideal circle; and Frequency 2 denotes the ovality of the circle. Frequency 3, 4 and 6 denote the geometry of triangle, square and hexagon, respectively.

The effects of machining process and heat treatment process on the distortion of the ring specimens can be found from the Fourier analysis. It is seen from Fig. 11 that for the machined rings the amplitudes at Frequency 3 and Frequency 6 are significant, indicating the ring shape after machining is influenced by the clamping apparatus illustrated in Fig. 1. For the oil-quenched parts, the amplitude at Frequency 2 is very big with a large scattering of data, showing the deformation of the ring to an ellipse with a high degree of ovality. The large standard deviation of measurement shows the complexity of oil quenching process for non-uniform distortion

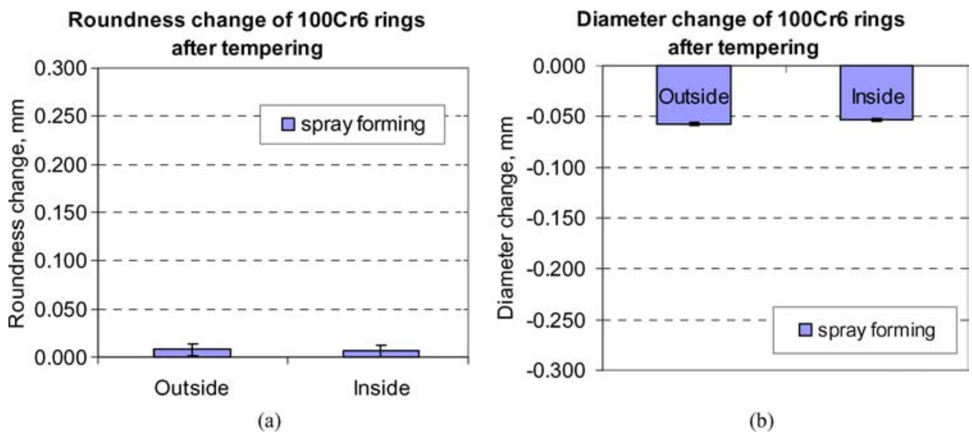


Figure 10 (a) Roundness and (b) diameter changes of the spray formed 100Cr6 rings after oil quenching plus tempering (200°C/2 h).

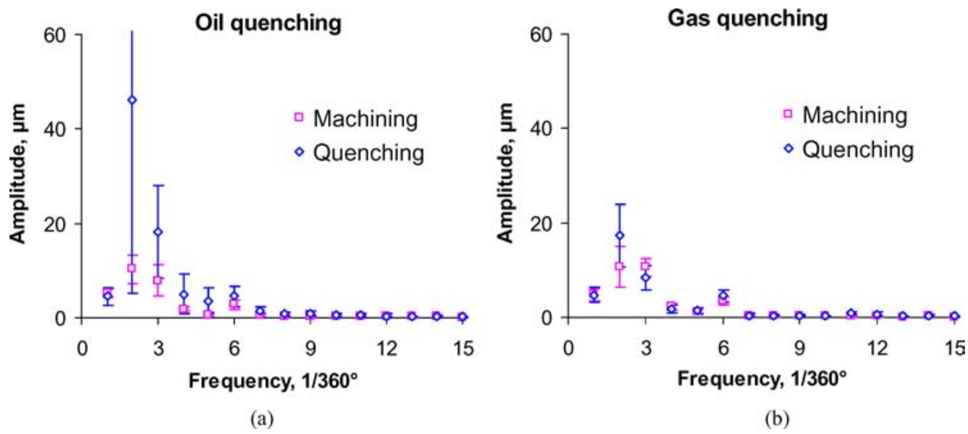


Figure 11 Fourier analysis of roundness of the spray formed 100Cr6 rings.

behaviour. For the gas-quenched parts, the amplitude at Frequency 2 is much smaller with a narrow scatter of data, showing the distortion of these rings is very small and more uniform. It is noted that there is a very slight variation of amplitude at Frequency 12 for the gas quenched parts, indicating the gas nozzles (12 nozzles homogenously distributed along the circumference, see Fig. 3) also have a little influence on the distortion behaviour of the ring specimen.

3.2. Residual stress of spray formed 100Cr6 rings

X-ray diffraction (XRD) provides an accurate method of determining the residual stress distributions in the components, which are calculated from the strain measured in the crystal lattice of the material based on linear elasticity. The circumferential residual stress distributions at the surface of the spray formed 100Cr6 rings after machining, stress relieving and oil quenching are given in Fig. 12, respectively. It can be seen that the stress distribution is not changing considerably along the circumference of the rings and the mean value of the residual tensile stress is about 600 MPa after machining. This uniformly distributed residual stress after machining makes no significant contribution to further distortion of the rings during proper stress relieving. Low residual tensile stress is detected at the surface of the rings after hardening due to stress relieving during heating phase of austenitizing process. Also for the ring treated by stress relieving, the residual stress is almost zero.

As we know, machining process plays an important role both on the roundness and geometry of the rings mainly owing to the configuration of the clamping apparatus. From the Fourier analysis of roundness in Fig. 11 we can see the amplitude at Frequency 3 and 6 for the machined rings. This shows the effect of the clamping apparatus on the shape of the rings. Also the roundness of spray formed rings after machining is about 30–40 microns, indicating a small distortion after machining. The residual stresses in the rings after machining is as high as 600 MPa (see Fig. 12), nevertheless homogeneously distributed. After proper stress relieving, these stresses will not cause large additional distortion. This result was achieved by using a well designed clamping system as shown in Fig. 1. When a normal clamping apparatus with three jaws was used for the machining of ring specimen, as reported by our collaborative project, non-uniformly distributed residual stresses were generated along the circumference of rings and much larger distortion resulted after heat treatment [3, 4].

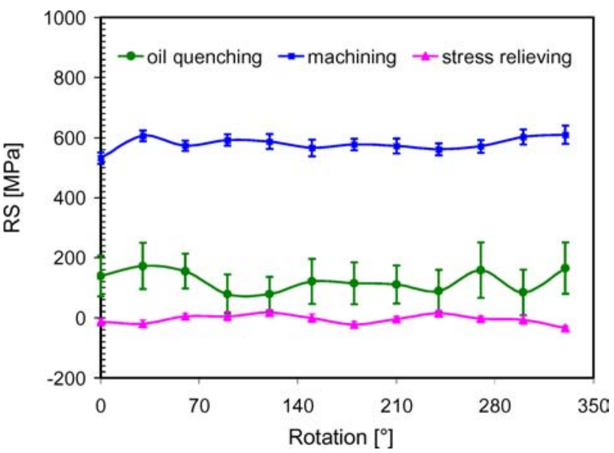
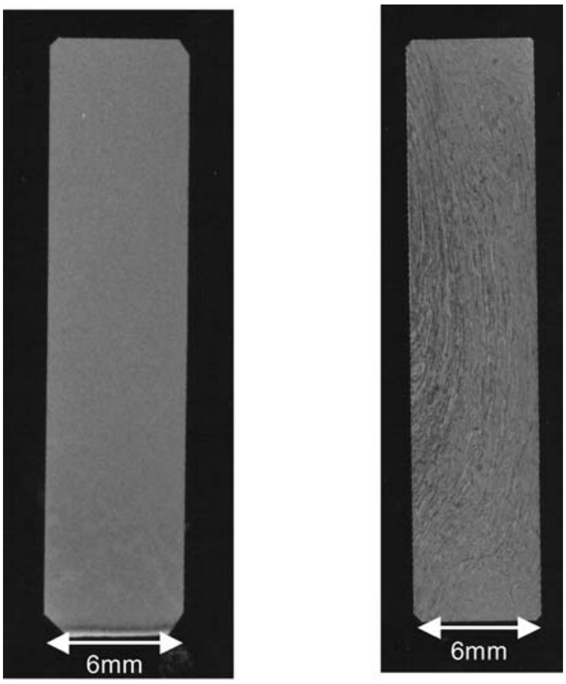


Figure 12 Residual stress at the surface of the rings made from spray formed 100Cr6 billets.

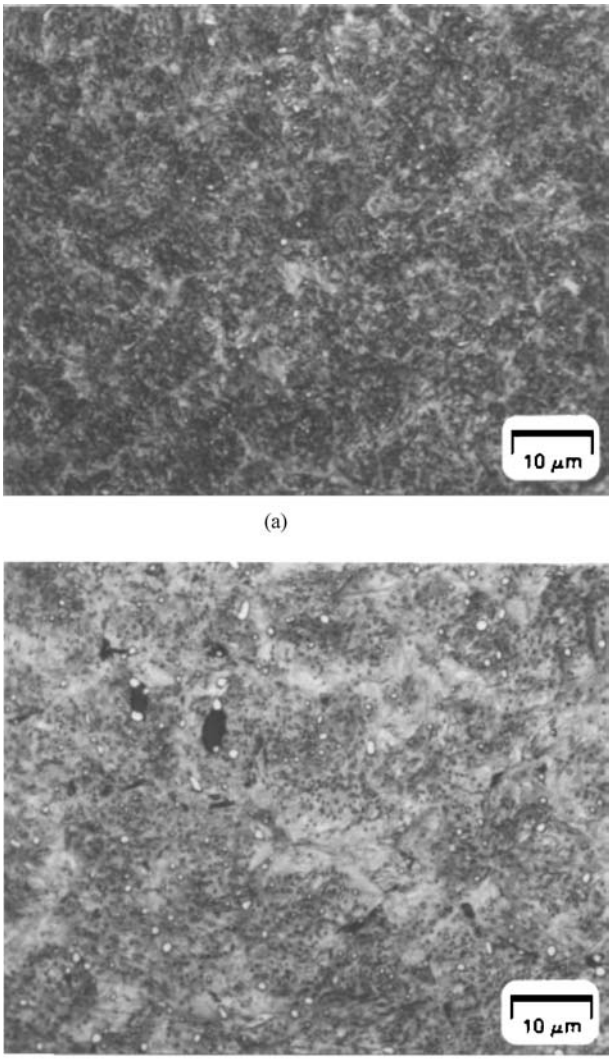
3.3. Microstructures of spray formed 100Cr6 rings

Metallographic structures of the as-quenched 100Cr6 rings made from the spray formed billets and continuous cast material were revealed by macro-etching on the cross section of the rings, as shown in Fig. 13. It can be seen that the microstructures are very homogeneous across all the section of the spray formed ring. In contrary to that, obvious fibre orientation of forging and rolling is seen in the continuous cast specimen, indicating a high degree of macro-segregation. The observation of the microstructures of both ring specimens show that the spray formed material consists of homogeneous martensite and fine carbides, while a few inclusions are visible in the continuous cast material (see Fig. 14). The homogeneous microstructures of



(a) (b)

Figure 13 Comparison of macrostructures of 100Cr6 rings by (a) spray forming and (b) continuous casting.



(a)

(b)

Figure 14 Comparison of as-quenched microstructures of 100Cr6 rings by (a) spray forming and (b) continuous casting.

the spray formed rings are apparently inherited from the spray formed 100Cr6 steel discussed in the first part [1]. Material homogeneity is again approved to be a feature of the spray formed material, contributing to lower distortion potential.

3.4. Hardness distribution of spray formed 100Cr6 rings

Two samples for hardness measurement were cut from a spray formed ring (SK01) after oil quenching at the degrees of 0° and 90°, corresponding to the positions of the smallest distortion X and the largest deformation Y, respectively (see Fig. 6). At each position the indentations were made from the inner surface to the outer surface of the ring at three heights: 3 mm to the top, middle height ($z = 13$ mm), and 3 mm to the bottom. The measurement results given in Fig. 15 show that the hardness is uniformly distributed in the ring specimen after oil quenching, with only slight decrease near the surface owing to decarburization zone (tens of micrometers thick). This indicates that the specimen is well through hardened even though the transformation may not take place in a simultaneous phase. In other words, the specimen undergoes nearly the same cooling rate and martensite transformation in different positions. However the hardening process in different positions may take place not simultaneously due to non-uniform heat transfer and unbalanced cooling in the oil bath. This leads to thermal stresses that may exceed the low yield strength of the material at high temperature and result in plastic deformation, i.e. distortion of the specimen.

From the above results, it is concluded that spray formed 100Cr6 steel exhibits lower distortion potential than conventionally manufactured material because of the highly homogenous microstructures and properties. However, it should be noted that the improvement of distortion behavior of the spray formed rings is not as significant as expected. The influence of material homogeneity on the distortion of a ring specimen is not very prominent since the specimen is so highly axisymmetric that the segregation of cast materials is also distributed in an axisymmetrical way. Effect of segregation on the distortion potential of the ring could be similar at any circumferential direction of the specimen. Moreover, the middle part of the hot rolled material where the segregation is the most severe (see Fig. 7 in the first part [1] of this investigation) is punched off during the hollow forging process, further decreasing the degree of segregation of the specimen. Therefore, the influence of material homogeneity on the distortion of ring geometry is not very significant. If a specimen in a non-axisymmetric geometry is produced of spray formed material, the distortion behaviour of this specimen is assumed to be remarkably different from that of continuous cast material. This hypothesis will be identified in future investigation.

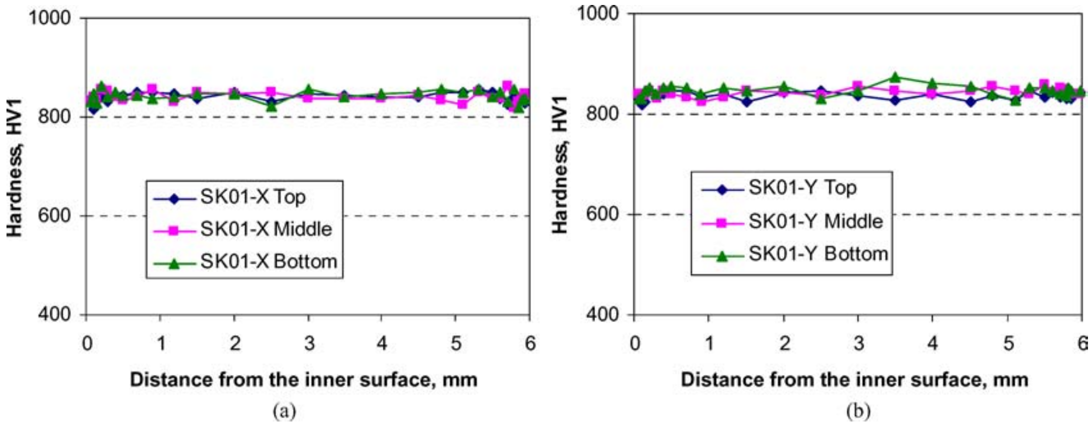


Figure 15 Hardness distributions in the spray formed 100Cr6 ring (SK01) at the degrees of (a) 0° and (b) 90° after oil quenching.

4. Conclusions

(1) The machining process plays an important role on the roundness and geometry of the spray formed 100Cr6 rings mainly due to the configuration of the clamping apparatus. With a well designed clamping system, the residual stresses generated by machining are homogeneously distributed and exert no significant influence on the further distortion of the rings.

(2) Quenching is the dominating influencing factor of the distortion of the spray formed 100Cr6 rings. Large and non-uniform distortion of oil-quenched parts is due to the complexity of oil quenching process. Gas quenching with evenly distributed gas nozzles around the specimen makes great contributions to the reduction of distortion. No remarkable change of the size and shape occurs after tempering of the spray formed rings.

(3) Spray formed 100Cr6 steel exhibits lower distortion potential than the conventional material due to much better metallurgical homogeneity. Spray forming has been approved to be an alternative process to conventional continuous casting for the production of homogeneous 100Cr6 bearing steel less sensitive to distortion.

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