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MECHANISM RESEARCH ON ELIMINATING VOIDS IN BEARING STEEL BALL BY FLOATING-PRESSURE METHOD (FPM)

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To eliminate internal void and improve the mechanical properties of steel balls formed by skew rolling, the floating-pressure method (FPM) using high-pressure gas to compact void is applied in this paper. By establishing void closure mechanical model, effects of various factors on void closure are obtained. The change rule of microstructures and outline of steel ball is investigated using DEFORM-3D Finite element software, and results show that when void is entirely closed, steel ball diameter decreases by less than 2 %, and its dimensional accuracy is guaranteed; the dynamic recrystallization of the metal around void promotes the healing of micro-cracks. The FPM experiments are performed, which verify the accuracy of the finite element model.

Key words: bearing steel ball, skew rolling, voids, strain, FPM

INTRODUCTION

As a core bearing component of high-speed railway and vehicle, steel balls formed by skew rolling need to maintain the smooth operation of axle and have an extremely strict forming quality requirement. However, due to the restriction of forming conditions of skew rolling, the large-scale discontinuity of metal easily appears in the core of steel ball with large diameter, which is called as void defect, so that a large number of steel balls are directly abandoned every year, resulting in the yield reduction of steel ball [1].

Some scholars always focus on improving the internal forming quality of bearing steel balls. Cao illustrated that the inner defect of steel ball is caused by the combined action of alternating shear stress and transverse tensile stress [2]; Du illustrated that the inner defects of steel ball can be reduced by adjusting the inclination angle of roller, the distance from the block to the billet and the rotational velocity [3]; Shu et al. proposed FPM of using high gas pressure to compact void in steel ball [4].

Based on the literature, the mechanism of eliminating inner void of bearing steel ball by FPM is further investigated in this paper [4]. The finite element simulations and experiments show that when the steel ball is under gas pressure for a few minutes, the ball outline is almost unaffected, and the microcracks that appear after the void closure can be automatically healed through heat treatment. The results provide the theoretical guidance for improving yield rate and the mechanical properties of the steel ball.

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THE MECHANICAL MODEL OF VOID CLOSURE IN STEEL BALL

In the process of skew rolling, because steel balls are subjected to alternating compressive stress and tangential stress, voids tend to appear in the center of steel ball, which is shown in Figure 1a, and the minimum circular outline of void can be taken as the index for measuring its dimension. FPM can be described as putting steel ball in the environment of high temperature and high gas pressure for a few minutes to guarantee the effective healing of void in steel ball. In order to explore the influence of various factors on void closure, a me-

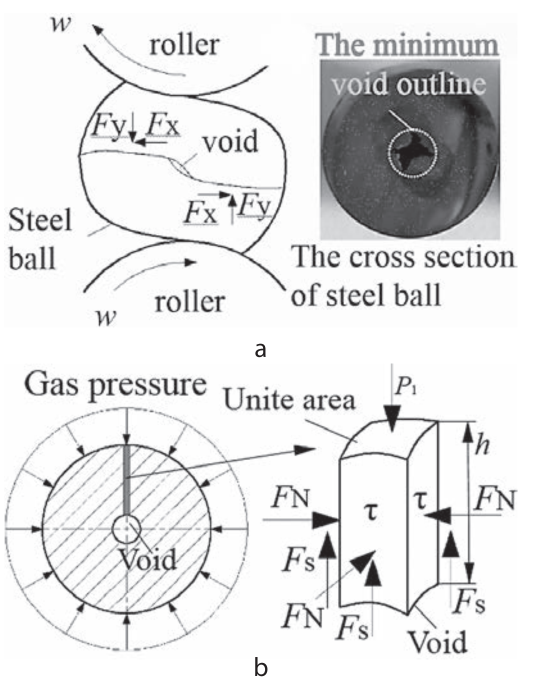


Figure 1 The mechanical model of eliminating void in steel ball

chanical model of compacting void in steel ball by FPM is established, which is shown in Figure 1b. The ball is divided into multi individual units along the void profile, and the force analysis is made on one of those units.

The equilibrium equations in the height direction of individual unit are established as follows:

$$4\tau \cdot h = P_1 - 4F_s \quad (1)$$

$$F_s = k \cdot F_N \quad (2)$$

$$F_N = m \cdot P1 \cdot h \quad (3)$$

$$k = J \cdot \frac{n}{T} \quad (4)$$

According to the formulas (1), (2), (3) and (4), the calculation formula of shear stress is deduced as follows:

$$\tau = P_1\left[\frac{1}{4h} - \frac{L \cdot n}{T}\right] \quad (5)$$

In the above formulas, τ is the shear stress, the most important factor affecting void closure, and it can be used as an evaluation index of void closure speed; h is the distance from the upper surface of individual unit to the contour surface of void; P_1 represents the gas pressure; F_s is the deformation resistance at the side of individual unit; F_N is the equivalent pressure at the side of individual unit; n is the material hardening index; T is material temperature; J, L, k, m are the constants related to the material properties. According the formula (5), it can be deduced that the void closure velocity is positively correlated with ball temperature and gas pressure and negatively correlated with the distance from void to the outer surface of steel ball and the material hardening index, which provides the theoretical guidance for the selection of process parameters.

THE ESTABLISHMENT OF FINITE ELEMENT MODEL (FEM)

In order to facilitate the establishment of the Finite element model and save calculation time, the 1/8 symmetry model of steel ball is set up in Pro/E software, and the contour of void in the center of steel ball is set to be spherical which is shown in Figure 2. The model with STL format is imported into DEFORM-3D Finite element software, and the thermal deformation dynamic recrystallization model of GCr9 steel is also imported into the software [5]. According to some relevant literatures, the steel ball is assumed to be a rigid plastic body, the mesh of which is divided into a number of tetrahedra; the amount of mesh is about 150 000; the initial temperature of the steel ball is 1 200 °C; the ambient temperature is 20 °C; the initial average grain size is 150 um; the heat transfer coefficient of air convection is 61,5 W/(m^2·K); the thermal emissivity between ball and air environment is 162,3 W /(m^2·K); because the gas pressurization phase is ignored and only the stable gas pressure phase is considered, the gas pressure imposed on the arc surface of ball is always 120 MPa; the loading time of gas pressure is 60 s.

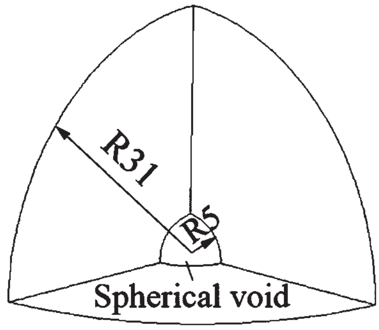


Figure 2 The 1/8 symmetrical model of the steel ball

SIMULATION RESULTS AND DISCUSSION

Figure 3 shows the overall equivalent stress distribution of the steel ball in the whole process of void closure, and it is illustrated that from the outer surface of ball to its core location, the equivalent stress presents a trend of gradually increment. In the initial stage of void deformation, the load imposed on the outer surface of ball is 120 MPa, but the equivalent stress at the central location of ball is only 73,4 MPa, the value of which is reduced by about 40 % compared with the surface load. With the void closure, the stress around void gradually decreases, and the metal flow velocity also decreases; when void is entirely closed, the value of equivalent stress decreases to zero, and the metal doesn't significantly flow any longer.

The equivalent strain distribution, the average grain size distribution and the dynamic recrystallization volume fraction distribution of steel ball are shown in Figure 4 a, b and c respectively. In order to explore the variation rules of the outer dimensions of the steel ball, five characteristic points are uniformly selected on the 1/2 arc contour of steel ball, which is shown in Figure 4 a, then the displacement curves of point P1 along X, Y, Z directions are obtained, which is shown in Figure 5 a, and Figure 5 b shows the equivalent strain distributions at points of P1-P5.

It is illustrated that from void to the outer surface of ball, equivalent strain decreases gradually; the displacements of P1 point in the directions of Y and Z are almost zero, and the metal only flows in the radial direction; with the reduction of void, equivalent stress gradually decreases, resulting in the reduction of the flow velocity of the metal around void; because of the steel ball being subjected to equal load and the uniform distribution of internal stress, the surface metal flows uniformly. When void is completely closed, the radial displacement of the surface metal is about 0,42 mm, and ball external dimension is reduced by 1,35 %. Hence the ball outline is not obviously affected. However, in order to ensure that ball has adequate cutting allowance for the next procedure, the cutting allowance of the steel ball should be appropriately increased in the rolling stage.

Simulation results show that the metal around void has a large plastic deformation, resulting in the increment of atomic activation energy and the dynamic re-

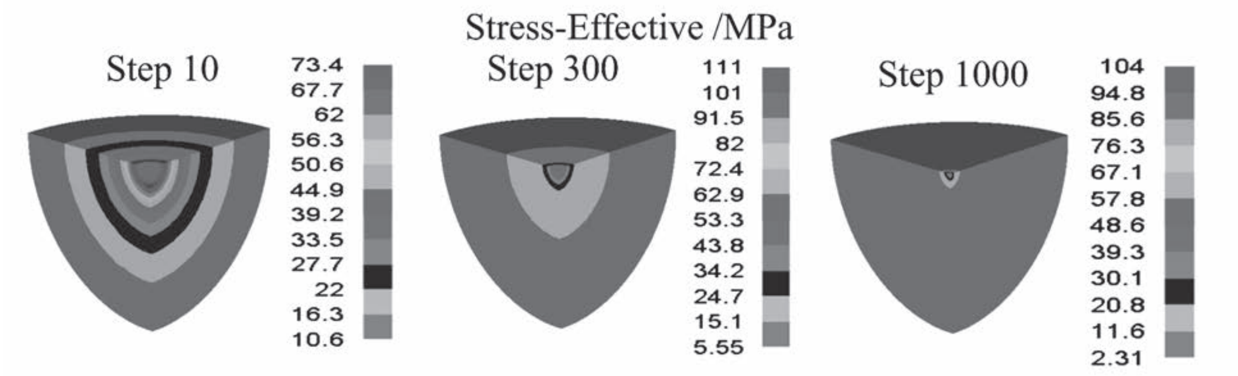
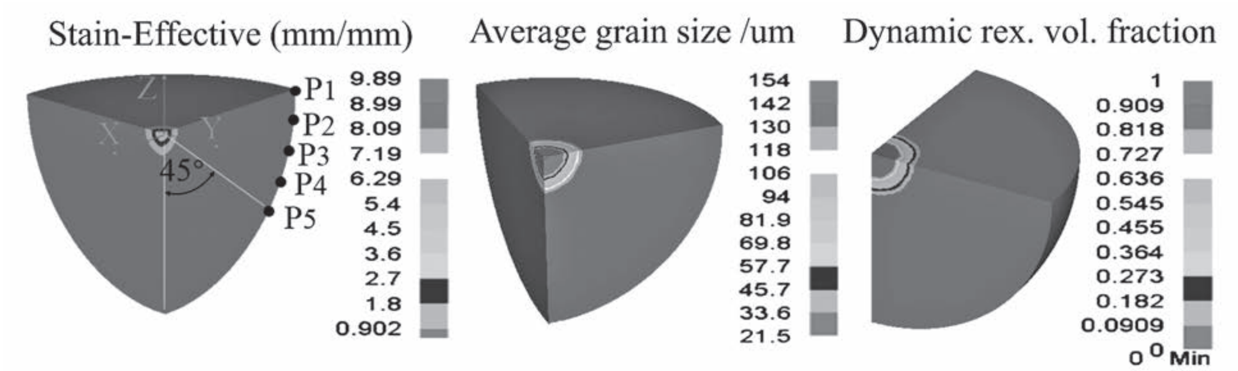


Figure 3 Equivalent stress distribution of the steel ball in the process of void closure



a b c

Figure 4 Macro and micro deformation laws in the process of void closure

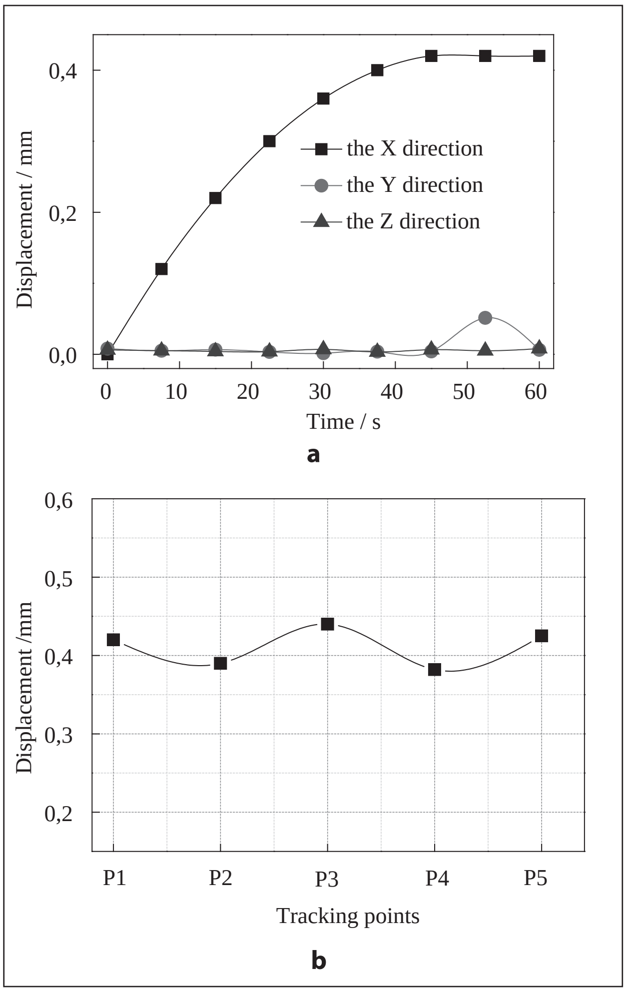
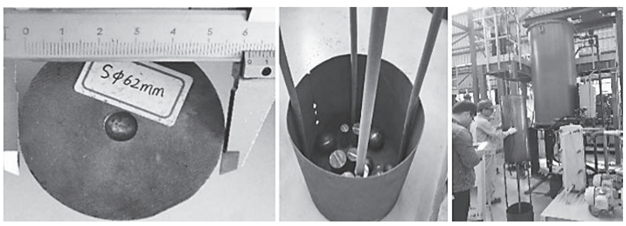


Figure 5 The variation rules of ball dimensions

crystallization of the metal in the steel ball, and the grain size in the core of ball is refined to 26 um. When void is completely closed, although the bonding interface still exists micro-cracks, the cracks can be automatically healed by heat treatment, further improving the mechanical properties of ball.

EXPERIMENTS

The FPM experiments are performed by the medium hot isostatic pressing (HIP) furnace in high-quality special steel metallurgy laboratory of Shanghai University, which is shown in Figure 6 b and c, and the maximum gas pressure and temperature of furnace can respectively reach 200 MPa and 2 000 °C. The GCr9 steel ball whose diameter is 62 mm is selected as specimen, and the specific experimental program is listed as follows: the specimen is cut into two equal parts, and a hemispherical void with a diameter of 10 mm is drilled in the center of the cross section, which is shown Figure 6 a; then two half-balls are chamfered on the edge of profile



a b c

Figure 6 The FPM experiments

a b c

Figure 7 The variation rules of the specimen shape and microstructure

and welded along the chamfer curve so that the good combination of two half-balls can be guaranteed by fixing up the chamfer gap with the welding material; finally, the welded specimens are put into the HIP furnace, and it is identified that the gas pressure in the furnace is 120 MPa, the gas temperature is 1 200 °C, and the experiment time is 30 minutes.

To explore the welding degree and grain size in the interface formed from void closure and the change rules of ball shape after experiment, the post-treatment program of the specimen is selected as follows: firstly, the outer diameter of specimen after experiment need be measured along the different places shown in Figure 7 a, and the specimen is divided into two equal parts along its original welding wire; secondly, a square sample with a side length of 10 mm is taken from the center of the cross section, which is shown in Figure 7 b, and one surface of the sample is polished and corroded; finally, the microstructure of the sample is observed under high power electron microscope. Figure 7 c shows the and microstructure distribution of the specimen after experiment.

It can be seen that the maximum value of ball diameter decrease after the experiment is 1,14 mm, and the outline of the steel ball does not obviously change; the inner void is completely closed and the interface is welded; the grain size in the core of specimen is refined to 34 μm; because the experimental error is less than 10 %, the correctness of the finite model is verified, and it is feasible to repair the internal defects of bearing steel ball by FPM. The results provide a new method to improve the mechanical properties and yield of bearing steel ball.

CONCLUSIONS

Simulation results show that the velocity of void closure is positively correlated with the gas pressure and temperature, and it has a negative correlation with the material hardening index and the distance from void to the spherical surface, which provides the theoretical guidance for the reasonable selection of process parameters; from the surface to void, the equivalent stress in steel ball gradually increases, and so does the metal flow velocity; with the decrease of void, the difficulty of void closure gradually increases; when void is entirely closed, there still exists micro-cracks at the interface, and these micro-cracks can be healed automatically through the functions of metal atoms freely diffusion and the dynamic recrystallization so that the internal quality of the bearing steel ball can be improved. Experiment results show that the ball outline does not change significantly when void is entirely closed, and the grain size can be further refined to improve the mechanical properties of ball, which further verifies the feasibility of the FPM. In addition, FPM can be also applied to repair the internal defects of steel ball with any type.

Acknowledgements

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Note: The responsible translator for the English language is Q. Q. Yan, Ningbo, China