Research on deformation coordination of composite metal gears in the process of cold extrusion

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Abstract: In order to realize lightweight manufacturing of gear parts, the cold extrusion forming process of steel-aluminum composite metal gears was studied. Using numerical simulation software Deform, the effects of five steel rings with different thicknesses on forming pressure and shapes of formed forgings were compared. The simulation results showed that final forming force of the gear was smaller and the radial deformation degree of steel ring was larger when using thinner steel ring. This radial deformation degree was characterized by height difference between the convex and the concave in steel-aluminum bonding position, and great deformation presented as obvious bimetal occlusion. The physical experiment verified numerical simulation results, and meanwhile found that the thickness of steel sleeve had an important effect on bonding tightness of steel-aluminum contact surface of formed part and the composite gear formed by thin steel ring had a gap at tooth tip between steel and aluminum. Comprehensive analysis suggested the ratio of outer diameter to inner diameter (R0/Ri) of steel sleeve reflected different deformation regularity. Consequently, the thick-walled axial compression model was used to analyze forming process of steel sleeve with high R0/Ri ratio, and the thin-walled cylindrical shell model was used to analyze forming process of steel sleeve with low R0/Ri ratio. The axial compression of thin cylindrical shell produced local buckling deformation, which led to the appearance of gaps in steel-aluminum bonding position. In order to avoid gaps in bimetal contact surface, the influence of steel ring thickness on deformation coordination of two metals should be fully considered in cold extrusion of steel-aluminum composite metal gear.

1. Introduction

Gear products are widely used in the automotive and aerospace industries. Due to large torque and load, gear parts are generally made of steel. Researchers have tried to use low density materials to manufacture gears so as to reduce the weight of cars and aircraft and increase their endurance mileage[1,2]. The density of aluminum alloy material is only 30% of that of steel, which is an ideal weight-reducing material, but the gear parts made of aluminum alloy alone can not achieve the bending strength and contact fatigue strength. In order to achieve lightweight manufacturing and ensure the performance to meet the requirements of use, scholars have proposed to use two materials to manufacture gear parts. The gear teeth involved in meshing are made of steel and the interior of the gear are made of aluminum.
Some achievements have been published. Bulent Chavda et al. tried to adopt a composite billet, which was made of aluminum alloy inside and steel tubes welded and sealed with steel covers on the upper and lower faces outside. When the aluminum alloy core was heated to liquid and the outer steel shell remained solid, lightweight bimaterial gears were formed by hot hydroforging [3-5]. Politis et al. used the copper (ring material) and lead (core material) to manufacture a bimetal gear by cold forging process, and investigated the effects of some aspects such as ring thickness, the friction, and different combinations of materials on metal flow [6]. But copper and lead are not commonly used in the gear industry, where steel is the common material. Pengfei Wu et al. introduced a hot forging process for bimetal gears made of steel (ring material) and aluminum (core material) [7]. The process was researched by finite element simulation and forming experiment. The law of metal flow was analyzed. The influences of clearance, height difference and thickness of core ring on metal flow and forming load were studied. Xusheng Chang et al. proposed a thixotropic-core compound forging process to form aluminum-steel bimetal standard cylindrical spur gears [8]. The effect of initial temperature and steel shell thickness on the synchronous deformation mechanism of gear bimetal was studied by finite element method, and experimental verification was carried out. Gang Chen et al. proposed a new thixotropic-core compound forging technology, using 7075 aluminum rods and 304L stainless steel shells as billets for composite forging [9]. However, metallurgical bonding interfaces, which are essential for the mechanical performance, are usually difficult to be obtained due to Al2O3 oxide film. The influence of compression displacement and initial temperature on bonding interface formation was studied. When the initial temperature and compression displacement of steel shell were 900 ℃ and 20 mm respectively, the best metallurgical bonding interface was obtained.

Because of different forging temperatures of steel and aluminum, it is difficult to form steel-aluminum bimetal gear by hot forming method. The problems, such as temperature control during the heating of steel ring and aluminum core, hot assembly of steel ring and aluminum core, heat loss of billet caused by too long operation time, and oxides formed on the surface of steel ring and aluminum core during heating, bring uncertainty to forging. This work tried to use cold extrusion technology to form bimetal gears. The billet was made of annealed steel ring and aluminum alloy core. The aluminum alloy core was placed inside the steel ring and served as extrusion billet. The influence of steel ring thickness on forming force and forging shape was studied by numerical simulation and experimental method, and further analysis was made on the phenomenon that the gear forging formed by thin-walled steel ring had a gap at tooth tip of steel-aluminum contact surface.

2. FE numerical simulation and experiment

2.1 Establishment of the FE numerical simulation model
The spur gear with module 2.5, tooth number 18, addendum circle diameter 51 mm, root circle diameter 40 mm and height 20 mm was selected as research object. In order to achieve the forging of bimetal gear, this paper adopted steel-aluminum composite billet to form gear. The 3D model is shown in figure 1. The outer ring is made of AISI 1045 steel, and the inner cylindrical bar is made of aluminum alloy 6061. The forging finite element model was designed according to dimensions of research object, as shown in figure 2. In order to improve simulation accuracy and reduce calculation time, two teeth of the gear, namely 1/9 of the gear, were selected for simulation calculation. As the billet is part of cylindrical bar, a symmetry relationship should be set between the 1/9 steel ring and the aluminum alloy core. In the Deform numerical simulation software, the billet was set as a plastic body, and the tooth die, top die and bottom die were set as rigid bodies. The friction relation between steel-aluminum composite billet and the die was set as shear friction model, the friction coefficient was set as 0.12, the friction coefficient between steel ring and aluminum alloy core was set as 0.4, and the calculated extrusion step was set as 0.1 mm [10-13]. In the numerical simulation of gear forging process, the cylindrical billet was put into the mold cavity, the position of tooth die and bottom die remained unchanged, and the top die moved downward to squeeze the billet. With the continuous extrusion of top die, the metal filled the mold cavity.
In order to research the effect of steel ring thickness on bimetal gear forging, five steel rings with different inner diameters and aluminum alloy cores with corresponding diameters were used as billets. The numerical simulation of bimetal gear was carried out by using these five billets with different specifications, as shown in table 1.

| NO. | Ring thickness (mm) | Diameter of core (mm) | Inner diameter of ring (mm) | Outer diameter of ring (mm) |
|-----|---------------------|-----------------------|-----------------------------|---------------------------|
| 1   | 3                   | 33.5                  | 33.5                        | 39.5                      |
| 2   | 3.5                 | 32.5                  | 32.5                        | 39.5                      |
| 3   | 4                   | 31.5                  | 31.5                        | 39.5                      |
| 4   | 4.5                 | 30.5                  | 30.5                        | 39.5                      |
| 5   | 5                   | 29.5                  | 29.5                        | 39.5                      |

2.2 Numerical simulation results
Deform-3D numerical simulation software was used to calculate the deformations of steel ring and aluminum alloy core in five billet schemes. As shown in figure 3, all the steel rings are fully filled in five billet schemes, the metal thickness at tooth root increases with the thickness of steel ring, and the deformation at middle part of steel ring through thickness direction is greater than that at two ends. As the thickness of steel ring billet increases, the deformation of inner part of steel ring along tooth tip direction becomes smaller. In billet scheme 5, the deformation of inner part along radial direction is very small, and the bimetal bite is not obvious. It can be seen from the figure that the deformation of aluminum alloy core corresponds to that of steel ring, which shows "drum shape" after deformation, that is, thick in the middle and thin at both ends. With the decrease of inner diameter and the increase of thickness of steel ring billet, the protrusions and depressions along radial direction of aluminum alloy core become less obvious, and its occlusion with steel ring also becomes shallow. The thinnest part of steel ring and the biggest radius of aluminum alloy core are located in middle height of forming gear, due to the "drum shape" of aluminum alloy core after deformation.
Figure 3. Numerical simulation results of five billets with different specifications: (a) Billet scheme 1; (b) Billet scheme 2; (c) Billet scheme 3; (d) Billet scheme 4; (e) Billet scheme 5

The thickness data of steel ring at tooth root of forming gear, and the radius data of tooth tip and tooth root of aluminum core after deformation were used to quantify the deformation of steel ring and aluminum core. As shown in figure 4, the minimum size of steel ring thickness at tooth root \((h_{\text{min}})\) is located in the cross section in middle height of the gear, and the maximum size \(h_{\text{max}}\) is located at the end of the gear. The difference between the maximum radius \(R_{\text{max}}\) and the minimum radius \(R_{\text{min}}\) of aluminum alloy core in the cross section in middle height of the gear reflects the bimetal bite depth. The numerical simulation results of five billets with different specifications were measured. The measurement data for steel ring thickness at tooth root and bimetal bite depth are shown in table 2.

Figure 4. Section position for measurement data: (a) The end position of the gear; (b) The cross section in middle height of the gear
Table 2. Measurement data for steel ring and aluminum core of forming gear (mm)

| Date No. | h\text{max} | h\text{min} | R\text{max} | R\text{min} | R\text{max} - R\text{min} |
|----------|-------------|-------------|-------------|-------------|-----------------|
| 1        | 1.8         | 1.2         | 21.8        | 19.5        | 2.3             |
| 2        | 2.3         | 1.4         | 21.1        | 19.3        | 1.8             |
| 3        | 2.8         | 1.8         | 20.5        | 19          | 1.5             |
| 4        | 3.1         | 2.3         | 19.9        | 18.6        | 1.3             |
| 5        | 3.5         | 2.68        | 18.8        | 18          | 0.8             |

The results of numerical simulation and measurement data showed that the bimetal gear was fully filled, and the steel ring and aluminum alloy bar fitted closely. As the thickness of steel ring decreased, the radial deformation of aluminum alloy core increased, the difference between the convex at tooth tip and the concave at tooth root was larger, and the bimetal bite was more obvious. When the steel ring thickness changed from 5 mm to 3 mm, bimetal bite depth varied from 0.8 mm to 2.3 mm. Meanwhile, with the decrease of steel ring thickness, the “drum shape” of aluminum core became to a greater extent. This phenomenon shows that the drum-shaped spline connection interface formed by thinner steel ring is beneficial to circumferential occlusion between two metals and the axial fixed connection of two metals. According to measurement results, the specific variation trend of bimetal bite depth is shown in figure 5.

Forming load is a key reference in forging process, which is employed to determine the tonnage of hydraulic press and judge whether forgings can be formed. In the forging process, low stress on the die was produced owing to small forming load and prolonged the service life of the die. Figure 6 shows the forming force curves corresponding to five billets with different specifications. The change trends of forming load on top die in different billet schemes is relatively consistent. At the initial stage of forming, the load increases slowly, and the bimetal downward accumulation is less hindered. In the second stage of forming, the frictions produced by bimetal flow increase, which lead to a fast increase in the load on top die, including the friction between the bimetal and the die, as well as the friction in bimetal interior. In the middle of forming, bimetal flow is relatively stable, further filling the tooth-shaped die, and the load on top die increases slowly. At the end of deformation, the bimetal is almost fully filling the mold cavity, and its free flow surface decreases rapidly, resulting in a sharp increase in the load on top die. The comparative analysis of five billet schemes shows that the load on top die increases gradually with the thickness of the steel ring billet, indicating that the steel ring thickness has a great influence on the forming load. Therefore, when forging bimetal gear, the reduction of forming load and the improvement of service life of the die can be achieved by reducing the thickness of steel ring billet and increasing the proportion of aluminum alloy.

Figure 5. The bite depth of bimetal varies with the thickness of steel ring
Figure 6. Load-time curves for top die in five billet schemes
2.3 Forming experiment

In order to research the influence of steel ring thickness on gear forming and avoid the interference of other factors, the same batch of annealed AISI 1045 steel bar and aluminum alloy bar were selected. The steel rings and aluminum alloy cores corresponding to five billet schemes as table 1 were machined. The inner diameter of steel ring was transitional fit with the outer diameter of aluminum alloy core. Figure 7 shows five experimental billets after assembly. In the process of cold extrusion precision forming, the friction between billets and dies has a great influence on forging quality, maximum forming force and die life, so the billets should be lubricated before forming [14]. Polymer lubricant was used to lubricate the assembled bimetal billets [15,16].

![Figure 7. Five specifications of experimental billets](image)

The forming process scheme of bimetal gear was described as follows. The pressing stroke of the tooth-shaped top die was preset as 7mm, the billet was put into the mold cavity, the top die was pressed to the specified position, and the gear was deformed. Then the formed gear forgings were pushed out by bottom die, that is, the forging of bimetal gear was completed. Bimetal gear forgings were obtained by the above operations for five kinds of billets. The formed bimetal gear was fully filled, the bimetal were closely combined in upper and lower end faces of the gear, and the steel ring and aluminum alloy core bitted each other in the form of "wavy lines". When using thin steel ring with large inner diameter, the deformation of aluminum alloy along radial direction at the end face was enlarged and the bimetal bite was deeper. The maximum forming loads corresponding to five billet schemes are shown in table 3. It can be seen that the forming loads in five billet schemes are very close to those in numerical simulation. The maximum forming load gradually increases when decreasing the inner diameter of steel ring billet and increasing its thickness. The results show that steel ring thickness plays a leading role on the forming load of bimetal gear. The decrease of steel ring thickness can reduce forming force and prolong die life.

| Billet No. | 1          | 2          | 3          | 4          | 5          |
|-----------|------------|------------|------------|------------|------------|
| Maximum forming load (N) | 2.8×10^6   | 3.1×10^6   | 3.6×10^6   | 3.8×10^6   | 4.2×10^6   |

Wire cutting equipment was used to cut the forming gear from tooth tip and tooth root to the circle center respectively, as shown in figure 8. The final forming shapes of the steel ring and aluminum alloy core were observed to be consistent with simulation results. The tooth root thicknesses at the cross section in middle height and the two ends of the steel ring were measured \((h_{\text{max}}, h_{\text{min}})\), and the protrusion and depression of the aluminum alloy core were also measured \((R_{\text{max}}, R_{\text{min}})\). The practically measured results were basically consistent with numerical simulation data. The experiment data for steel ring thickness at tooth root and bimetal bite depth are shown in table 4.
Table 4. Experiment data for steel ring and aluminum core of forming gear (mm)

| No. | Date | h_{\text{max}} | h_{\text{min}} | R_{\text{max}} | R_{\text{min}} | R_{\text{max}} - R_{\text{min}} |
|-----|------|----------------|---------------|---------------|---------------|-------------------------------|
| 1   | 1    | 1.9            | 1.2           | 21.7          | 19.3          | 2.4                           |
| 2   | 2    | 2.3            | 1.5           | 21.0          | 19.1          | 1.9                           |
| 3   | 3    | 2.9            | 1.9           | 20.4          | 18.8          | 1.6                           |
| 4   | 4    | 3.2            | 2.5           | 20.1          | 18.6          | 1.5                           |
| 5   | 5    | 3.5            | 2.8           | 19.2          | 18.2          | 1.0                           |

The sections of bimetal gear cut respectively along tooth tip and tooth root to the center were observed to further investigate bimetal combination states at corresponding tooth root (figure 9) and tooth tip (figure 10). It can be seen from figure 9 that the bimetals formed from five billets with different specifications were closely bonded at corresponding tooth root, and the bending radian along bimetal boundary line at tooth root was small. Further microscopic observation showed that there was no metallurgical bonding between two metals. Figure 10 shows that obvious gaps appeared in the joint of tooth tip orientation in billet scheme 1, billet scheme 2 and billet scheme 3, which indicated that the bimetallic elements were not fully bonded. But the bimetals in billet scheme 4 and billet scheme 5 were closely bonded, and there was no gap observed. Further microscopic observation showed that no metallurgical bonding occurred between two metals. The bending radian along bimetal boundary line at tooth tip was large. However, the gaps in bimetal joint surface at tooth tip did not appear in numerical simulation, so this gap phenomenon was further analyzed.

Figure 8. Measurement position of formed gear
3. Discussion

The theoretical basis of Deform software is the revised Lagrange theorem, which belongs to rigid plastic finite element method and cannot accurately calculate elastic deformation. The compression deformation for aluminum core sleeved with steel ring is complex, in which elastic deformation and plastic deformation interact each other, and the finite element numerical simulation software cannot accurately predict deformation process. Therefore, the stress analysis for steel ring was carried out, and the stress diagram of bimetal billet under unidirectional extrusion was shown in figure 11. The bimetal billet was placed in the mold cavity, and the top die was used to squeeze the billet. With the increase of
extrusion pressure, both aluminum alloy core and steel ring firstly made upsetting elastic deformation. Following with elastic deformation, the radial dimension of aluminum alloy core became larger, resulting in a certain extrusion pressure on metal interface. When the extrusion force reached yield strength of aluminum alloy core and steel ring, the top die continued to move downward to squeeze bimetal billet, so that the upsetting plastic deformation of bimetal occurred under the action of axial stress $\sigma_z$. In the process of axial plastic deformation of bimetal billets, the internal pressure generated at bimetal junction gradually increased, under the action of which the radial stress $\sigma_r$ and circumferential stress $\sigma_\theta$ gradually appeared on inner surface of steel ring and then this inner surface made elastic deformation. When the inner metal of steel ring reaches its yield limit, plastic deformation occurred. With the increase of internal pressure, the plastic deformation layer gradually expanded outward until the steel ring was fully yielding. Plastic deformation of steel ring is the result of combined action of axial stress produced by top die extrusion and internal stress produced by upsetting deformation of aluminum alloy core. With the extrusion of top die, the bimetal billet continued plastic deformation until billet metal fully filled the cavity and the gear forming was completed [17-19].

When analyzing the internal pressure of steel sleeve, its deformation problems are usually divided into two categories according to the ratio of internal and external diameters $R_0 / R_i$, one belongs to the deformation of thick-walled sleeve when the ratio is greater than 1.2, otherwise, the other pertains to the deformation of thin-walled sleeve.

The stress generated by axial extrusion of thick-walled steel sleeve under internal pressure includes direct axial stress $\sigma_z$, radial stress $\sigma_r$, and circumferential stress $\sigma_\theta$. The circumferential stress and radial stress are not uniformly but gradiently distributed along wall thickness. The axial stress is related to the extrusion force of top die and the area of end face of steel sleeve. As shown in figure 12, it is a thick-walled sleeve in elastic-plastic state, where $R_0$ is outer radius of the sleeve, $R_i$ is the radius of boundary line between elastic zone and plastic zone, $R_i$ is inner radius of steel sleeve, $p_i$ is inner pressure of steel sleeve, $p_e$ is external pressure of plastic zone and also internal pressure of elastic zone, the external pressure is 0, $F_1$ is axial pressure of steel sleeve. $R_{st}$ is yield strength of steel ring material. According to Lame formula and Mises yield criterion, the stress at any position of steel sleeve under inner pressure can be expressed as shown in table 5 [17].

![Figure 11. Axial compression stress model of bimetal billet](image)
Table 5. Stress in elastic-plastic zone of thick-walled sleeve

| Failure criterion | Stress | Plastic zone $(R_i \leq r \leq R_c)$ | Elastic zone $(R_c \leq r \leq R_0)$ |
|-------------------|--------|--------------------------------------|-------------------------------------|
| Radial stress $\sigma_r$ | $\frac{2}{\sqrt{3}} R_{el} \ln \frac{r}{R_i} - p_i$ | $\frac{R_{el} R_c^2}{\sqrt{3} R_0^2} \left(1 - \frac{R_0^2}{r^2}\right)$ |
| Circumferential stress $\sigma_{\theta}$ | $\frac{2}{\sqrt{3}} R_{el} \left(1 + \ln \frac{r}{R_i}\right) - p_i$ | $\frac{R_{el} R_c^2}{\sqrt{3} R_0^2} \left(1 + \frac{R_0^2}{r^2}\right)$ |
| Axial stress $\sigma_z$ | $\frac{F_{cr}}{(R_0^2 - R_i^2) \pi}$ | |

The stress produced by axial extrusion of thin-walled steel sleeve under internal pressure includes direct axial stress $\sigma_z$ and circumferential stress $\sigma_{\theta}$. Due to thin wall, the radial stress $\sigma_r$ produced by internal pressure is small, which can be ignored. The circumferential stress produced by internal pressure was analyzed. A unit length ring was taken out from the cylinder, and the ring was cut in half by the plane through y-axis and perpendicular to x-axis. Take the half ring for analysis, as shown in the figure 13. According to the equilibrium condition, the external force on the ring in x-axis direction is equal to the internal force on y section, and it can be obtained that:

$$2 \int_0^{\frac{\pi}{2}} p_i R_i \sin \alpha \, d\alpha = 2t \sigma_{\theta}$$

(1)

Because $D \approx 2R_i$, we can get $\sigma_{\theta} = p_i D/2t$, where $R_0$ is the outer radius of the sleeve, $R_i$ is inner radius of the sleeve, $p_i$ is inner pressure of the sleeve, $t$ is thin-walled sleeve thickness, $D$ is the diameter of middle part of thin-walled sleeve.

When the axial load exceeds bearing limit of the material, the local buckling instability deformation will occur in short thin-walled sleeve subjected to axial compression, and the buckling deformation is symmetrically distributed [20-22]. As shown in the figure 14. The critical stress expression of local buckling as:

$$\sigma_{cr} = \frac{1}{\sqrt{3(1-\mu^2)}} E_t \left(\frac{t}{R_i}\right)$$

(2)

where $R_i$ is inner radius of the sleeve, $t$ is the thickness of thin-walled sleeve, $E_t$ is tangent modulus of the sleeve, $\mu$ is the Poisson’s ratio of the sleeve, $F_{cr}$ is axial pressure of steel sleeve. The space generated by local buckling of steel sleeve makes it difficult to supplement internal aluminum alloy metal. The deformations of two metals are uncoordinated, which produces gaps at tooth tip orientation of two metal contact surfaces.

It is found that the occurrence of gaps is closely related to the ratio of outer diameter to inner diameter of steel sleeve $(R_0/R_i)$. When the ratio is small, that is, the steel sleeve is thin, the gaps are easy to form at tooth tip of bimetal contact surface. When the ratio is large, that is, the steel sleeve is thick, it is not expected to form gaps. The ratios of five billets are in the range of 1.179-1.338. The ratios of billet scheme 1, billet scheme 2 and billet scheme 3 are small, so their forming pertains to axial compression...
of thin-walled sleeve. According to the above analysis, it can be seen that the cylindrical thin shell with supports will undergo local buckling deformation when subjected to axial compression, and the buckling deformation generates gaps between steel sleeve metal and aluminum core metal. The ratios of billet scheme 4 and billet scheme 5 are large, and their forming follows the deformation law of thick-walled sleeve. The aluminum alloy core and inner side of steel ring are throughout in the state of mutual extrusion and these two metals are always in contact during the forming process, thus no gaps are formed.

4. Conclusions
In this investigation, the gear forming of five steel-aluminum composite metal billets with different specifications was studied by numerical simulation and experimental methods. The following conclusions can be drawn from the investigation.

1) Through the finite element numerical simulation method, the forming pressure and shapes of forgings for five steel rings with different thickness are compared. The results show that the final forming force of the gear is smaller and the radial deformation degree of steel ring is larger when using thinner steel ring. This radial deformation degree was characterized by height difference between the convex and the concave in steel-aluminum bonding position, and great deformation showed obvious bimetal occlusion.

2) The forming results of physical experiment are basically consistent with those in numerical simulation, except for finding that the thickness of steel sleeve has an important influence on bonding tightness of steel-aluminum contact surface of the formed part and the gear formed by thin-walled steel sleeve is prone to have gaps at tooth tip of bimetal contact surface.

3) Using axial compressive stress model of thick-walled cylinder, the forming of thick-walled steel sleeve with large ratio of outer diameter to inner diameter ($R_o / R_i$) was analyzed, and the forming of thin-walled steel sleeve with small ratio ($R_o / R_i$) was analyzed by using axial compressive stress model of thin-walled cylinder. Due to local buckling instability deformation of thin-walled steel sleeve under axial extrusion, the space of steel sleeve makes it difficult to supplement internal aluminum alloy metal, and the deformation of two metals loses coordination, resulting in gaps at tooth tip orientation of bimetal contact surfaces.

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