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Formation Mechanism of Inclusion Defects in Large Forged Pieces

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Abstract: Nonmetallic inclusions mixed into large forged metal objects destroy the continuity in the metal and affect the quality of the forged product. Research on how inclusions affect the plastic deformation of a matrix shows the significance of the formation mechanism of inclusion defects. For upset forging, the nonlinear finite element model was shown to be appropriate for the ingot hot-forging process by comparing the results with experiments involving plastic and hard inclusions inserted into the forged piece. The high-temperature stress-strain curves of MnS plastic inclusions were obtained experimentally. The results show how, during upsetting, the morphology of MnS plastic inclusions varies from spherical to ellipsoidal, until finally becoming flat in shape. The larger the inclusion is, the larger the degree of deformation of the inclusion is, and large inclusions enhance the risk of the final product failing to pass inspection for inclusion flaws. Strain significantly concentrates in the matrix near a hard inclusion. When the hard inclusion reaches a certain size, conical fractures form on both sides of the inclusion. To pass inclusion-flaw inspection and close hole defects to the extent possible, the flat-anvil upsetting is recommended. Finally, the inclusion-deformation state obtained by finite element simulation is verified experimentally.

Key words: large forging; MnS; inclusion defect; anvil type; finite element method

Nonmetallic inclusions mixed into large forged metal objects constitute metallurgical defects and destroy the continuity of the forged material, reducing the reliability and safety of the forged piece[1-3]. At the same time, one of the main reasons that large forged pieces are scrapped is that they fail to pass flaw inspection because of inclusion defects. In addition, such defects have the potential of causing the failure of forged products[4,5], which can lead to significant losses for both the producer and consumer. In recent years, an increase have been seen in the size of high-end equipment and large forged products, which further increases the expense of broken forged pieces caused by inclusion defects. Thus, research on breaking plastic inclusions without causing inclusion-fracture porosity defects in the forging process has become even more important.

The finite element method is widely used to research inclusion deformation in a matrix. For example, Luo et al.[6,7] and Yu et al.[8,9] studied the deformation of inclusions in the hot rolling process by using the finite element method and analyzed how the process parameters affected the evolution of the morphology of the inclusions. Other groups used the nonlinear finite element method to analyze the species and deformation characteristics of inclusions inside bulk ingot (central spherical plastic and hard inclusions)[10]. Other numerical studies considered hot-rolled steel by analyzing the evolution of inclusion morphology and the formation rules near void[11]. In these studies, how the hot-rolling parameters and the size and location of inclusions affect the evolution of different types of inclusion defects was considered. The effects of temperature, friction, tooling, and other factors on forging and inclusion deformation were studied for upset forging by using three-dimensional finite-element software (Deform-3D). The deformation laws governing the inclusion shape and size for various upsetting processes were obtained[12].

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According to the plastic deformability, nonmetallic inclusions in steel ingot can be classified as hard inclusions (e. g. , Al_2O_3) and plastic inclusions (e. g. , MnS). Research on how ingot-matrix inclusions obey the plastic deformation law is important for recognizing how inclusion-crack defects form. In addition, because experimental data on physical-function parameters are lacking, research into the performance parameters of nonmetallic inclusions in hot deformations has used some assumptions that lack a solid theoretical or experimental foundation[10-12]. In the present work, however, the high-temperature rheological parameters of MnS plastic inclusions were directly measured by experiment, and the results of measurements of MnS high-temperature flow stress were used in the finite element simulation. It was analyzed how the parameters of the forging process affect the deformation status of MnS inclusions. Furthermore, it also studied how hard inclusions affect the formation of large-forging deformation defects. The veracity of the finite element description of inclusion deformation was also verified experimentally.

1 MnS High-temperature Stress-strain Curve

1. 1 Specimens and experimental apparatus

The MnS cylindrical specimens of 10 mm in diameter and 15 mm in length were prepared by hot-press sintering using industrial-grade MnS powder as raw material. The MnS specimens had a relative density of 93. 93% and an apparent porosity of 4. 90%. Fig. 1 shows a scanning electron microscope (SEM) image of the fractured surface of a MnS sintered specimen. The specimen has few pores, and the MnS particles are closely integrated. For hot-compression measurements, the Gleeble-3500 thermal-mechanical simulator was the main experimental equipment. Fig. 2 shows the apparatus for heating and applying pressure to a MnS specimen. The device consists of two tubes and two anvils, one at an end of each tube. The specimen was placed centrally in the space formed by the tubes and anvils and was clamped by the two anvils. To measure temperature, the thermocouples were welded onto the cylindrical surface of the steel anvils.

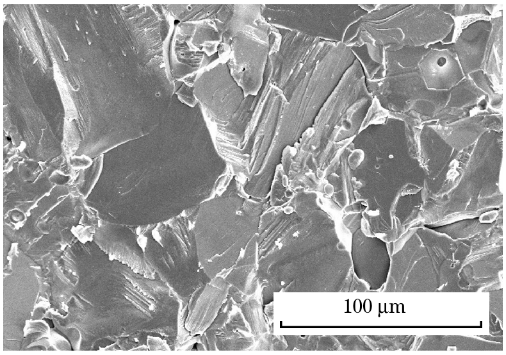

Fig. 1 SEM images of fractured surface of MnS specimen

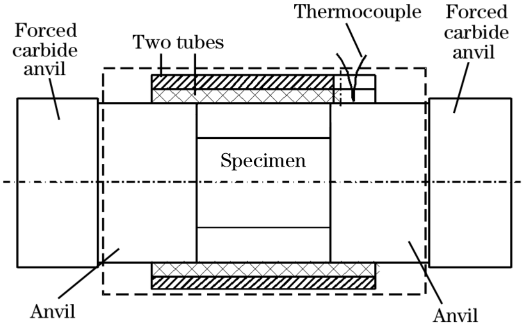

Fig. 2 Apparatus for heating and applying pressure to MnS specimen

1. 2 Experimental procedure

During the hot-compression measurements, a high-temperature lubricant was applied and graphite paper was placed on both ends of the specimens to decrease friction effects and ensure uniform and stable deformation. The measurements were made in an argon atmosphere and the MnS specimens were heated by conduction and radiation. The MnS specimens were heated at 55 ℃/min to the deformation temperatures, held at this temperature for 5 min, and then subjected to compressive deformation. After compression, the specimens were slowly cooled to room temperature. Because of the large size of the hydraulic equipment and the distribution of inclusions in the ingot, the deformation temperature was chosen to be 1150 and 1200 ℃, and the strain rate was 0. 0001, 0. 001, and 0. 01 s^{-1}, respectively.

1. 3 Experimental results

Fig. 3 shows the MnS high-temperature stress-strain data. The results show that, for strain rates of 0. 0001 and 0. 001 s^{-1}, stress mutations occur at the onset of deformation (the stress increases and then decreases). As the strain increases, the stress increases and tends to stabilize by the end of deformation. For a strain rate of 0. 01 s^{-1}, the stress rapidly increases at the deformation prophase, and then decreases slowly and finally stabilizes. At the same strain, the stress increases with increasing the strain rate. For a deformation temperature of 1150 (1200) ℃, the stress stabilizes at approximately 3. 3, 5. 6, and 7. 5 MPa (3. 0, 4. 3, and 4. 8 MPa). These results show