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An Experiment on the Mechanical Properties of Metal Rubber Processed by Improved Processing Techniques and the Construction of Its Constitutive Relation

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ABSTRACT

To figure out the performance of dampers made of metal rubber (MR) that are installed in bridge and frame shear wall structures to change the energy consumption mode of artifacts, experiments were performed on the MR material processed by improved processing techniques to test its compression and shear hysteresis properties in high-temperature environment, and discover the laws of the impact of factors such as the improved processing techniques and temperature on the compression and shear hysteresis of the material. At the same time, based on test curves and the strain hardening laws of the material, this paper employed the least square method to perform piecewise linear fitting on MR curves, and the corresponding strain hardening constitutive model was established and verified. The study suggests that, after processed by the improved processing techniques, the compression and shear hysteresis energy consumption performance of the MR test pieces is very stable, and the shear strength had been improved. As the temperature increases, the metal rubber consumes more vibrational energy, and the stiffness of MR vibration isolator increases as well; at a same temperature, as the strain amplitude and relative density increase, the vibrational energy consumed by the MR damping material increases accordingly. The simplified constitutive model constructed in the paper has a simple form, it can not only describe the strain hardening features of the material, but also conform to the test curves, therefore, it can facilitate the parameter design and the calculation of MR dampers. The research conclusions obtained in this paper can provide theoretical and experimental evidence for the processing, preparation, and application of MR dampers, and it is of very important theoretical significance and practical value.

1. INTRODUCTION

Metal rubber (MR) is a kind of elastic material with homogeneous porous structure. Using a certain processing method, thin metal wires were rolled into spring coils, and then braided and stamped to mold into components that have both the intrinsic properties of metals and the elasticity of rubbers, thus it is called the metal rubber material [1]. Its internal structure is a spatial network resembling the structure of rubber polymer formed by interlacing metal wires, the structure can consume a large amount of energy when subjected to vibration and act as a damper [2]. MR is being widely applied in fields of construction machinery, military, aerospace, and marine ships due to its features of large damping, light weight, good flexibility, high impact energy absorption, resistance to high and low temperature effects, and resistance to aging [3-7]. Numerous experiments have proved that MR is a non-linear dry friction damping material with good deformation self-recovery ability [8-11]. Besides having a bi-polyline functional constitutive relation (memory recovery ability), its elastic recovery force contains obvious cubic nonlinear component during non-memory recovery [12], while the linear viscous damping term in the main component in the damping force, and the high-order speed term could be ignored. From dynamic test results, it's known that the recovery force of MR damper has nonlinear hysteresis characteristics, and its damping components contain both viscous damping and dry friction damping, and these complex factors should be taken into consideration when establishing the constitutive relation [13]. At present, the most influential constitutive models of MR proposed by world field scholars can be divided into two types: meso-mechanical models, and macro-mechanical models. Ao et al. [14] proposed a compressive stress calculation model based on the assumption of equal probability distribution of three-dimensional vertical axis of metal wire coils, the model only has one material constant, which is simple to calculate and suitable for isotropic bodies. Chen et al. [15] proposed to use series and parallel connections of small-curvature beams to describe material's overall stiffness, the messy metal wires are regarded as multiple layered tiny springs with different shapes, which can be taken as small-curvature beams that have a small angle α (helix angle) with the molding pressure surface. Each small spring has a certain stiffness, and their joint action forms the overall stiffness property of MR on the macroscopic scale. Bai and Huang [16] proposed a mesoscopic constitutive model based on the combined deformation of micro springs, and introduced a layering proportionality coefficient of material parameters to better describe the distribution of micro spring orientations in the mesoscopic structure. Ponomarev et al. [17] employed macro-mechanical analysis method to establish the cubic nonlinear hysteresis functional constitutive relation of the force-displacement of MR dampers, that is, the recovery ability of MR is formed by the superposition of elastic force containing third-order nonlinear polynomial and the equivalent viscous damping force, and the least square method was adopted in their study to identify each parameter. Jiang et al. [18] proposed to use experimental method to establish the deformation model of MR components. To research the energy consumption and vibration absorption dampers made of MR material, this paper tested the high-temperature compression and shear mechanical properties of MR processed by improved processing techniques, explored the law of the impact of factors such as the test pieces' processing techniques and temperature on the compression and shear hysteresis performance of the material, analyzed the mechanical and damping properties of the test pieces, and studied the energy consumption and vibration absorption mechanism of MR. At the same time, based on the test curves, the least square method was used to perform piecewise linear fitting on the MR curves according to the principle equal envelope area (namely equal energy), then, a constitutive model of strain hardening was constructed and verified in software.

Above-mentioned studies suggest that, compared with test pieces processed by ordinary processing techniques, the MR test pieces processed by improved processing techniques exhibit very stable properties in terms of compression and shear hysteresis energy consumption, and their shear strength has been improved as well. As the temperature increases, MR consumes more vibrational energy, and the stiffness of MR vibration isolator increases as well; at a same temperature, as the strain amplitude and relative density increase, the vibrational energy consumed by MR damping material increases accordingly. The simplified constitutive model constructed in the paper has a simple form, it can not only describe the strain hardening features of the material, but also conform to the test curves, therefore, it can facilitate the parameter design and the calculation of MR dampers. The research conclusions obtained in this paper can provide theoretical and experimental evidence for the processing, preparation, and application of MR dampers, and it is of very important theoretical significance and practical value.

2. MECHANICAL PROPERTIES OF MR MATERIAL PROCESSED BY IMPROVED PROCESSING TECHNIQUES

2.1 Shear test

2.1.1 Test results and discussion of test pieces processed by ordinary processing techniques

Figure 1 shows the OMR-A static shear stress-strain hysteresis characteristic curves of test pieces processed by ordinary processing techniques. According to the figure, when the strain amplitude reached 15%, the maximum shear stress was only 0.31 MPa. In contrast, in the previous compression test of MR, the compressive stress of the same amplitude reached 1.6 MPa, and the shear strength of MR in the direction of the non-compression molding surface was relatively low. Under compression load, the stress-strain curves showed nonlinearity with obvious strain hardening features; while under shear load, the curves were almost linear and had no strain hardening feature, the impact of strain amplitude on shear stiffness was little. The number of loading cycles had almost no impact on the stress-strain hysteresis performance, and the loading/unloading stress-strain curves of each circle showed good repeatability.

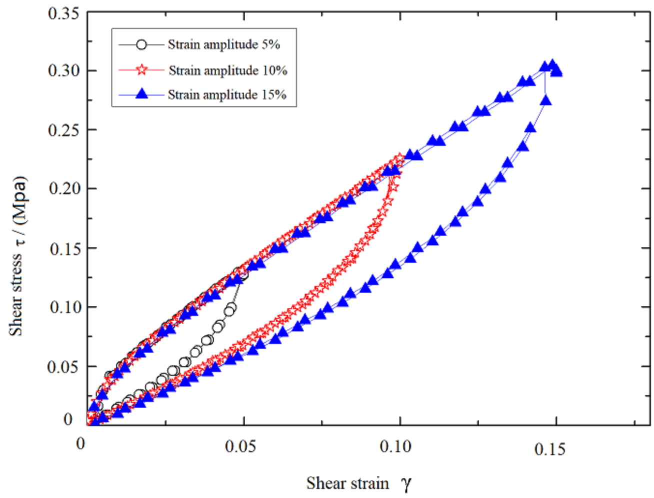

Figure 1. Stress-strain curves of components under static shear loads

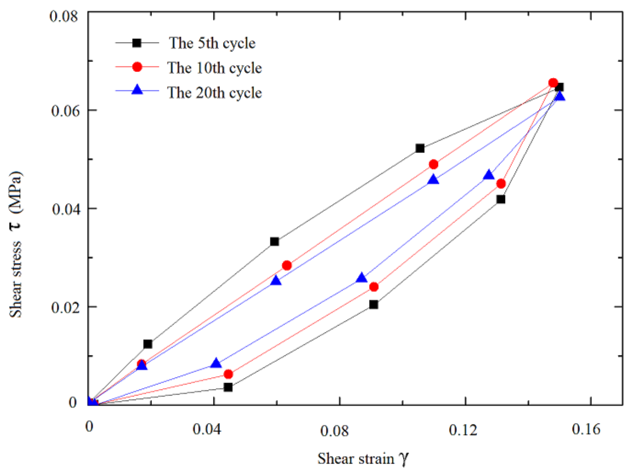

Figure 2. Stress-strain curves of components under dynamic shear loads

When analyzing the results of shear test under dynamic loads, since there're many loading cycles, three cycles (the 5th, 10th, and 20th cycles) with a strain amplitude of 15% were selected and their hysteresis loops were plotted, as shown in Figure 2. According to the curves, different from static shear test, with the increase of the number of loading cycles, the enveloping area of hysteresis loops in dynamic test became smaller, indicating that damping performance degradation had occurred when ordinary MR underwent shear deformation under dynamic loads, which was very bad for taking it as energy consumption and vibration absorption material to bear seismic loads.

For this reason, based on current ordinary processing techniques, the braiding and molding techniques of MR were improved, and the number of metal wires in the molding direction was increased. The method was implemented following these steps: first, thin metal wires of different types were winded into spiral coils and stretched evenly; second, according to the structure of these components, the spoke-type braiding device was selected and assembled; third, according to the calculated layers of latitude and longitude lines, the stretched spiral coils were arranged and laid evenly on the spoke-type braiding device to obtain blank of MR components; fourth, the blank was dismounted from the spoke-type braiding device and put into a mold for cold stamping; fifth, the MR components were subject to tempering treatment to improve the shear strength of the non-compression molding surface, then, shear test was performed again on test pieces processed by improved processing techniques.

2.1.2 Test results and discussion of test pieces processed by improved processing techniques

Taking the OMR-8 dynamic shear test of MR processed by improved processing techniques as an example, static shear test with a strain amplitude of 20% and dynamic shear test with a strain amplitude of 30% were carried out, the test curves are shown in Figures 3 and 4.

By comparing with test curves of test pieces before and after processed by the improved processing techniques, we can see that, in contrast with MR processed by ordinary processing techniques, the degradation of MR processed by improved processing techniques during dynamic loading was not obvious.

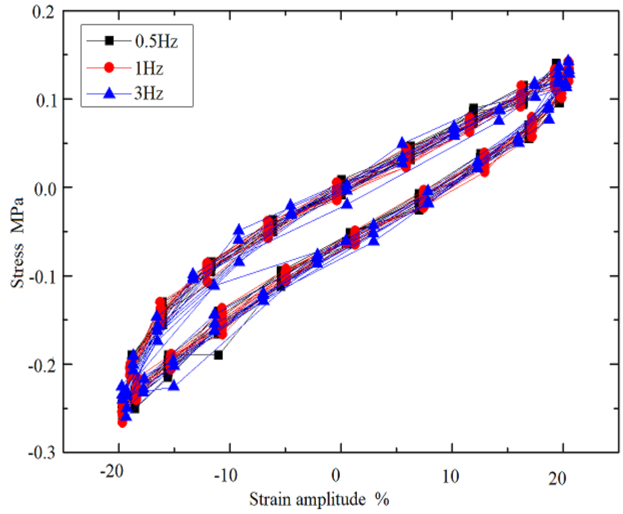

Figure 3. Stress-strain curves of components under static shear loads and a strain amplitude of 20%

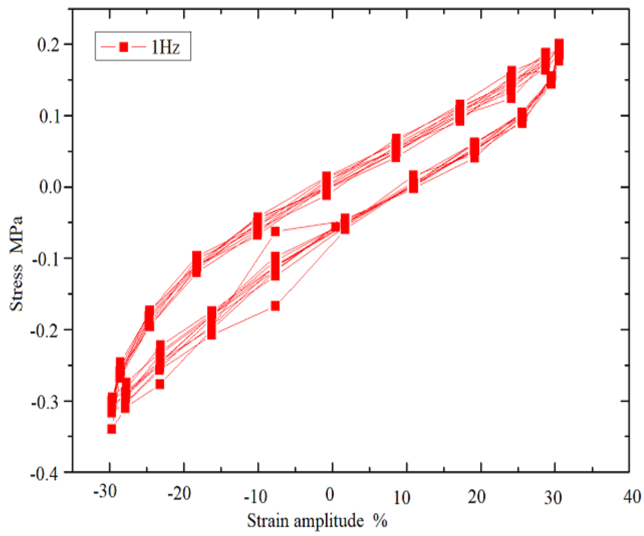

Figure 4. Stress-strain curves of components under dynamic shear loads and a strain amplitude of 30%

2.2 Compression test

In order to study the mechanical properties of metal rubber with improved processing technology, we compare the static and dynamic compression curves of MR test pieces processed by ordinary and improved processing techniques, the test curves are shown in Figures 5, 6 and 7.

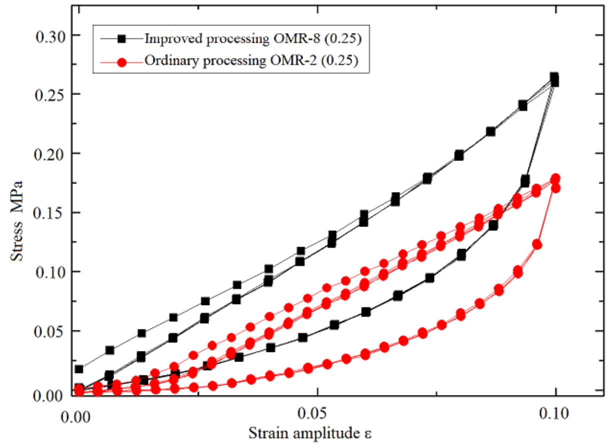

Figure 5. Stress-strain curves of compression test of components under static loads and a strain amplitude of 10%

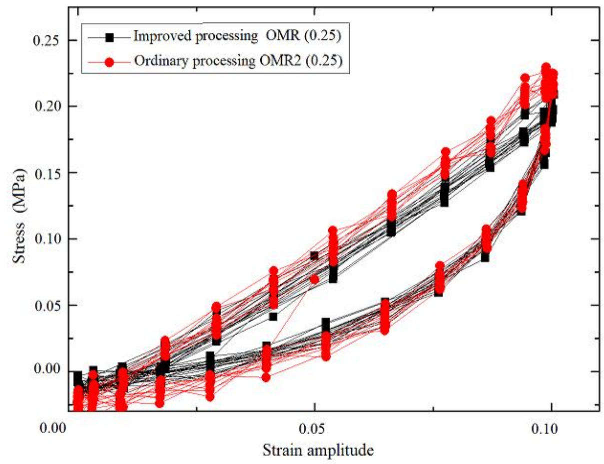

Figure 6. Stress-strain curves of compression test of components under dynamic loads and a strain amplitude of 10%

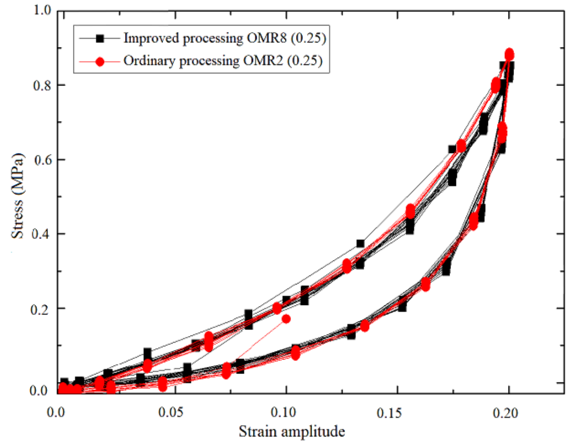

Figure 7. Stress-strain curves of compression test of components under static loads and a strain amplitude of 20%

According to above figures, it can be concluded that, under static compression, compared with ordinary MR, the strength of improved MR hadn't been improved; under dynamic compression, the strength of improved MR was close to that of ordinary MR. In summary, after the improved processing and braiding techniques had been adopted, the distribution of the inner and outer layer structure of MR, especially its edge structure, became more uniform, and the overall elasticity and damping performance of MR had been improved.

3. THE EFFECT OF HIGH TEMPERATURE ON THE HYSTERESIS PERFORMANCE OF MR

To figure out the impact of external environment temperature on the hysteresis characteristics of MR damping material, this chapter analyzed the laws of dynamic compression performance, elastic modulus, and hysteresis performance of MR test pieces made of stainless steel in high temperature environment.

3.1 Test conditions

In the high-temperature hysteresis test, the test equipment was the INSTRON Fast Track TM8801 electro-hydraulic servo dynamic fatigue testing machine, and temperature adjustment was achieved by the high-temperature box equipped in the test equipment. During the test, MR test pieces were clamped on the testing machine by a special clamp and then placed in the high-temperature box. In order to study the hysteresis characteristics of MR under different temperatures, the tests pieces of improved MR with a relative density of 0.23 and numbered OMR9 were chosen for the test. According to previous analysis, loading frequency had no impact on the compression performance of MR, so the dynamic loading mode had been adopted, frequency was 1 Hz, temperature values were 80°C and 150°C, and loading amplitude values were 5%, 10%, 15%, and 20%.

3.2 Test results and analysis of the hysteresis characteristics of MR test pieces in high-temperature environment

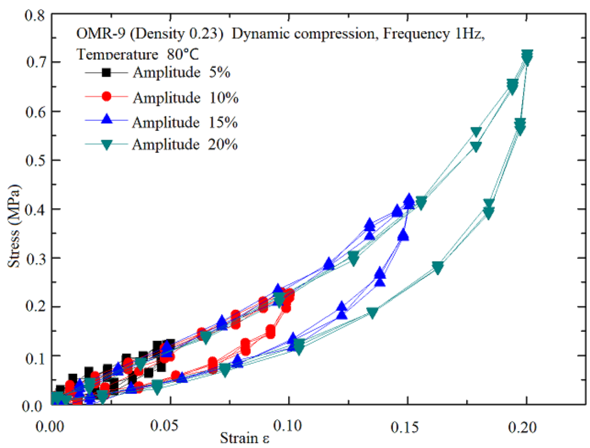

Figure 8. σ-ε hysteresis curves of OMR-9 with different strain amplitude at 80°C

Figures 8 and 9 give the hysteresis characteristics curves of stress-strain amplitude of MR component OMR-9 at two temperature values of 80°C and 150°C under conditions that the relative density and deformation amplitude are constant. According to the figures, in high-temperature environment, the shape of the compression hysteresis performance curves of MR elastic components still retained strain hardening features, which was basically the same with the shape of hysteresis curves under normal temperature state.

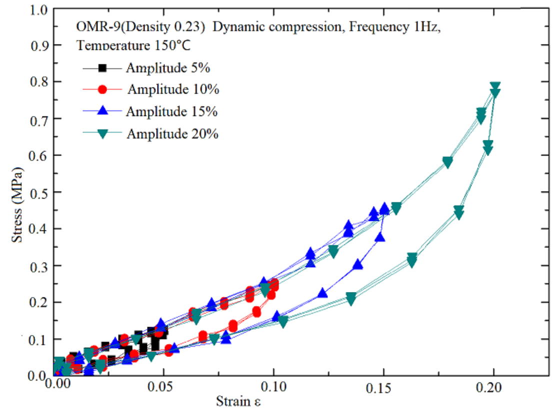

Figure 9. σ-ε hysteresis curves of OMR-9 with different strain amplitude at 150°C

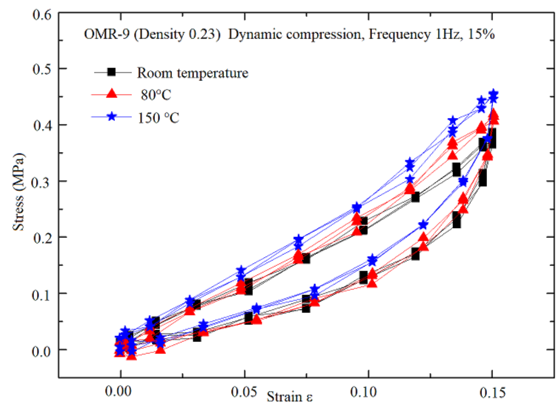

Figure 10. σ-ε hysteresis curves of OMR-9 at different temperatures under 15% strain amplitude

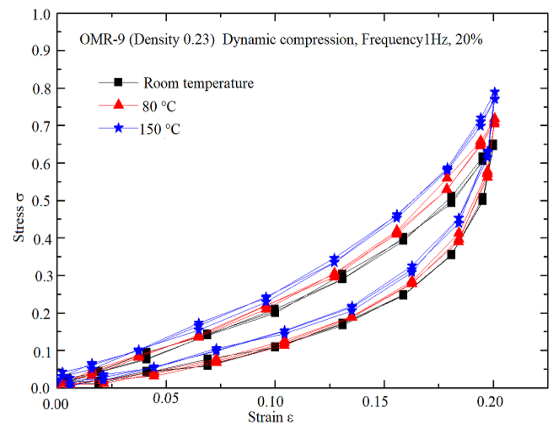

Figure 11. σ-ε hysteresis curves of OMR-9 at different temperatures under 20% strain amplitude

Figures 10 and 11 give the hysteresis loops of MR test pieces at different temperatures under the conditions of two strain amplitude values of 15% and 20%. As can be seen from the figures, on the one hand, under a same strain amplitude, the recovery force of test pieces increases with the rise of temperature. The main reason is that as the temperature rises, the coefficient of dry friction between stainless-steel wires in MR increases, and the friction increases as well. On the other hand, as the temperature rises, the strength and stiffness of metal wires both decreases, but the decrement of the strength and stiffness of metal wires is smaller compared with the increment of friction, therefore, at higher temperatures, overall speaking, the stiffness of MR elastic test pieces increases and their load bearing ability enhances, that is, the recovery ability enhances with the increase of temperature.

4. ESTABLISHMENT OF THE STRAIN HARDENING POLYLINE CONSTITUTIVE MODEL

This paper constructed the constitutive model of MR based on experimental method, and the test data were calculated by the least square method according to the principle that equal envelope area means equal energy. For MR with a relative density of 0.27 obtained in the test mentioned in above text under the conditions of room temperature and a frequency of 1 Hz, the stress-strain curve of the last cycle under the maximum strain amplitude of 20% was subject to piecewise linear fitting and calculated in MATLAB: at first, the MR stress-strain curve measured in the test was divided into two segments: the loading segment, and the unloading segment; then, the loading segment was subject to piecewise fitting to obtain two segments OA and AB as shown in the figure, thus the initial elastic modulus of the simplified model, the elastic modulus of the strain strengthening segment, and the strengthened stress and strain were determined; after that, according to the principle of equal energy, the BC and CO segments in the figure were determined to make the area enclosed by the simplified model be equal to the area enclosed by the measured test curve. The loading and unloading segments of the model were respectively divided into two sections of polylines, wherein the stiffness of the loading segment of the second section was greater than the initial loading stiffness, namely the first stiffness of the material K_d, as shown in Figure 12. The constitutive model simplified by the experimental method is simple in form, and its characteristic parameters of each segment are definite, so it's easier to design the various parameters of the dampers made of MR. The simplified model can not only describe the strain hardening features of the material, but also conform to test curves; the consumed energy was the same as the test curve, and it's easier to calculated, which had simplified the seismic response analysis method of energy consumption and vibration reduction structures based on MR material.

Taking the curve of MR test piece with a strain amplitude of 20% as an example, the least square method was adopted to compile the calculation program, and the fitting steps are as follows:

(1) For the test curve, according to corresponding conversion relations, the nominal stress and strain were converted into real stress and strain (conversion formulas will be described in detail in later paragraphs); the converted data were copied into a txt file so that MATLAB can read it.

(2) After the fitting curve was determined, the origin and the maximum stress were taken as the two points of the fitting polyline; first, the loading point in the middle was approximately found on the curve, then, its coordinates were read and written into the program; and cx and cy were the largest abscissa and ordinate of the curve. bx and by were the coordinates of the selected inflection point of stiffness change.

(3) The matrix of output area difference i=1: 223 represents that the maximum abscissa value of the curve is multiplied by 10 times and the 223 vertical points in the matrix represent that there're 223 strain points on the curve; the ordinate j=1:20 represents there're 20 points.

(4) In specific calculations, taking above data as an example: if the coordinates of the largest point (22.3) on the curve and the inflection point (15.04) of the loading segment are determined, then the abscissa (strain) of the unloading segment should be between the two coordinates; if the abscissa of the unloading inflection point takes x=19 at this time, then the corresponding row in the matrix is the row where 190 is located. After that, the point with the smallest area difference in this row 0.2337 was found, and the corresponding j=8, which was then substituted into j=1:20, y=(j/2-1)*(-1)*0.1 to calculate the value of y, at this time, the ordinate of the unloading point had been determined.

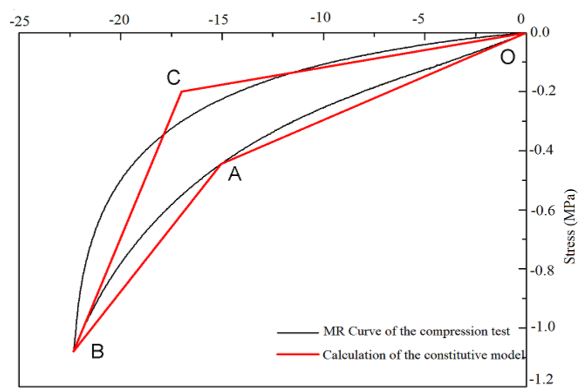

Figure 12. Fitting of the strain hardening polyline constitutive model

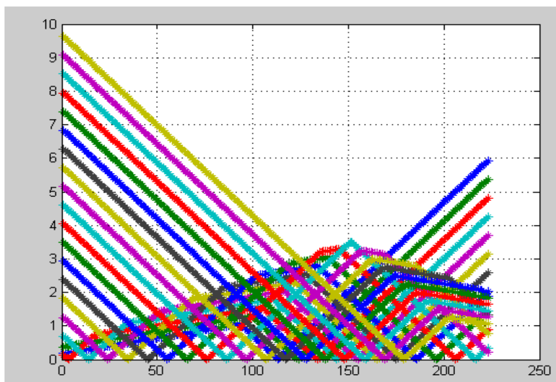

Figure 13. Unloading points with equal areas in constitutive fitting

Two things need to be noticed when applying this method: (1) It's better to put the abscissa of the unloading point in the middle; (2) The calculation should be performed based on the principle of smallest area, some unloading points may have two points that can meet the requirements (see Figure 13), then at this time, it depends on whether the abscissa conforms to the actual law of the test curve.

After values of first stiffness inflection point and unloading stiffness inflection point of the MR material were determined according to above constitutive relation, the parameters of MR subprogram in ABAQUS were adjusted according to these values.

5. CONCLUSIONS

This paper tested the compression, shear, and high-temperature mechanical properties of MR processed by improved processing techniques, and proposed a strain hardening polyline constitutive model on this basis. Then, taking the test curves of MR with a strain amplitude of 20% as an example, the least square method was employed to compile calculation program and adjust the MR subprogram in ABAQUS; the parameter model was fitted and verified, and main conclusions are as follows:

(1) The braiding and molding processing techniques of MR were improved based on current conditions, the number of metal wires in the molding direction was increased, compared with MR processed by ordinary processing techniques, the shear strength of improved MR in the non-compression molding direction had been enhanced; the distribution of its inner and outer layer structure, especially the edge structure, was more uniform; the overall elasticity and damping performance of MR components had been improved.

(2) At higher temperatures, overall speaking, the MR test pieces showed greater stiffness and stronger load bearing ability, that is, its recovery ability enhanced with the increase of temperature.

(3) The simplified constitutive model fitted according to the test curves can conform to the actual law of MR experiment. The proposed model can not only describe the strain hardening features of the material, but also conform to the test curves, the consumed energy was the same as the test curve, and it's easier to calculate.

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