Selection criterion of material filling in ridge grooves for reducing cross-sectional deformation of double-ridged rectangular bent tube

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Abstract

In order to satisfy the further improvement of new communication equipment, filling the ridge grooves on side walls with fillers is the effective method to improve the quality of double-ridged rectangular bent tube in H-typed rotary draw bending. However, how to choose appropriate material filling in ridge grooves to reduce deformation more effectively is a critical issue. Therefore based on the reliable FE models of H-typed rotary draw bending and twice-springback of double-ridged rectangular tube with fillers with different material parameters, a selection criterion of the material of filler to minimize the cross-sectional deformation of bent tube was studied. The selection criterion is that only the height size accuracy of filler should be made sure to be consistent with that of the ridge groove. The strength coefficient $K$ of filler should be considered firstly, and the larger $K$ can reduce the deformation more effectively. The yield strength $\sigma_y$ and hardening exponent $n$ can be considered secondly, and filler with higher $\sigma_y$ or smaller $n$ can be selected as far as possible. Elastic modulus $E$ may not be taken into account. The reliability of this selection criterion is verified by using 65Mn spring steel filler.

1. Introduction

With the advantages of wider bandwidth and lower loss, the small-sized double-ridged rectangular tube (DRRT) and its bent tube obtained by rotary draw bending (RDB) have been widely used in microwave communication equipments of aerospace, radar and so on [1, 2]. However, the cross-sectional deformation which affects the forming quality of bent tube occurs easily during the bending process. With the further improvement of new communication equipment, it is urgent to produce complex and precise double-ridged rectangular bent tube, which meet the higher mechanical strength parameters and electrical transmission index. So, controlling cross-sectional deformation has become the primary task to improve the quality of double-ridged rectangular bent tube.

The method of using rigid mandrel or filling other materials in DRRT has been usually used to reduce the cross-sectional deformation. But only the internal support can not well restrict the severe deformation of the ridge groove [3, 4], like the H-typed bent tube as shown in figure 1(a), which was bent along the narrower plate without ridge grooves. It is noteworthy that the magnetic field near the ridge grooves is relatively more dense. When small deformation of ridge groove occurs, magnetic field may undergo changes that cannot be ignored [5]. Liu et al. [6, 7] found that, when tube is bent along the wider plate with ridge grooves, that is E-typed RDB, the significant shrinkage deformation of inner ridge groove of bent tube can be restrained effectively by adding bulge on the bending dies or adding filler into the ridge groove. But considering the possibility of installing and unloading the bending dies, it is difficult to realize the method of adding bulge on H-typed RDB dies. So an effective method of filling the ridge grooves on side walls with fillers was put forward to reduce the deformation...
of ridge grooves [8], as shown in figure 1(b). However, which material is more suitable as fillers, and how to choose the material of fillers are urgent problems to be solved.

Some scholars studied the influence of different fillers on the cross-sectional distortion and formability of profiles with complex cross-section in bending process, including the DRRT. Chen et al [9, 10] proposed that using polymer as filler in DRRT and ridge grooves, it is found that with the increase of hardness of polymer fillers, the collapse of tube could be reduced effectively. However, the deformation of ridge grooves is not restrained significantly and effectively by the polymer fillers.

For some complex-section profiles, Lu [11] discovered that polyurethane with Shore 80A hardness was the most suitable filler to restrain the cross-sectional deformation of semi-open Al-Li alloy profile in roll-bending process. Combining the finite element simulation and experiment, Guo et al [12] found that the low-melting-point mandrel could make L-shaped hollow parts with better formability and quality than the polyurethane rubber mandrel and ball bearing mandrel. For a kind of complex-section profile with groove, which is used for side windows of metro vehicles, Wang and Chen [13] put forward the method of filling low melting point alloys in grooves to avoid excessive depression of profile. It was found that when the size of low melting point alloy strip was too large, that is the size of strip was consistent with the size of groove, the toughness of strip was not enough, fracture would occur on the alloy strip and bent profile. In order to avoid this defect, the whole alloy was cast into several small strips and placed side by side in the groove, which would not be broken due to uneven stress. This means that the size and shape of filler also affect the bending quality of profiles.

In the above researches, most fillers are low melting point alloys and polymer materials. However, the low melting point alloy is brittle and has poor flexural and torsional resistance, it is easy to adhere to the profile to form a corrosion source, so it is not suitable as the ridge groove filler. For polymer materials, there are too many kinds with different hardness, which may increase the difficulty and cost of material selection. At the same time, Liu et al [8] also found that the support effect of polymer material on ridge grooves was far smaller than that of metal materials, such as H96 brass and 3A21 aluminium alloy with better strength and stiffness. These metal fillers are machined from metal sheets, which not only play a good supporting role in the ridge grooves, but also have low processing difficulty and cost. It is also found that, as metal fillers, 3A21 aluminum alloy filler can reduce the deformation of bent tube more effectively than H96 brass filler. However, whether there are other kinds of metal fillers that can reduce the deformation more effectively is still unknown.

Up to now, there is no detailed and reliable criterion for the selection of filling materials, which can not effectively guarantee the stability of forming quality of DRRT in bending process. How to choose appropriate material and size of filler to reduce cross-sectional deformation is also unknown. So in this paper, combined with experiment and finite element (FE) simulation, the influence rules of size and material parameters of filler on the cross-sectional deformation of double-ridged rectangular bent tube and sensitivity of deformation on material parameters are studied to determine the selection criterion of material filling in ridge grooves. This research can provide the foundation for choosing the appropriate material parameters and size of ridge groove filler to manufacture the double-ridged rectangular bent tube with better quality.

2. Description of cross-sectional deformation

In the previous study of this laboratory [8], it was found that when the ridge groove fillers are used, the deformation difference between different cross sections along the bending direction is small and the distribution of deformation is more uniform. So in this paper, the average values \( \delta_{11}, \delta_{10}, \delta_{1b} \) and \( \delta_{h} \) of the maximum height
deformation of tube $\delta_{H_{\text{max}}}$, the maximum height deformation of ridge groove $\delta_{h_{\text{max}}}$, the maximum width deformation of tube $\delta_{B_{\text{max}}}$ and the maximum spacing deformation of the ridge grooves $\delta_{b_{\text{max}}}$ of different cross sections are used to describe quantitatively the cross-sectional deformation of the bent tube, as shown in equations (1)–(4).

\[
\delta_H = \text{Avg} \left( \sum \delta_{H_{\text{max}}} \right) = \text{Avg} \left( \sum \max \left( \frac{H - H_i}{H} \times 100\% \right) \right) \tag{1}
\]

\[
\delta_h = \text{Avg} \left( \sum \delta_{h_{\text{max}}} \right) = \text{Avg} \left( \sum \max \left( \frac{h - h_i}{h} \times 100\% \right) \right) \tag{2}
\]

\[
\delta_B = \text{Avg} \left( \sum \delta_{B_{\text{max}}} \right) = \text{Avg} \left( \sum \max \left( \frac{B - B_i}{B} \times 100\% \right) \right) \tag{3}
\]

\[
\delta_b = \text{Avg} \left( \sum \delta_{b_{\text{max}}} \right) = \text{Avg} \left( \sum \max \left( \frac{b - b_i}{b} \times 100\% \right) \right) \tag{4}
\]

where $H$ and $h$ are the original height of the tube and the ridge groove; $B$ and $b$ are the original width of the tube and the original spacing of ridge grooves; and $H_i$, $h_i$, $B_i$ and $b_i$ are those dimensions at node $i$ after deformation as shown in figure 2.

3. Establishment and verification of FEM of H-typed RDB of DRRT with fillers

In this study, because of the use of ridge groove fillers, the FE model of H-typed bending of H96 brass DRRT consists of three sub-models, namely, the bending model, the first springback model after unloading rigid dies and the second springback model after removing fillers.

3.1. Bending model

3.1.1. Mesh generation

According to the previous research work [8], a reliable finite element model of H-typed RDB of H96 brass DRRT with 3A21 aluminum alloy fillers has been established. In order to improve the accuracy and efficiency of calculation, the model established in this paper is to optimize the previous model. The H96 brass tube is defined as a continuous isotropic shell element, and 3A21 aluminum alloy filler is defined as a continuous isotropic solid element. The Swift constitutive equation, $\sigma = K (\varepsilon^p + b)^n$, is employed to describe the plastic deformation of material. Through the uniaxial tensile tests, the main mechanical properties of these two materials are obtained and shown in table 1.

The mesh of DRRT is still divided into the finer 1 mm $\times$ 1 mm. The meshes of rigid dies are still divided into sparse 3 mm $\times$ 3 mm. The function of filler is to support ridge groove to prevent its excessive deformation. The mesh generation of filler will affect the calculation accuracy of its deformation in thickness direction, which also
directly affects the simulation accuracy of cross-section deformation of double-ridged rectangular bent tube. Therefore, the optimization of the mesh of filler is important.

Four different mesh sizes, as shown in Table 2, are selected to divide the filler, and then the effects of mesh sizes of filler on the simulation accuracy of cross-sectional deformation of tube are compared. As shown in Table 2, it can be seen that when the mesh size is 0.5 mm × 0.5 mm, the cross-sectional deformation \( \delta_H \), \( \delta_B \), \( \delta_h \) and \( \delta_b \) gradually converge to 4.03\%, 6.87\%, 1.80\% and 9.49\%, respectively. When the mesh size is reduced to 0.3 mm × 0.3 mm, the computational time increases significantly. The mesh generation needs to deal with the contradiction between the accuracy of solution and the calculation time properly. Therefore, compared with the model established in the previous work, where the filler is divided into 1 mm × 1 mm, dividing the filler into 0.5 mm × 0.5 mm meshes in this paper will make the calculation more convergent and accurate in a reasonable computational time.

On the other hand, considering that the filler only has large deformation in the bending area. In order to further shorten the calculation time without affecting the accuracy of simulation calculation, the mesh of the bending deformation area of filler is divided into smaller 0.5 mm × 0.5 mm, while the mesh of non-bending straight area is divided into larger 1 mm × 1 mm. The final filler with local mesh refinement and the meshed model of H-typed bending of DRRT are shown in Figure 3.

### 3.1.2. Selection of mass scaling factor

During the module solving process of ABAQUS/Explicit, the larger the time increment step \( \Delta t \), the less the incremental step needed to complete the analysis step, and the shorter the calculation time used. In the analysis process, the time increment step must be less than a certain limit value, that is, the stable time increment step \( \Delta t_s \), otherwise it is difficult to accurately integrate the solution variables. The stable time increment step \( \Delta t_s \) can be calculated by equation (5) [14]:

![Figure 3. Meshed model of H-typed RDB of DRRT.](image-url)
where $L_e$ is the smallest element size, $\rho$ is the density of material, $\lambda$ and $\mu$ are the effective Lame constants of material.

It can be seen from the formula that when $L_e$ is fixed, the greater $\rho$, the larger $\Delta t_s$. Mass scaling is based on this principle, artificially increasing the $\rho$, thereby increasing the limit of $\Delta t_s$ and shortening the analysis time to improve the efficiency of calculation. The size of mass scaling is measured by the mass scaling factor. The influence of mass scaling factors of 1500, 3000, 4500, 6000, 7500, 9000, 10 500 and 12 000 on the computational efficiency is studied, and then the relationship between simulation time and mass scaling factors is shown in figure 4.

It can be obtained that the simulation time decreases with the increase of mass scaling factor, which indicates that it is effective to use the mass scaling technology to improve the simulation efficiency. In the model established in the previous work, the mass scaling factor is set as 10 000. Figure 4 shows that when the mass scaling factor reaches 6000, the decline of simulation time begins to become gentle, that is when the mass scaling factor is 10 000 and 6000, the calculation time in these two conditions is similar. However, it is worth noting that increasing the density of materials will lead to too much inertia effect, reduce the accuracy of dynamic solution, so the allowable time increment step should not be too large. Therefore, the mass scaling factor of the model established in this paper is 6000.

On the basis of the established model in the previous research [8], by optimizing the mesh generation and mass scaling factors, the optimized model of H-typed RDB of H96 brass DRRT with ridge groove fillers with higher calculation accuracy and efficiency is established, as shown in figure 5.

### 3.2. Twice-springback model

The springback of bent tube will occur after bending, which has a certain impact on the final cross-sectional deformation of bent tube. So in order to improve the accuracy of the research results, the springback model must be indispensable. Due to existence of filler, there will be twice-springback after bending process, that is, the first
springback of the bent tube with fillers after unloading the rigid dies and the second springback of the tube itself after removing the fillers, so a twice-springback model should be established. The springback process is the release process of stress and strain. It is necessary to import the information of stress and strain fields of the bent tube and fillers calculated from the previous model into the next springback model. At the same time, in order to keep the total energy of system unchanged during unloading process, the encastre boundary is applied to the bending front position of bent tube that does not deform to restrain its rigid body motion in the springback model.

Based on the above analysis, the final established first springback model after unloading the rigid dies and the second springback model after removing the fillers are shown in figures 6(a) and (b), respectively.

Table 3. Experimental and simulation conditions.

| Parameters                              | Experiment | Simulation |
|-----------------------------------------|------------|------------|
| Angular velocity of bending, \( \omega \) (rad·s\(^{-1}\)) | 0.5        | 0.5        |
| Bending angle, \( \theta \) (°)         | 90         | 90         |
| Bending radius, \( R \) (mm)            | 60         | 60         |
| Boosting velocity of pressure, \( V_p \) (mm·s\(^{-1}\)) | 35.21      | 35.21      |
| Friction coefficient-tube/filler        | A little hydraulic oil | 0.27      |
| Friction coefficient-tube/clamp die     | Dry friction | Rough      |
| Friction coefficient-tube/mandrel       | Large quantity of hydraulic oil | 0.01 |
| Friction coefficient-tube/other dies    | A little hydraulic oil | 0.17 |
| Clearance-tube/mandrel, \( C_m \) (mm) | 0.2        | 0.2        |
| Clearance-tube/other dies (mm)          | 0          | 0          |

springback of the bent tube with fillers after unloading the rigid dies and the second springback of the tube itself after removing the fillers, so a twice-springback model should be established. The springback process is the release process of stress and strain. It is necessary to import the information of stress and strain fields of the bent tube and fillers calculated from the previous model into the next springback model. At the same time, in order to keep the total energy of system unchanged during unloading process, the encastre boundary is applied to the bending front position of bent tube that does not deform to restrain its rigid body motion in the springback model.

Based on the above analysis, the final established first springback model after unloading the rigid dies and the second springback model after removing the fillers are shown in figures 6(a) and (b), respectively.

3.3. Verification of FEM

Using bending dies and rigid mandrel, H-typed RDB experiment of H96 brass DRRT with 3A21 aluminum alloy ridge groove fillers is carried out on CNC tube bending machine. The simulation conditions are consistent with the experimental conditions, as shown in table 3.

The profiles of the final bent tube in simulation and experiment are obtained and shown in figure 7(a). Then measuring the bent tube mentioned above, the distribution of the maximum spacing deformation of ridge grooves \( \delta_b \) along the bending direction are depicted in figure 7(b), in which according to whether springback is considered or not, the simulation results include two cases, one is after twice-springback, the other one is before springback.

From figure 7(a), it can be found that simulation results coincide well with the experiment results and the tube is well deformed without obvious defects. Furthermore, it can be found from figure 7(b) that, whether or not to consider springback, the distribution trend of \( \delta_b \) of the simulation results are close to the experiment results. When springback is not considered, that is if the twice-springback model is not established, the maximum relative error between experimental and simulation results is up to 14.3%, and the average error is
about 10.8%. However, when considering springback, that is the simulation result is obtained through twice-springback model, the maximum and average errors will be reduced to 9.1% and 3.6%, respectively.

It can be seen that the consistency between simulation results after twice-springback and experimental results is higher than that without considering springback. Thus, it can be concluded that the establishment of twice-springback model is very necessary, and the established FE models of bending and twice-springback are reliable. So the data analyzed in the later study are simulation results after twice-springback.

4. Effect of filler parameters on cross-sectional deformation of DRRT

4.1. Impact of size of filler

The size of ridge groove is 1.85 \( \times \) 2.79 mm, the size of filler should be the same as that of the ridge groove, that is 1.85(h') \( \times \) 2.79(b') mm. The metal filler is generally obtained from metal sheet by wire cutting. The thickness of commonly used sheet is produced in multiple of 0.5 mm. Considering the small size of filler, processing cost and efficiency, the height and width of filler can not be guaranteed to match the size of ridge groove simultaneously. For example, the sheets with thickness of 1.5 mm and 2.5 mm can be chosen and directly processed into fillers with size of 1.5(h') \( \times \) 2.79(b') mm, 1.85(h') \( \times \) 2.5(b') mm and 1.5(h') \( \times \) 2.5(b') mm. Taking fillers with the above-mentioned sizes as simulation objects, the impact of size of filler on cross-sectional deformation of double-ridged rectangular bent tube is studied to obtain the reasonable size of filler, the results are shown in figure 8.

It can be seen that when the size is 1.5(h') \( \times \) 2.79(b') mm and 1.5(h') \( \times \) 2.5(b') mm, each deformation is similar but large. When the size is 1.85(h') \( \times \) 2.79(b') mm and 1.85(h') \( \times \) 2.5(b') mm, that is, when the height of filler is consistent with the height of ridge groove, the difference of each deformation is also not large. But except for the width deformation of the tube, other deformations are significantly smaller than that when the height of filler is 1.5 mm. This indicates that the height size of filler has a greater significant effect on the cross-sectional deformation of double-ridged rectangular bent tube than the width size. Therefore, it is only necessary to keep the height size accuracy of filler approximately identical with that of the ridge groove, and the width of filler is arbitrary.

4.2. Effect of material parameters of filler

4.2.1. Selection of material parameters

Generally speaking, elastic modulus \( E \) refers to the ability to resist elastic deformation, the larger the value, the smaller the elastic deformation under the same stress condition. Yield strength \( \sigma_r \) measures the difficulty of plastic deformation, the greater the value, the plastic deformation will occur more difficulty. Hardening exponent \( n \) represents the resistance to continue plastic deformation and the ability of uniform plastic deformation of material, the higher the value, the stronger the ability of uniform plastic deformation. The strength coefficient \( K \) reflects the comprehensive effect of \( \sigma_r \) and \( n \), which can be used as a comprehensive index to measure the formability of metal material. The material parameters of filler affect its deformation,
furthermore directly affect the cross-sectional deformation of double-ridged rectangular bent tube in the H-typed bending process.

In order to select the suitable filler material which can effectively improve the forming quality of double-ridged rectangular bent tube, taking the material parameters of previously studied 3A21 aluminum alloy as the reference values, the values of each parameter are selected within a certain range based on those reference values, as shown in table 4. Through single factor method, the effects of $E$, $\sigma_s$, $n$ and $K$ on the height deformation of tube $\delta_H$, the height deformation of ridge groove $\delta_h$, the width deformation of tube $\delta_B$ and the spacing deformation of ridge grooves $\delta_b$ are studied. When researching the influence of one parameter, the values of other parameters remain unchanged as the reference ones. The stress-strain curves of fillers with different material parameters required in the simulation are shown in figure 9, and the simulation conditions are as shown in table 3.

4.2.2. Effect of elasticity modulus
The effect of elastic modulus $E$ of filler on cross-sectional deformation $\delta_H$, $\delta_h$, $\delta_B$ and $\delta_b$ of double-ridged rectangular bent tube is shown in figure 10. It can be seen that with the increase of $E$, $\delta_H$ and $\delta_B$ decrease gradually, while $\delta_h$ and $\delta_b$ remain stable and basically unchanged. In addition, for the most significant deformation $\delta_b$, when $E$ reaches near 100 GPa, the variation trend of $\delta_b$ tends to be stable. But in general, the influence of elastic modulus on the cross-sectional deformation is not significant.

This is because when $E$ increases, the elastic deformation in total deformation of filler will be smaller and the plastic deformation will increase. Before $E$ increases to 92.81 GPa, which is the value of $E$ of H96 brass DRRT, the elastic deformation of filler will be larger than that of the tube, so that the deformation of ridge groove decreases with the increase of $E$. When $E$ reaches 92.81 GPa, there is a good synergistic deformation between filler and DRRT, and then the deformation of the ridge groove tends to be stable. Therefore, although the effect of modulus of elasticity is not obvious, when selecting filler with different $E$, the filler whose elastic modulus $E$ is greater than or close to that of the tube should be selected as far as possible.

4.2.3. Effect of yield strength
The effect of the yield strength $\sigma_s$ of filler on cross-sectional deformation $\delta_H$, $\delta_h$, $\delta_B$ and $\delta_b$ of double-ridged rectangular bent tube is shown in figure 11. It can be get that with the increase of $\sigma_s$, the deformation in height

| Elastic modulus $E$ (GPa) | Yield strength $\sigma_s$ (MPa) | Hardening exponent $n$ | Strength coefficient $K$ (MPa) |
|--------------------------|--------------------------------|----------------------|-----------------------------|
| 40                       | 60                             | 0.05                 | 120                         |
| 60.2                     | 80                             | **0.145**            | 170                         |
| 80                       | 99.75                          | 0.25                 | **225.28**                  |
| 100                      | 120                            | 0.35                 | 270                         |
| 120                      | 140                            | 0.45                 | 320                         |

Figure 8. Impact of size of filler on cross-sectional deformation of bent tube.

Table 4. Material parameters of filler in numerical simulation.
direction $\delta_H$ and $\delta_h$ decrease gradually, $\delta_B$ decreases first and then tends to be stable, and $\delta_b$ decreases with a very small extent.

This is because with the increase of $\sigma_s$, the plastic deformation of filler is very difficult to occur, and the support force of filler to ridge groove is greater. At the same time, the elastic deformation and elastic recovery of filler will increase, while the elastic recovery of double-ridged rectangular bent tube itself is small, so that the filler will squeeze the ridge groove and cause the ridge groove to be loaded in reverse direction.

All these reasons mentioned above will make the cross-sectional deformation reduced with the increase of $\sigma_s$, especially $\delta_h$. Therefore, the material of filler with higher yield strength $\sigma_s$ should be selected as far as possible.

Figure 9. The stress-strain curves of ridge groove fillers with different material parameters.

Figure 10. Effect of elastic modulus on cross-sectional deformation of bent tube.
4.2.4. Effect of hardening exponent

The effect of the hardening exponent $n$ of filler on cross-sectional deformation $\delta_H$, $\delta_h$, $\delta_B$ and $\delta_b$ of double-ridged rectangular bent tube is shown in figure 12. It can be seen that with the increase of $n$, the deformation in height direction $\delta_H$ and $\delta_h$ both increase. After $n$ reaches 0.145, the upward trend of both deformations weakens and tends to be gentle. For the deformation in width direction, $\delta_B$ increases slightly, it can be approximated that $\delta_B$ remains basically unchanged. $\delta_b$ increases significantly, and decreases sharply when $n$ is 0.35, but $\delta_b$ when $n$ is 0.45 is still greater than that when $n$ is 0.05.

The above analysis can be considered that the smaller the $n$, the smaller the cross-sectional deformation of double-ridged rectangular bent tube. This is because with the increase of $n$, the ability of uniform deformation of material becomes stronger. The strain distribution in the whole deformation zone is more uniform and plastic deformation is prone to occur. That is, with the increase of $n$, the plastic deformation of filler will also increase, which results in the decrease of the support effect of filler on the ridge groove, so that the deformation of ridge groove increases gradually. Therefore, the material of filler with smaller hardening exponent $n$ should be chosen as far as possible.

4.2.5. Effect of strength coefficient

The effect of the strength coefficient $K$ of filler on cross-sectional deformation $\delta_H$, $\delta_h$, $\delta_B$ and $\delta_b$ of double-ridged rectangular bent tube is shown in figure 13. It can be seen that each deformation of bent tube decreases while $K$ increases, only the degree of reduction varies.

This is because the strength coefficient $K$ reflects the local ultimate load that the material can bear within the range of uniform plastic deformation. With the increase of $K$, the load that the filler can bear by ridge groove increases, that is, the reaction force exerted by the filler on the ridge groove increases, so that the deformation of ridge groove decreases obviously. Therefore, the material of filler with larger strength coefficient $K$ should be chosen as far as possible.
5. Selection criterion of material filling in ridge grooves

5.1. Sensitivity analysis method

Only the influence of each material parameter of filler on the cross-sectional deformation of double-ridged rectangular bent tube is obtained in the above research, but which parameter has the most significant effect on the cross-sectional deformation, and which parameter should be emphasized as the criterion to select the material of filler remains to be discussed. Combining the sensitivity analysis method and finite element simulation, the significance and sensitivity of material parameters of filler on cross-sectional deformation of bent tube can be obtained, which provides guidelines for the selection of filler material.

Sensitivity analysis method is less affected by the range of parameters, and the factors with different dimensions can be put together for comprehensive comparison. The systematic characteristic of sensitivity analysis in this study is cross-sectional deformation $\delta_H, \delta_h, \delta_B$ and $\delta_b$ of double-ridged rectangular bent tube, the sensitivity analysis parameters are the material parameters of filler, namely its elastic modulus $E$, yield strength $\sigma_s$, hardening exponent $n$ and strength coefficient $K$. Then the sensitivity values of each deformation to the material parameters of filler can be obtained by equation (6) [15].

$$
S(\alpha_k) = \frac{1}{n-1} \sum_{k=1}^{n-1} \left[ \alpha_k \right] \frac{P_k - P_{k+1}}{P_k} \left( \frac{\alpha_k - \alpha_{k+1}}{P_{k+1}} \right) \quad (k = 1, 2, \cdots, n - 1)
$$

where, $\alpha_k$ is the k-th parameter value of a certain parameter, and $P_k$ represents the cross-sectional deformation when the parameter is $\alpha_k$.

5.2. Sensitivity analysis of material parameters of filler

The sensitivity values of each deformation to the material parameters of filler are shown in table 5. In order to more directly analyze the sensitivity of the material parameters of filler to the deformation and the primary and secondary order, the data in table 5 are shown in figure 14 in the form of a histogram.

As shown in figure 14(a), the sensitivity of one material parameter to each deformation is compared. It can be obtained that: (1) $E, n$ and $K$ have the most significant effect on $\delta_H$, then $\delta_b$ and $\delta_H$ in turn, and the effect on $\delta_B$ is very slight. (2) $\sigma_s$ also has the greatest impact on $\delta_B$, followed by $\delta_H$ and $\delta_b$, and that on $\delta_h$ is the smallest. The comprehensive analysis shows that these material parameters of filler have the most significant effect on $\delta_B$, while the effect on other deformation is small and inconsistent.

| Systematic characteristic $P$ | $S(\delta_H)$ | $S(\sigma_s)$ | $S(n)$ | $S(K)$ |
|-------------------------------|--------------|--------------|--------|--------|
| $\delta_H$                   | 0.0244       | 0.0405       | 0.0246 | 0.0298 |
| $\delta_h$                   | 0.0844       | 0.5234       | 0.3588 | 0.6206 |
| $\delta_B$                   | 0.0027       | 0.0062       | 0.0025 | 0.0079 |
| $\delta_b$                   | 0.0294       | 0.0350       | 0.0490 | 0.0543 |

Figure 13. Effect of strength coefficient on cross-sectional deformation of bent tube.
The sensitivity comparison of different deformation to material parameters of filler is shown in figure 14 (b). It can be discussed that: (1) $\delta_h$ is most significantly affected by each material parameter of filler. $K$ has the greatest influence, followed by $\sigma_s$ and $n$, the effect of $E$ is far less than that of other parameters. (2) The sensitivity of $\delta_H$ to each material parameter is low, among which the effect of $\sigma_s$ is the greatest, while $E$, $n$ and $K$ have little and similar influence. (3) The sensitivity value of $\delta_B$ to each parameter is approximately zero, which shows that the material parameters of filler basically have no effect on the width deformation of tube. (4) $\delta_B$ is also less affected by these parameters. Among them, $K$ is the most sensitive parameter, then $n$, and the effects of $\sigma_s$ and $E$ are the smallest and similar. It can be found from comprehensive analysis that $K$ has the most significant effect on most deformations. $\sigma_s$ and $n$ have different effects on different deformations, and $E$ has the least effect.

Therefore, combining the research and analysis in section 4 and section 5, when choosing the material filling in ridge grooves, the strength coefficient $K$ should be considered as the first choice, and the larger $K$ can reduce the deformation more effectively. The yield strength $\sigma_s$ and hardening exponent $n$ can be considered secondly, and filler with higher $\sigma_s$ or smaller $n$ is a better choice. Elastic modulus $E$ may not be taken into account. The above criterion for choosing the material of ridge groove filler can provide a basis for effectively reducing the cross-sectional deformation of double-ridged rectangular bent tube in H-typed RDB.

### 6. Verification of selection criterion

According to the selection criterion proposed above, 65Mn spring steel with larger strength coefficient $K$ is selected as another material filling in ridge grooves to further verify the reliability of this selection basis.

The material parameters of 65Mn spring steel are also obtained through the uniaxial tensile test and shown in table 6. Comparing to 3A21 aluminum alloy, $K$, $E$ and $\sigma_s$ of 65Mn spring steel are much larger, and $n$ of these two kinds of materials is similar. The simulation results of cross-sectional deformation of double-ridged rectangular bent tube are shown in figure 15, when the materials of filler are 3A21 aluminum alloy and 65Mn spring steel respectively. The results show that the 65Mn spring steel filler can reduce the height and spacing deformation of ridge grooves $\delta_h$ and $\delta_b$ more significantly than the 3A21 aluminum alloy filler. $\delta_h$ can be reduced to 0.3%, which is approximately zero, and it can be considered that the height of ridge groove is basically not

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**Table 6. Main mechanical properties of the selected filler.**

| Parameters         | 65Mn spring steel | 3A21 aluminum alloy |
|--------------------|-------------------|---------------------|
| Elasticity modulus | $E$ (GPa)         | 210.0               | 60.2                 |
| Yield strength $\sigma_s$ (MPa) | 418.0 | 99.8               |
| Hardening exponent $n$ | 0.162 | 0.145             |
| Strength coefficient $K$ (MPa) | 1074.38 | 225.28 |

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deformed. Although the height and width deformation of tube $\delta_H$ and $\delta_B$ is also reduced slightly when using the 65Mn spring steel filler, the effect is not much different from that of the 3A21 aluminum alloy.

This result proves that the above selection criterion of material filling in ridge grooves is reliable, it can provide credible guidance for choosing suitable filler material to effectively reduce the cross-sectional deformation of double-ridged rectangular bent tube in H-typed RDB.

7. Conclusion

(1) Based on ABAQUS/Explicit, the FE models of H-typed RDB and twice-springback of H96 brass DRRT with 3A21 aluminum alloy ridge groove fillers have been established and validated by the experiment.

(2) Through the study of the influence of filler size on the cross-sectional deformation of double-ridged rectangular bent tube, it is obtained that only the height size accuracy of filler should be guaranteed, which is consistent with that of the ridge groove, and the width size of filler can allow certain errors.

(3) The cross-sectional deformation of bent tube decreases with increase of yield strength or strength coefficient, and decrease of hardening exponent of filler. That is, the material of filler with larger strength coefficient, higher yield strength and smaller hardening exponent can reduce the deformation more effectively. While the effect of elastic modulus on the deformation is not obvious.

(4) Using the sensitivity analysis method, it is obtained that when selecting the material of filler, the strength coefficient should be considered firstly, the yield strength and hardening exponent can be considered secondly, elastic modulus may not be taken into account. The reliability of this criterion is verified by using 65Mn spring steel filler.

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