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Metal Rubber Current Welding Reinforcement Based on Skin Effect

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In view that the metal rubber (MR) on the forming direction can bear larger load, but has the disadvantage of low tensile and shear resistance, and according to the characteristics of MR wire overlapping each other, the resistance structure model of MR was analysed and constructed. Current sintering method based on skin effect was put forward. Analysis and calculation of wire skin depth, equivalent resistance, joule heat was carried out on the basis of using 20MHz, 10A,10min alternating current sintering experiment, and resulted in the MR internal formed part of fusion welding where contacted. The tensile deformation and shear performance of MR after sintering are better than that of non-sintered MR. The results show that the mechanical properties of the MR can be improved based on the skin effect current sintering, and thus increase the service life and expand the application field.

1. Introduction

Resistance to high and low temperature, corrosion resistance, anti-radiation, not volatile in vacuum, not easy to aging and other characteristics of metal rubber which the traditional rubber is unmatched, make it been widely used in the national defense, industrial harsh environment, vibration damping, noise absorption, pressure, sealing, etc. The metal rubber is made of a series of mechanical processes such as 1Cr18Ni9Ti stainless steel wire with a wire diameter, and a series of mechanical processes such as cold-pressing and post-treatment, which interchanges with each other and has a certain porosity of the space network structure. The metal rubber not only has the inherent physical and mechanical properties of the selected stainless steel wire, but also its porous and stainless steel wire spiral coil arch structure so that the metal rubber has a similar elasticity and large damping characteristics of traditional rubber, when it is subjected to the load caused by deformation. Metal rubber material has the performance of the stainless steel wire hook structure between the slip, friction, extrusion, deformation in microscopic view, and thus dissipates a large amount of vibration energy (Li et al., 2011; Hu et al., 2009).
The special preparation technology and structure of the metal rubber decide that the metal rubber is an anisotropic material, which can bear a large compression load in the molding direction. But the tensile strength and shear strength are weak, especially under high frequency dynamic stretching or lateral shear load. It is easy to lead to the dense structure of spiral steel wire stripping, or even the stainless steel wire strain fracture, which greatly reduced the service life. In the practical application, the working environment of metal rubber is generally relatively poor, and may also bear a variety of loads. Although the metal rubber force state can be changed by improving the stainless steel wire cross-section, winding, forming pressure and shape, which avoids or can withstand greater tensile and shearing forces, the metal rubber process design and engineering implementation will become complicated and the cost will increase. At present, there are many domestic and foreign researches on the preparation of metal rubber and mechanical dynamic characteristics (Wang et al., 2011; Guo et al., 2009; Liu, 2003; Wang et al., 2010; Yang et al., 2015), the metal rubber sintering, making the internal stainless-steel spiral turning between the staggered contact area welding point by metal rubber sintering. The improvement of its strength and stiffness is still in the experimental stage. In order to facilitate the text, the metal rubber as a whole through the current is called sintering. Internal contact area through the current process is known as welding.

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For the metal rubber blanks to be sintered, it is necessary to ensure that the blank can pass a certain amount of current, and the purpose is to make the blank material to the melting point. During the sintering process, in order to prevent oxidation and other reactions, the blank must be oxygen, but from the tests, the use of inert gas isolation effect is better than the vacuum. When the current flows through the stainless-steel wire spiral, the current and the change of the spiral flow of the stainless steel wire are determined by the resistance of the wire, the stray inductance and the contact resistance of the hook wire (Yan et al., 2011). And with the change of temperature of the metal rubber pressure, these parameters nonlinear change. In the literature (Li et al., 2007), the temperature characteristics of the metal rubber materials were studied. The relationship between the linear expansion coefficient of the metal rubber material and the linear expansion coefficient of the metal material was deduced theoretically. It is revealed that the thermal expansion of the metal rubber material is influenced by the temperature change. The weaving process and the electric pulse strengthening system of the metal rubber material are introduced and a method to evaluate the sintering quality of the metal rubber by monitoring the instantaneous value of the dynamic resistance is presented. In the literature (Hou et al., 2006)), the mechanism and influencing factors of the resistance of the metal rubber discontinuous material were expounded from the internal structure, and the non-linear characteristics of the resistance and pressure of the metal rubber material and the relationship with the static stiffness were analyzed. However, the high-energy electric pulse sintering using single-pulse capacitor storage form, the current size and waveform by the line and the metal rubber itself do not have a greater impact on the resistance. Aiming to establish the model of metal rubber resistivity, the feasibility of welding high-frequency current on the internal contact area of metal rubber is analyzed based on the skin effect, and the theoretical analysis is carried out.

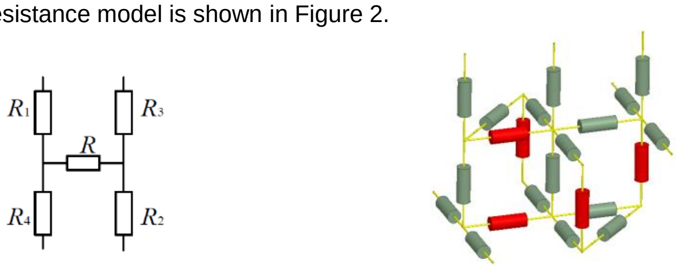
2. Metal rubber structure

Metal rubber is a kind of space network structure intertwined by the metal wire interlocking, and the cross contace between wire spirals forms a number of contact points. The internal structure of the metal spiral wire between the wire determine the number of hook contact points, contact form, contact resistance and other parameters. These parameters have an important impact on the metal wire hook lap joint welding point welding and welding quality. Common cylindrical metal rubber and metal spiral wound wire cross-contact structure are shown in Figure 1.

(a) Cylindrical metal rubber (b) Metal spiral wound wire cross - contact structure

Figure 1: Cylindrical metal rubbers and metal wire cross contact structure

Due to the mutual overlap between the metal spiral filaments, the resistance of the metal rubber specimen can be seen as being formed by a plurality of tiny resistive elements through complex series-parallel connections, including the internal resistance of the wire material itself and the wire contact resistance. Metal rubber resistance model is shown in Figure 2.



(a) Two metal spirals formed by contact (b) Multiple contact point spatial structures

Figure 2: Resistance model of MR

Figure 2 (a) is the schematic diagram of the two-spiral roll to form a contact point; R is the contact resistance; R_1-R_4 are the wire internal resistance. As for the metal rubber for the three-dimensional model structure, there are contact points in the space in all directions, as shown in Figure 2 (b). The size of the contact resistance is directly related to the contact area and the pressure between the spiral filaments. With the increase of pressure, the contact area increases and the contact resistance decreases. As the wire is the same material, the factors that affect the value of R_1-$R4$ are only related to the length of the wire. During the current sintering process, the increase in the pressure applied to the metal rubber will result in an increase in the number of internal contacts of the metal rubber, and the structure of the resistance model will be more complicated.

In the case of the internal structure of the metal rubber and the requirement of the decrease in the performance of the metal rubber after sintering, it is difficult for the spiral coil to contact the loose point or the non-contact part to form the welding point. The influence of the internal structure of the metal rubber on the current sintering process is as follows:

(1) Wire diameter is very small, usually between 0.1-0.3mm, belonging to the micro-wire welding. When the current through the wire, due to the fact that the existence of internal voltage drop is different from the resistance value, the current will appear redistribution of the situation. The temperature of small current wire is difficult to reach the melting point in a certain period. The big current wire will cause fusing, and these all will have an adverse effect on sintering.

(2) The great number of lap between the wire and the high density of these laps leads that it is difficult to control the contact point between the metal wire and the welding points. And complex process, low efficiency welding cannot complete the welding task.

(3) The welding process should not be involved in the solder. The tiny pore structure inside the metal rubber makes it difficult to fill in the contact point enough solder, and will have an impact on the performance of metal rubber.

3. Feasibility analysis of metal rubber welding

From the perspective of a single contact area within the metal rubber melt welding, the principle of current welding of metal rubber and resistance welding is similar; but from the overall situation inside the metal rubber, there is a big difference with the resistance welding. Because each branch in the metal rubberat different pressure with a small resistance must be different, resulting in uneven current distribution. The current is small, and the Joule heat is difficult to form nuggets. Large current is easy to cause liquid metal splash, so that the stainless steel wire fuses. The key to welding metal rubber is the control of the current. 1Cr18Ni9Ti stainless steel melting point is 1120-1398 ℃, and due to the different stainless steel mixed trace elements, 1200 ℃ is taken for the assumed melting point. According to the thermodynamic formula: $\mathrm{Q} = \mathrm{C} \times \mathrm{m} \times \Delta\mathrm{T}$

In this formula, Q is Joule heat, kJ; C is the specific heat capacity, 0.5 kJ / (kg.K); M is the mass, kg; ΔT is the temperature rise, K.

The ambient temperature is set to 298.15K (25 ℃), the temperature of the metal spiral coil is heat up to 1473.15 K (1200 ℃); and the temperature rise is 1175 K. The quality of metal rubber test product is 10 g, so the required heat of the specimen reaching melting point is about 5875 J.

The resistivity $\rho_t = \rho_0\ (1 + \alpha T)$ of 1Cr18Ni9Ti stainless steel is 0.73 μΩ / m at 20 ℃, where ρ_0 is the resistivity at 0 ℃; α is the temperature coefficient, 0.004; T is the temperature (℃), so the resistance of stainless steel wire can be expressed as: $\rho_t = 0.6759 \times (1 + \alpha \times T) \times 10^{-6}$

The electrical conductivity of stainless steel wire is available from equation: $\sigma = 1.4759 \times 10^6/(1 + \alpha \times T)$

The purpose of the metal rubber sintering is to form the fusing point at the hook contact and does not affect the mechanical properties of the other parts. If it meets the thermal energy required to the melting point of the 10 g mass metal rubber calculated by the formula (1), it will cause the metal rubber to melt into the whole liquid. Therefore, the use of current hook connection contact sintering must be based on skin effect, so that most of the current flow from the wire surface. When the temperature reaches the melting point value, in the case of external pressure, the contact point will generate a melting solid link point.

As shown in Figure 3, when the high-frequency current passes, regardless of the proximity effect and the ring effect, most of the current passing from the cylinder has the thickness of the wire Δr (the depth of the skin). Only the cylindrical part of the wire has a hindrance to the current.

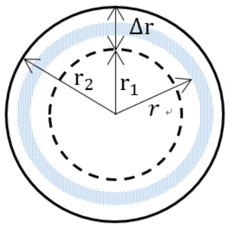


Figure 3: Schematic diagram of the skin effect of wire

Assuming that the equivalent resistance of the wire cylinder is R_{eq}, the inner and outer diameters are r_1 and r_2 respectively, and the length of the wire is L, and the micro-element dR of the shaded part in Figure 3, then: $dR=L/(2\pi r\sigma dr)$

Each resistor element is parallel in topology, so the equivalent resistance R_{eq} is: $R_{eq}=1/\int_{r_1}^{r_2}\frac{1}{dR}$

From formula (4), (5), it can be available: $R_{eq}=\frac{1}{\pi\sigma(r_2^2-r_1^2)}$

Since $r_1 = r_2 - \Delta r$, from (6), it can be available: $R_{eq}=\frac{1}{\pi\sigma(2r_2\Delta r-\Delta r^2)}$

According to the electromagnetic theory: $\Delta r - 1/\sqrt{\pi f\mu\sigma}$

Where μ is the permeability, from (7) we can see: $R_{eq}=\frac{L\mu\sigma}{2r_2\sqrt{\pi f\mu\sigma}-1}$

Resistance power consumption: $P_R=I^2R_{eq}$

Then in the current effective time t, the resulting Joule heat is: $Q_R=I^2R_{eq}t$

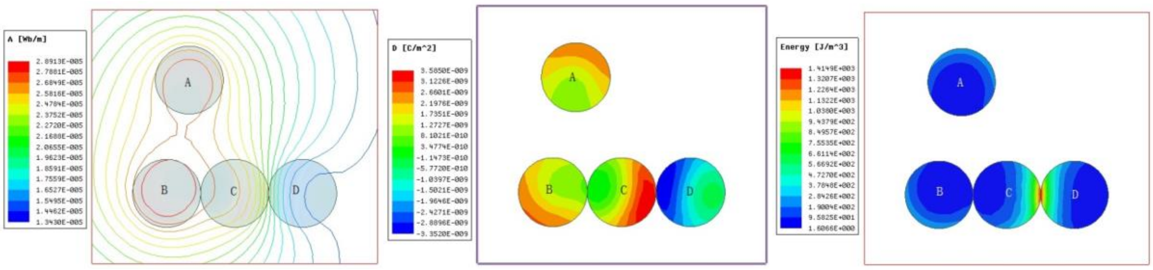
Under the action of the current skin effect, the effective flow area is reduced. According to the formula (8), the skin depth is 0.0925 mm at the frequency of 20 MHz. In this case, it can be considered that the quality of the metal rubber product is reduced, but the stainless-steel wire is a good conductor of heat, and the flow-through part will heat it in a heat conduction area with a small flow density. After considering various factors, (1) calculated by the Joule heat multiplied by the coefficient of 0.8. According to (8) - (11), there are:

$4700=I^2L\mu ft/(2r_2\sqrt{\pi f\mu\sigma}-1)$

When the length of the metal spiral wire is 1 m, the diameter is 0.3 mm and the frequency is 20 MHz, so the equation (12) can be further calculated as: $4700=\frac{25.1327\times\sqrt{1+0.004T}}{3.2425-\sqrt{1+0.004T}}I^2t$

From formula (13) we can see that the required Joule heat is related to the sintering time and the rms value of the current. After calculation, it can be seen that the time is 4.2 s, 17 s and 420 s when the current rms is 10 A, 5 A and 1A, respectively.

The above analysis shows that the wire through the high frequency current time is long enough, and it can be achieved by the outside of the melting, which is that the metal rubber can be a prerequisite for current sintering. However, there is a large amount of contact between the metal within the micro-element. When the current flows through the alternating current, the electromagnetic field generated by the wire will affect each other. The current density based on the skin effect must be redistributed, and the ANSYS software is used to flow through 20MHz, 20A current. The current density and Joule thermal effect simulation results are shown in Figure 4. Where the wire A, B, C flow through the same current direction, D flows through the opposite direction of the current. It can be seen from Figure 4 (b) that the current density of the wire is larger than that near the outer surface, but the current density is concentrated on the side of the coupling magnetic field due to the mutual influence of the electromagnetic field. It is apparent from Figure 4 (c) that melting welding is more likely to occur between the wires passing through the opposite current and the contact.



(a)Magnetic flux density distribution (b) Current density distribution (c) Joule heat effect

Figure 4: Metallic magnetic fields interact with each other

4. Verification and evaluation of welding of metal rubber

Increasing the sintering current is effective, and it can reduce the sintering time, but the high frequency current generation puts forward higher requirements. According to the literature [8], we can see that when the metal rubber component resistance is in the order of hundreds of milliohms, a certain current required voltage level is not high, and the power supply should be constant current source. Design of the principle of the main circuit sintered is shown in Figure 5, and sintering control of the main circuit is the H-bridge form. Q1, Q2 are using two high-frequency power transistor 2SC3255 parallel, and Q3, Q4 are the complementary PNP-type transistor 2SA1291. The same two parallels are used in order to improve the flow capacity. Transistor voltage is 80 V, and rated current is 10 A, β = 170. The working state of power amplifier is switching frequency up to 100MHz. PWMA, PWMB are the timing complementary drive signal generated by high-performance singlechip TMS32F407 I / O port. Due to limited microcontroller drive capacity, the transistor 2N5551 (Q5, Q6) is used as power amplification. At the time of sintering, the electrode (copper plate, one fixed and the other can be moved longitudinally) exerts a certain pressure on the metal rubber under the control of the servo motor and maintains the pressure constant to ensure reliable contact of the metal spire coil.

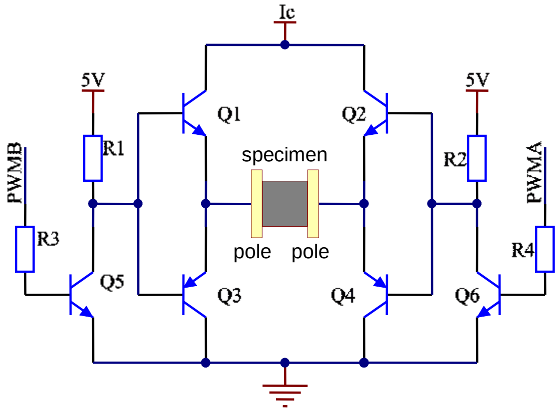


Figure 5: Control main circuit of MR sintering

From the control feasibility point of view, set the constant current source current 10 A. Considering the loss of heat during the sintering process, and the wire multiple resistance branch in parallel reducing the tributary current, the actual sintering time is set to 10 min. The sintering effect is shown in Figure 6. As shown in Figure 6, the two-metal helical wire contact portions are formed with a relatively smooth weld point. However, due to the uneven density of the wire itself or the length of the wire overlap, the resistance values are different from Figure 2. The current in the metal rubber inside the various flow branches is not equal, resulting in the erosion of part of the metal wire, as shown in Figure 6 area B.

Stretching comparison was made between those of the metal rubber subjected to current sintering and no sintering treatment, and the curves of tensile deformation are shown in Figure 7. Compared with the curve, it can be seen that the tensile strength of the metal rubber specimen subjected to current discharge sintering is obviously higher than that of the non - discharge welding specimen. In the case of the curve, the tensile force and the tensile length are approximately linear in the 60 mm tensile amount, which indicates that the internal structure is stable during the stretching process. After more than 60 mm elongation, the rising trend of the curve of the discharged welding specimen slightly slows down and the fluctuation is small, but the overall trend change is still relatively stable. This indicates that the solid metal hook formed between the internal metal wire of the metal rubber has played a stable relationship. But the beginning of the curve of the test piece which is not through the discharge begins to fluctuate apparently, and the tensile force declines more seriously in the situation at back. At this time, the inner part of the metal rubber specimen has begun to break.

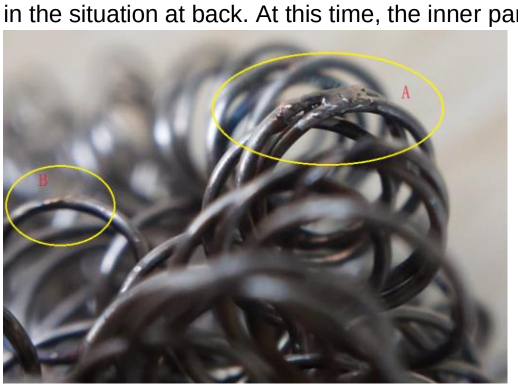


Figure 6: Effect of MR sintering

The tensile strength of the metal rubber is 80 mm; the length of the twist arm is 190 mm; the height of the platform is 70 mm at the initial position; and the height of the platform is 70 mm. In the experimental process, the descending displacement of the platform is 120 mm. After the calculation, the maximum linear displacement is converted to the maximum torsional angle of 27.5 °. At this time, the pressure applied to the rocker arm is 0.31 kN and 0.2 kN respectively, and the pressure exerted by the elevator is converted into metal rubber according to the relationship between arm length and angle. And the torsional moments applied to the metal rubber by the rocker arm are 55.89 N·m and 36.1 N·m respectively. The load-displacement contrast curve of the metal rubber torsion process is shown in Figure 8. It can be clearly seen through the comparison that the anti-torsion ability of discharged welding metal rubber specimen is significantly stronger than the test pieces of metal rubber without discharge welding.

Through the above experiment, a smoother welding point is formed inside the metal rubber which is sintered through the current. To a certain extent, it improves the tensile resistance and shear resistance of the metal rubber material.

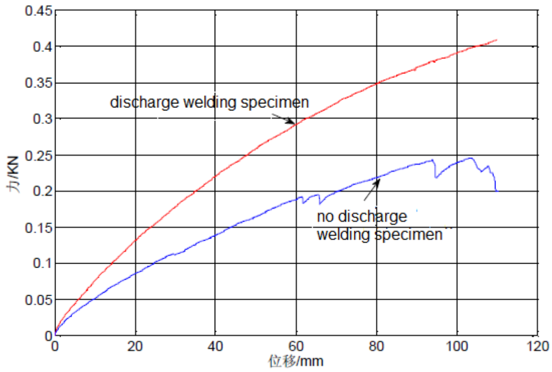


Figure 7: Tension-deformation contrast curve

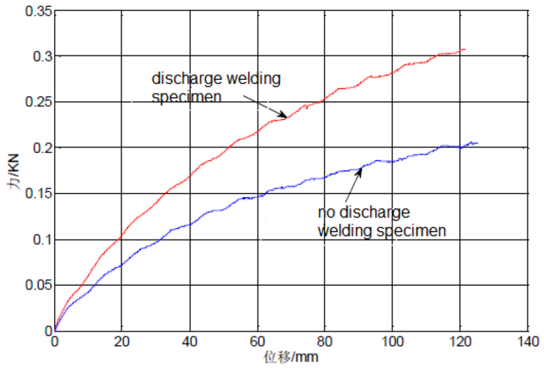


Figure 8: Load-displacement contrast curve

5. Conclusion

(1) Based on the intertwined contact structure of the spiral rubber inside the metal rubber, a three-dimensional model of the metal rubber was established, which provided the theoretical basis for the internal contact area of the metal rubber.

(2) Based on the Joule heat law, the current required to form the welding point inside the metal rubber was analyzed. The simulation of the current density and Joule heat energy distribution under the skin effect were carried out by ANSYS, which indicated that the contact area flowing through the opposite direction of the current was prone to welding.

(3) A high frequency alternating pulse current generation circuit was built, and the metal rubber sintering formed a welding structure in the metal rubber within the contact area.

(4) The mechanical properties of the same type of metal rubber before sintering indicated that after the current welding strengthening, the metal rubber shear resistance and tensile properties have improved.

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