WITHDRAWN: Drawing-upsetting-extrusion-clinching of high strength steel and aluminum alloy

Lingfeng Luo
Shangyu Huang
Yang Mei
gaolym@163.com

Shanghai University of Engineering Science
Jianhua Hu
Bing Ou

Research Article

Keywords: clinching, high-strength steel, aluminum alloy, process parameters, joint strength

Posted Date: June 9th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1663423/v1

EDITORIAL NOTE:

The full text of this preprint has been withdrawn by the authors while they make corrections to the work. Therefore, the authors do not wish this work to be cited as a reference. Questions should be directed to the corresponding author.

Abstract

To realize good point connection between high-strength steel and aluminum alloy, a process of drawing-upsetting-extrusion-clinching was proposed. First, the sheets were thinning drawn, then the bottom of the protrusion part was extruded, forming the necessary initial interlock, finally the protrusion part was reverse press clinched, forming a certain height of the clinched head. Taking DP980 high strength steel and Al5083 aluminum alloy as the connection objects, using the method of numerical simulation combined with experimental test, the mold was made and the experiment was carried out on the basis of numerical simulation. The experimental results proved the feasibility of the process and the effectiveness of the numerical model. The simulation and experimental results show that the necessary interlock in the drawing-upsetting-extrusion stage is the premise of effective connection. The relative protrusion height should be around 55.6% after reverse-press-clinching. The best comprehensive mechanical properties measured by strength test were shear resistance of 2644N, fatigue life of 24535 times and peel resistance of 1522N. Through failure form analysis, the relationship between the interlock Tu and the neck thickness Tn of the joint with the best comprehensive mechanical properties was established: $T_u = 0.35T_n$. The design method of die and process parameters when the sheet thickness changes was researched by numerical simulation. The results show that the clearance between the punch and die, bottom thickness are directly proportional to the sheet thickness, and the drawing depth is directly proportional to the punch radius.

1. Introduction

Automotive lightweight is one of the most effective measures to reduce energy consumption and emissions. Automobile bearing structure is generally characterized by thin wall. Tisza et al. [1] reported that the mixing of aluminum alloy and high-strength steel can give full play to their respective advantages, and has become an inevitable choice for the lightweight of automobile body at present.

The connection and assembly of metal parts can adopt point connection mode, mainly including: resistance spot welding, mechanical connection. However, Wallerstein et al. [2] reported that in spot welding of high-strength steel and aluminum alloy, it is difficult to form an effective joint due to the large difference in melting point and linear expansion coefficient and the formation of brittle and hard intermetallic compounds at the weld. In addition, Taufiqurrahman et al. [3] reported that the austenite changes into other low-strength structures rather than high-strength martensite during the welding process, resulting in a significant reduction in the tensile strength of the high-strength steel at the welding part. As a plastic cold connection technology of light alloy sheet, traditional clinching has the advantages of simple equipment, low cost, little surface damage and stable connection quality. Peng et al. [4] reported that clinching has been widely used in automobile body assembly in aluminum alloy sheet parts and the connection between aluminum alloy and low strength steel parts.

Due to the low ductility and poor plasticity of high-strength steel, the interlock of high-strength steel and aluminum sheet after clinching is small. In addition Abe et al. [5] reported that compared with the flat bottom die, the clinching die with annular groove will increase the tendency of cracks in the sheet and seriously affect the clinching quality. For the more, the joint has protrusion, which makes the clinching connection unable to be used on the outer surface or functional surface. In recent years, to solve these problems, many researchers optimized die parameters or improved forming process to increase the joint connection quality. Abe et al. [6] proposed a preformed clinching process. The lower sheet was preformed before clinching to reduce the thinning degree of the upper sheet at the joint neck which can avoid cracking and effectively improve the rivetability of low ductility materials. Lee et al. [7] proved the practicability of pre-punched clinching method in the connection between lightweight plastic materials and high-strength and low ductility materials. Wen et al. [8] proposed a pre-punched clinching method suitable for the connection of different sheets without protrusion joints. The upper sheet is punched into the pre-punched hole of the lower sheet to form an interlock structure. This technology is applied to the connection between Al6063 and AZ31, and the strength of the formed joint is greater than that of the traditional clinching. However, this process is complex and costly. To solve this problem, Horhold et al. [9] proposed a shear clinching connection technology, which can complete the shear punching and stamping connection of the lower sheet after one stamping without pre-punched, simplifying the pre-punched multi-stage clinching connection technology. However, for high strength steel with high shear strength and poor plasticity, it is difficult to achieve shear punching of the lower sheet. On this basis, the same authors [10] studied the influence of the distance between the clinching point and the material boundary on the material flow. The material flow depends on the edge distance, as a lower edge distance causes a lower resistance against material flow outside of the joining zone. Lambiase et al. [11] used the two-step clinching method to connect aluminum sheet and carbon fiber reinforced polymer sheet, found that the shear strength and absorption energy of the joint increased by 32% and 30% respectively compared with that of the non-reformable joint.

In order to improve the plasticity of materials, many researchers use external heat sources to heat and soften the sheet to improve the ductility of materials. Osten et al. [12, 13] applied laser heating to the clinching of high-strength steel, analyzed the thermal effect and heating process, and realized the rapid clinching of high-strength steel with the help of laser. They found that there was a loss of joint strength due to the introduction of laser heating during the laser assisted clinching. Vorderbruggen et al. [14] found that the formability of metal materials and tension-shear strength of the joint could be improved by using a heat assisted elastic die for clinching. Zhuang et al. [15] proposed hot clinching cold die quenching clinching process, verified the feasibility of the process through experiments, made the high-strength steel at the joint have full martensite structure, ensured the strength of the joint, and found that 700°C is the best initial clinching temperature of high-strength steel sheet. Han et al. [16] verified the feasibility of thermal assisted pre-punched clinching process for connecting magnesium alloy and ultra-high-strength steel by combining numerical simulation and experiment. It is found that the temperature of the upper sheet has a significant effect on the connection ability, and the connection can be realized when the upper sheet temperature is 250°C. Wang et al. [17] placed two layers of ductile copper foil above the perforated stainless steel sheet, and applied impulse laser to the upper foil. The two layers of foil were concave downward through the hole of the perforated sheet, impacting the rigid bottom support, and then expanded radially to produce a double interlock, so as to connect the three sheets together.

In order to solve the problems of small interlock and large protrusion in the clinching process of high-strength steel and aluminum alloy sheet, this paper presents a drawing-upsetting-extrusion-clinching process. At first, the double-layer sheet was thinned and drawn, and then the bottom was upsetted and extruded to form interlock. Finally, the protrusion after upsetting -extrusion was reverse press clinched to increase the interlock and neck thickness, reduce the relative protrusion height of the joint and improve the quality of the joint. Taking DP980 high strength steel and Al5083 aluminum alloy as the connection objects, the influence of process parameters on deformation, clinching strength and failure form were studied by numerical simulation and experiment.

2. Experimental And Numerical Analysis Methods

The drawing-upsetting-extrusion-clinching process is shown in Fig. 1. First, the sheets are thinning drawn: the double sheets is stacked on the appropriate position of the die, according to the depth of the drawing requirements the punch moves to the corresponding position and locks, the blank holder presses the sheets, the upper punch draws the sheets downward until the lower sheet contacts with the lower punch; then the die goes down until its upper surface is flush with the lower punch. The upper punch continues to descend and extrude the bottom of the protrusion part, forcing the material in this area to flow outward along the radial direction, forming the necessary initial interlock. Then reverse-press-clinching is carried out: unloading the upper punch pressure, the lower punch and the die move upward synchronously to reverse press clinch the protrusion part, the upper punch is pushed by the bottom of the protrusion part and moves synchronously, forming a certain height of the clinched head. Finally, the clinching process is completed after resetting.

2.1. Experimental scheme

In order to analyze the influence of process parameters on the clinching deformation and quality conveniently, the process is divided into two stages: drawing- upsetting-extrusion and reverse-press-clinching.

2.1.1. Experiment of drawing-upsetting-extrusion stage

To facilitate mold making and simplify the experimental equipment, the experimental tooling in the drawing-upsetting-extrusion stage is simplified to the form shown in Fig. 2, so as to be realized on the ordinary hydraulic press: the aluminum sheet is stacked on the die with the steel sheet below, the pressure sensor is placed on the upper end of the punch, the punch moves downward with the hydraulic press equipment and controls the stroke by adjusting the thickness of the backing block, and the upper and lower sheets are pulled into the die, forming drawing protrusion. The punch force was recorded, and the samples were cut along the center of the punch. The parameters (interlock, neck thickness and bottom thickness) were measured.

2.1.2. Experiment of reverse-press-clinching stage

As shown in Fig. 3, the reverse-press-clinching experiment was also completed on the hydraulic press equipment. The sample after drawing-upsetting-extrusion experiment is placed on the punch, the punch moves downward with the hydraulic press equipment, and the stroke is controlled by adjusting the thickness of the gasket. The samples were cut along the center, and the interlock, neck thickness and bottom thickness were measured.

2.1.3 Mechanical property test

Shear, fatigue and peel tests were performed on clinched samples. The shear and peel tests of clinched samples were carried out on Instron 5967 electronic universal material tester and the tensile rate was set to 10 mm/min. Fatigue tests were performed on the MTS Landmark 370 test machine at a load of 70% of the sample's shear resistance and the frequency was 80 Hz. The clinched samples for shear, fatigue and peel tests are shown in Fig. 4. Each group of tests was repeated for 3 times, and the test results were averaged.

2.2. Numerical analysis method

2.2.1. Analysis model of drawing-upsetting-extrusion process

The numerical model of high strength steel-aluminum alloy drawing-upsetting- extrusion process was established by Abaqus.

Since the geometric model and load boundary conditions are symmetric to the central axis of the joint, a two-dimensional axisymmetric model was adopted in the simulation, as shown in Fig. 5. In the figure, X is the vertical distance between the upper surface of the upper sheet and the lower surface of the lower sheet after drawing-upsetting-extrusion, that is, the bottom (rivet head) thickness; Tn is the minimum wall thickness of the circular surface depression of the upper sheet, referred to as neck thickness; R_{max} is the radial distance from the maximum convex point to the axis of the annular surface of the upper sheet; R_{min} is the radial distance between the maximum inner concave of the annular surface of the lower sheet metal and the axis, Tu is the radial distance between the upper sheet and the lower sheet embedded in the neck, referred to as the interlock, and $Tu = R_{max} - R_{min}$; R_p is the punch radius, r_p is the punch fillet radius, R_d is the die radius, r_d is the die fillet radius, H is the die depth (corresponding to drawing depth), T_1, T_2 are the initial thickness of the upper and lower sheets respectively. In order to facilitate the analysis of clinching deformation rule and quality, the following parameters are further defined:

$B = 1 - X / (T_1 + T_2)$

$C = (R_d - R_p) / (T_1 + T_2)$

$U = R_{max} / R_{min}$

$N = Tn / T_1$

$K = H / 2R_p$

Where, *B* is the bottom thinning rate, *C* is the relative clearance between the punch and die, *U* is the relative interlock, *N* is the relative neck thickness, *K* is the relative drawing depth.

The molds were made of isotropic analytical rigid materials. The upper sheet is 1 mm thick Al5083 aluminum alloy, the lower sheet is 0.8 mm thick DP980 high-strength steel. The material properties and model dimensions are shown in Table 1 and Table 2, respectively.

Table 1
Material properties

Material	Density (kg/m^3)	Elastic Modulus (GPa)	Poisson's ratio	Yield stress (MPa)	tensile strength (MPa)	Johnson-Cook model
Al5083	2700	67	0.30	167	280	$167 + 300\varepsilon^{0.12}$
DP980	7900	210	0.28	590	980	$590 + 1123\varepsilon^{0.46}$

Table 2
Parameters of the model

Punch radius R_p/mm	Punch fillet radius r_p/mm	Die radius R_d/mm	Die fillet radius r_d/mm	Die depth H/mm
3.1 ~ 3.3	0.5	4.5	0.5	1.6 ~ 1.9

The mesh division of the model was partitioned, and the upper and lower sheets were divided into three areas (see Fig. 6). Area A and B are the main deformation areas with fine mesh division: area B is the neck forming region of the joint with the largest deformation and mesh size is 0.05 mm×0.1 mm axisymmetrical element; the deformation of area A is large, and the mesh size is 0.1 mm×0.1 mm axisymmetric element; area C has small deformation and is not the main area for investigation, so the mesh size is large with a 0.1 mm×0.2 mm axisymmetric element. The die, punch and blank holder need not to be meshed because they are analytical rigid bodies.

In addition, the die was completely constrained, and the whole process was completed by defining the displacement of the punch, and the solution time was set as 1s.

2.2.2 Analysis model of reverse-press-clinching stage

The upper and lower sheets after drawing-upsetting-extrusion were introduced into the reverse-press-clinching model shown in Fig. 7. The model was composed of guide sheet, punch, terrace die, blank holder, aluminum sheet and steel sheet. In addition, the guide sheet was completely constrained, and the whole reverse-press-clinching process was completed by defining the displacement of the punch, and the solution time was set as 0.5s.

In the figure, *Hp* refers to the protrusion height of rivet head after reverse-press-clinching, and the relative protrusion height is defined as $P = H_p / (T_1 + T_2)$.

3. Analysis Of Clinching Experiment And Simulation Results

3.1. Analysis of drawing-upsetting-extrusion process

Figure 8 shows the relationship between forming force and bottom thinning rate in the drawing-upsetting-extrusion experiment with different parameters (punch radius R_p and die depth H (corresponding to drawing depth)). As can be seen from the figure, the forming force increases with the increase of punch radius, this is because the wall thickness reduction of thinning drawing increases with the decrease of relative clearance between the punch and die, so the required forming force increases accordingly. Under the same punch radius, the forming force decreases with the increase of drawing depth, this is because the sheet size is larger than that of the punch radius, the material at the flange region is hard to flow into the die, during the descending process of the punch, the bottom sheet is thinned due to expansion and drawing. Therefore, the initial thinning of the bottom caused by bulging increase with the increase of drawing depth, so the forming force required for upsetting-extrusion to the same bottom thickness decreases. It should be noted that when the punch radius increases to 3.3 mm, the forming force is so large that the data of some experimental points are difficult to obtain due to the strength limitation of the punch.

Figure 9 shows the relationship between the relative interlock, the relative neck thickness and the bottom thinning rate of the protrusion in drawing-upsetting-extrusion stage under different parameters, in which the solid line is the experimental value and the dotted line is the simulation value. It can be seen that the relative interlock increases significantly and the relative neck thickness increases slightly with the increase of the bottom thinning rate. With the increase of relative drawing depth, the relative interlock increases and the relative neck thickness decreases. This is because during the punch upsets the bottom of the protrusion, before the lower sheet contacted with the side wall of the die completely, the resistance of the horizontal flow of the bottom sheet is much smaller than that of the upward flow, most of the sheet will flow horizontally, and a small portion will flow upward; after the lower sheet contacted with the side wall of the die completely, the resistance of the horizontal flow of the bottom sheet is much bigger than that of the upward flow, most of the sheet will flow upward, and a small portion will flow horizontally, so with the increase of the bottom thinning rate, the relative interlock significantly increases, the relative neck thickness slightly increases. When the relative drawing depth increases, the neck thickness decreases due to the aggravation of thinning, and the resistance of upward flow in the upsetting-extrusion process of bottom sheet increases accordingly, so the relative interlock increases. By comparing Fig. 9 (a), (c), (e) and (b), (d), (f), it can be found that the relative interlock increases and the relative neck thickness decreases with the increase of the punch radius. This is because with the punch radius increase, the relative clearance between the punch and die decreases, the thinning amount of the neck wall thickness increases, and the resistance to upward flow of the bottom sheet increases in the upsetting-extrusion process, so the relative neck thickness decreases and the relative interlock increases.

Comparing the experimental and simulation values, it can be found that the experimental values of interlock are slightly larger than the simulation values; the experimental values of neck thickness are slightly smaller than the simulation values. The experimental values are in good agreement with the simulation values, indicating that the model can accurately simulate the deformation of drawing-upsetting-extrusion stage of steel and aluminum sheets.

3.2. Analysis of reverse-press-clinching process

Based on simulation, the relationship between relative interlock, relative neck thickness and relative protrusion height after drawing upsetting-extrusion and reverse-press-clinching under five process conditions was obtained, as shown in Fig. 10. It can be seen from the figure that with the increase of relative drawing depth, the relative interlock increases, and the relative neck thickness decreases. It can also be seen from the figure that when the relative protrusion height is small, the relative interlock increases with its increase. When the relative protrusion height increases to 55.6%, the relative interlock tends to be constant. The relative neck thickness decreases monotonically with the increase of the relative protrusion height. Generally speaking, the interlock and neck thickness both affect the joint strength. The greater the interlock is, the more favorable it is to resist the peel load. The larger the neck thickness is, the more favorable it is to resist shear load. The influence of interlock may be more critical to the quality of clinching joints. Considering comprehensively, the value of relative protrusion height around 55.6% is more reasonable.

Under the conditions of different punch radius and relative drawing depth, the protrusion part after drawing upsetting-extrusion was reverse press clinched to a reasonable relative protrusion height of 55.6%, and the relationship between relative interlock, relative neck thickness and bottom thinning rate could be obtained, as shown in Fig. 11, in which the solid line is the experimental value and the dotted line is the simulated value. Similar to the drawing upsetting-extrusion process, the experimental values of interlock are slightly larger than the simulated values, and the experimental values of neck thickness are slightly smaller than the simulated values. The experimental values are in good agreement with the simulated values, which further verifies the accuracy and reliability of the simulated results. It can be seen from the figure that the effect of bottom thinning rate on interlock after reverse-press-clinching inherits the characteristics of drawing-upsetting-extrusion process, but has almost no effect on neck thickness. That is, the greater the bottom thinning rate is, the greater the relative interlock after reverse-press-clinching is, and the better the clinching quality is. The relative neck thickness of reverse-press-clinching with different bottom thinning rate has little change under the same process parameters. According to Fig. 9, if there is no interlock between upper and lower sheet before reverse-press-clinching, that is, if the interlock is 0 (corresponding relative interlock value is 1), the interlock cannot be realized after reverse-press-clinching (relative interlock is still 1). There is a critical value of the bottom thinning rate. Under the experimental conditions of this paper, when the bottom thinning rate is greater than 61%, the relative interlock after reverse-press-clinching under various process conditions will increase, with an increase of 15% ~ 40%. After reverse-press-clinching, the relative neck thickness increased by 15% ~ 25%.

4. Analysis Of Joint Strength And Failure Form

According to the simulation and experiment, with the increase of bottom thinning rate, the interlock and neck thickness increase, the joint strength increases. Therefore, samples with the bottom thinning rate of 72.2% were prepared for mechanical property test under experimental allowable conditions. It should be noted that when the punch radius is 3.3 mm and the relative drawing depth is 0.242 and 0.258 respectively, the bottom thinning rate of the corresponding sample is only 61.1% and 66.7% due to the mold strength limitation. The shear, fatigue and peel failure forms of the joint are shown in Fig. 12, and the corresponding mechanical property test results are shown in Fig. 13.

It can be seen from Fig. 12 (a) and (b) that shear failure has two failure forms: interface collapse and neck fracture. In Fig. 13(a), the shear strength of the joint increases firstly and then decreases with the increase of the relative drawing depth, and reaches the maximum value near 0.266. The smaller the relative clearance between the punch and die is, the smaller the relative drawing depth corresponding to the maximum value is. When relative drawing depth is small, the joint has larger relative neck thickness and smaller relative interlock, the shear bearing area of neck is larger, the ultimate load of interface collapse failure is smaller than that of neck fracture failure, so the failure form of the joint is interface collapse, and its shear strength is determined by relative interlock. With the increase of the relative drawing depth, the relative interlock increases and the relative neck thickness decreases, and the ultimate load required for interface collapse increases, so the shear strength increases with the increase of the relative drawing depth. Because the shear bearing area of neck decreases continuously with the increase of relative drawing depth, the ultimate load required for fracture failure decrease continuously, when the ultimate loads corresponding to the two failure forms are equal, the shear strength of the joint reaches the maximum and the failure form changes from interface collapse to neck shear fracture. As the relative drawing depth continues to increase, the shear strength depends on the relative neck thickness and decreases with the increase of the relative drawing depth.

It can be seen from Fig. 12 (c) and (d) that fatigue failure also shows two failure forms: interface collapse and neck fracture. In Fig. 13(b), when the punch radius is 3.1 mm, the relative interlock of the joint is very small due to the large relative clearance between the punch and die. The fatigue failure form is interface collapse due to the insufficient relative interlock, and the fatigue life is determined by the relative interlock. With the increase of relative drawing depth, the relative interlock increases and the fatigue life increases.

When the punch radius increases to 3.2 mm, the fatigue failure of the joint shows interface collapse and neck of aluminum alloy shear fracture due to the decrease of the relative clearance between the punch and die and the increase of the relative interlock of the joint. When the relative drawing depth is small, the relative interlock is smaller and the neck of aluminum alloy is relatively thicker, the failure form is the interface collapse. With the increase of the relative drawing depth, the relative interlock of the joint increases and the relative neck thickness decreases, and the ability of resisting interface collapse failure increases, but the ability of resisting neck fracture failure decreases. Therefore, under the interface collapse failure form, the fatigue life increases with the increase of the relative drawing depth. When the relative drawing depth increases to a certain value, the ability of the joint to resist the two failure forms tends to balance, and the failure form also transitions from interface collapse to neck aluminum alloy fracture. At this time, the fatigue life is determined by the relative interlock and the relative neck thickness, and reaches the maximum value. With the relative drawing depth increasing continuously, the fatigue life is determined by the relative neck thickness and decreases with the increase of the relative drawing depth.

There are three failure forms in the peel test of the joint: interface pull-off, interface pull-off combined with fracture of partial aluminum alloy neck and neck fracture as shown in Fig. 12 (e) (f) (g). In Fig. 13(c), the relationship between the peel strength of the joint and the relative drawing depth is similar to the fatigue life.

When the punch radius is 3.1 mm, due to the large relative clearance between the punch and the die, the relative interlock of the joint is small, the failure form is always a single interface pull-off due to the insufficient relative interlock. The peel strength depends on the relative interlock and increases with the increase of the relative drawing depth. When the punch radius increases to 3.2 mm, the relative interlock of the joint increases due to the decrease of the relative clearance between the punch and die. With the increase of the relative drawing depth, the relative interlock further increases and the relative neck thickness decreases, so the ability of the joint to resist interface pull-off increases, while the ability to resist neck fracture decreases. When the former is lower than the latter, the joint shows a single interface pull-off, and the peel strength depends on the relative interlock and increases with the increase of the relative drawing depth. When the relative drawing depth increases to a certain value, the two approaches to balance, and the failure form of the joint transitions to interface pull-off combined with fracture of partial aluminum alloy neck. The peel strength of the joint is determined by the relative interlock and the relative neck thickness, and reaches the maximum value at this time. With the relative drawing depth increasing continuously, the relative interlock of the joint continues to increase and the relative neck thickness further decreases. Its ability to resist interface pull-off is higher than that of resisting neck fracture. The failure form transitions to a single neck aluminum alloy fracture. The peel strength depends on the relative neck thickness and decreases with the increase of relative drawing depth.

The above analysis shows that the shear strength, peel strength and fatigue life of the joint depend on the relative interlock and relative neck thickness, and are closely related to the process parameters. It can be seen from Fig. 13 that the sample obtained under the condition of relative clearance 0.722 (die radius 4.5 mm), relative drawing depth 0.266 and bottom thinning rate 72.2% has the best comprehensive mechanical properties.

5. Effect Of Sheet Thickness On Die Parameters

In the clinching process of high-strength steel and aluminum alloy sheet, most researchers only verified the feasibility of the clinching process for the specific sheet thickness combination, and did not explore the influence of the change of die size on the clinching process under different sheet thickness. Therefore, when it is applied to industrial production, the clinching die of high-strength steel and aluminum alloy plate with different shhet thickness combination must be redesigned, which consumes a lot of manpower and material resources. On the premise that the accuracy of the simulation model is confirmed, this chapter simulates and studies the variation law of die parameters under different sheet thickness, so as to provide reference for engineering application.

5.1 Simulation analysis method

According to the analysis of mechanical properties in Chap. 4, the shear strength is determined by the neck thickness, and the maximum shear force of the joint increses with the increase of neck thickness. The fatigue strength and peel strength increase with the increase of neck thickness; when the neck thickness is constant, the fatigue strength and peel strength increase with the increase of interlock value, and the failure form is the interface pull failure. Beyond the bearing range of neck thickness, even if the interlock value increases, the fatigue strength and peel strength will not increase, and the interface failure form is neck thickness fracture failure. Therefore, when the maximum force that the neck thickness can bear is equal to the maximum force that the interlock can bear, the comprehensive mechanical properties are better.

Let Fn and Fu be the maximum force that the neck can bear and the maximum force that the interlock can bear respectively.

$$\mathrm{Fn} \approx \pi\left[\left(\mathrm{R_p} + Tn\right)^2 - \mathrm{R_p}^2\right]\sigma_\mathrm{b} = \pi\left(Tn^2 + 2Tn\cdot\mathrm{R_p}\right)\sigma_\mathrm{b} \qquad (1)$$

$$\mathrm{Fu} \approx \frac{\pi\left[\left(\mathrm{R_{min}} + Tu\right)^2 - \mathrm{R_{min}}^2\right]\sigma_\mathrm{s}}{\sin^2\theta} = \frac{\pi\left(Tu^2 + 2Tu\cdot\mathrm{R_{min}}\right)\sigma_\mathrm{s}}{\sin^2\theta} \qquad (2)$$

In which, θ, σ_b, σ_S are the angle between the interlock curve and the axis, and the yield strength and tensile strength of the aluminum alloy sheet respectively (see Fig. 5). Let Fn = Fu, then:

$$\frac{Tu^2 + 2Tu \cdot \mathrm{R}_{\mathrm{min}}}{Tn^2 + 2Tn \cdot \mathrm{R}_{\mathrm{p}}} = \frac{\sigma_{\mathrm{b}} \cdot \sin^2\theta}{\sigma_{\mathrm{s}}} \quad (3)$$

Among the effective joints obtained by clinching, the θ is about 25°, Tu is very small relative to R_{min}, Tn is very small relative to Rp and $R_{min} \approx R_P$ + Tn. The tensile strength of 5083 aluminum alloy sheet after clinching is about twice the yield strength, so formula (5 – 3) can be simplified as:

$Tu \approx 0.35 Tn$ (4)

That is, when the interlock value of the joint is about 0.35 times of the neck thickness, the comprehensive mechanical properties are the best. In Chap. 4, the interlock value and neck thickness of the joint with the best mechanical properties are 0.183 mm and 0.554 mm respectively, and the interlock value is about 0.35 times of the neck thickness.

To reduce the cost and improve the universality of the die, the increment of the die radius is set as 0.5 mm, so that the same die can be used when the sheet thickness changes slightly. According to the mechanical test in Chap. 4, when the comprehensive mechanical properties of the joint are the best, the relative clearance C of the punch and die is about 0.722, the relative drawing depth K is about 0.266, the bottom thinning rate B is about 72.2% and the relative protrusion height P is about 55.6%. For a certain sheet thickness t_0, given the die radius R_d, there are:

$$\mathrm{R_p} = R_d - \mathrm{C} \cdot t_0 \quad (5)$$

$$\mathrm{H} = 2\mathrm{K} \cdot R_p \quad (6)$$

$$\mathrm{X} = t_0 \cdot (1 - \mathrm{B}) \quad (7)$$

$$\mathrm{H_p} = \mathrm{P} \cdot \mathrm{t_0} \quad (8)$$

The simulation analysis process can be divided into the following steps:

(1) Given t_0 and initial R_d, calculate the corresponding punch radius R_P, drawing depth H, bottom thickness X and protrusion height P according to the formula, then simulate and record its interlock value and neck thickness.

(2) Change R_P or H in increments of 0.1 mm until the best combination of interlock value and neck thickness under this die radius is found.

(3) Change the die radius and repeat the processes (1) and (2). Finally, compare the optimal combination of interlock value and neck thickness to obtain the optimal die parameters under the given sheet thickness.

(4) Change t_0 and repeat the process (1 ~ 3).

5.2 Analysis of optimization results

According to the simulation method in the above section, the optimal die parameters under different sheet thickness combinations were obtained by simulation, and the corresponding relative clearance C, relative expansion depth K and bottom thinning ratio B were calculated, as shown in Fig. 14. It is worth mentioning that the thickness of aluminum alloy sheet is greater than or equal to the thickness of high strength steel sheet in all sheet thickness combinations.

As can be seen from Fig. 14: when the sheet thickness t_0 is not more than 1.8 mm, the concave die radius is 4.5 mm; when the sheet thickness t_0 is less than 2.2 mm, the die radius is 5.0 mm; when the sheet thickness t_0 is equal to 2.2 mm, the die radius is 5.5 mm. The relative clearance C, relative drawing depth K, bottom thinning rate B and relative protrusion height P fluctuate about 0.75, 0.25, 72% and 55%, respectively. The clearance between the punch and die, the bottom thickness and the protrusion height are proportional to the sheet thickness t_0, and the relative drawing depth is proportional to the punch radius. Therefore, as long as the sheet thickness t_0 is determined, the die radius R_d can be selected, and then according to Eq. (5, 6, 7, 8), the punch radius R_p, the drawing depth H, the bottom thickness X, and the protruding height H_p can be calculated.

6. Conclusion

Taking 0.8 mm thick DP980 and 1.0 mm thick Al5083 sheets as connecting objects, the feasibility of the process of drawing-upsetting-extrusion-clinching was verified. The influence of process parameters on the deformation process, joint strength and failure form was investigated. The conclusions can be summarized as follows:

1. In the process of drawing-upsetting-extrusion and reverse-press-clinching, the relative interlock increases and the relative neck thickness decreases with the decrease of the relative clearance between the punch and die (the increase of the punch radius). The relative interlock increases and the relative neck thickness decreases with the increase of relative drawing depth. With the increase of the bottom thinning rate of the protrusion, the relative interlock increases, the clinching quality is better, but the forming force required is larger, mold strength requirements are higher. The interlock in the drawing upsetting-extrusion stage is the premise of effective clinching. The relative clearance between the punch and die should be less than 0.778. After reverse-press-clinching, the relative protrusion height is reasonable at 55.6%.

2. Under the conditions of experimental sheet thickness, when the die radius is 4.5 mm, the relative clearance between the punch and die is 0.722, the relative drawing depth is 0.266, the bottom thinning rate of upsetting-extrusion is 72.2%, and the relative protrusion height is 55.6%, the shear resistance, peel resistance and fatigue life of the joint are the best, which are 2644 N, 1522 N and 24535 times respectively.
3. The clearance between the punch and die and bottom thickness are proportional to the sheet thickness, and the drawing depth is proportional to the punch radius. Therefore, as long as the sheet thickness t_0 is determined, the die radius R_d can be selected, and then the punch radius R_p, the dawing depth H, the bottom thickness X, and the pritrusion height Hp can be calculated.

Declarations

Author contribution Provide funds and equipment: Shangyu Huang; Design and implementation of the experiments: Lingfeng Luo, Shangyu Huang and Jianhua Hu; Experimental material preparation and processing: Lingfeng Luo, Mei Yang and Bing Ou; Mechanical property testing: Lingfeng Luo and Mei Yang; Writing and image processing: Lingfeng Luo, Shangyu Huang and Mei Yang; English instruction and grammar check: Mei Yang and Lingfeng Luo; All authors have checked and approved that the final article is true and valid.

Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

1. Tisza M, Czinege I (2018) Comparative study of the application of steels and aluminium in lightweight production of automotive parts. Int J Lightweight Mater Manuf 1(4):229–238
2. Wallerstein D, Solla EL, Lusquiños F, Comesaña R, Jesús DV, Riveiro A, Juan P (2021) Advanced characterization of intermetallic compounds in dissimilar aluminum-steel joints obtained by laser welding-brazing with Al Si filler metals. Mater Charact 179:111345
3. Taufiqurrahman I, Ginta TL, Mustapha M (2021) The effect of holding time on dissimilar resistance spot welding of stainless steel 316L and Ti6Al4V titanium alloy with aluminum interlayer. Materials Today: Proceedings. 46: 1563–1568

4. Peng H, Chen C, Ren X, Wu J (2021) Development of clinching process for various materials. Int J Adv Manuf Technol 119(1–2):99–117
5. Abe Y, Mori K, Kato T (2011) Joining of high strength steel and aluminium alloy sheets by mechanical clinching with dies for control of metal flow[J]. J Mater Process Tech 212(4):884–889
6. Abe Y, Ishihata S, Maeda T, Mori KI (2018) Mechanical clinching process using preforming of lower sheet for improvement of joinability[J]. Procedia Manuf 15:1360–1367
7. Lee CJ, Lee JM, Ryu HY, Lee KH, Kim BM, Ko DC (2014) Design of hole-clinching process for joining of dissimilar materials-Al6061-T4 alloy with DP780 steel, hot-pressed 22MnB5 steel and carbon fiber reinforced plastic[J]. J Mater Process Tech 214(10):2169–2178
8. Wen T, Huang Q, Liu Q, Ou WX, Zhang S (2016) Joining different metallic sheets without protrusion by flat hole clinching process. Int J Adv Manuf Technol 85:217–225
9. Hörhold R, Müller M, Merklein M, Meschut G (2016) Mechanical properties of an innovative shear-clinching technology for ultra-high-strength steel and aluminium in lightweight car body structures. Weld World 60:613–620
10. Hörhold R, Müller M, Merklein M, Meschut G (2017) Specimen's geometry related influences on load-bearing capacity of joining aluminium and UHSS by innovative shear-clinching [J]. J Mater Sci Res 6(4):19–22
11. Lambiase F, Ko DC (2017) Two-steps clinching of aluminum and Carbon Fiber Reinforced Polymer sheets[J]. Compos Struct 164:180–188
12. Osten J, Sllig P, Reich M (2014) Softening of High-Strength Steel for Laser Assisted Clinching [J]. Advanced Materials Research, 2014, 966–967: 617–627
13. Reich M, Osten J, Milkereit B, Kalich J, Füssel U, Kessler O (2014) Short-time heat treatment of press hardened steel for laser assisted clinching[J]. Mater Sci Technol 30(11):1287–1296
14. Vorderbrüggen J, Gröger B, Kupfer R, Hoog A, Meschut G (2019) Phenomena of forming and failure in joining hybrid structures–Experimental and numerical studies of clinching thermoplastic composites and metal[C]//AIP Conference Proceedings. AIP Publishing LLC, 2113(1)
15. Zhuang W, Wang P, Xie D, Shi H (2019) Experimental study and a damage model approach to determine the effect of hot forming deformation on the service performance of 22MnB5 steel[J]. J Manuf Process 47(C):10–21
16. Han S, Wang Z, Wang Z, Li Z, Li Y (2021) Heat-assisted hole-clinching process for joining magnesium alloy and ultra-high-strength steel. Int J Adv Manuf Technol 115:551–561
17. Wang X, Ji Z, Liu R, Zheng C (2018) Making interlock by laser shock forming[J]. Opt Laser Technol 107:331–336

Figures

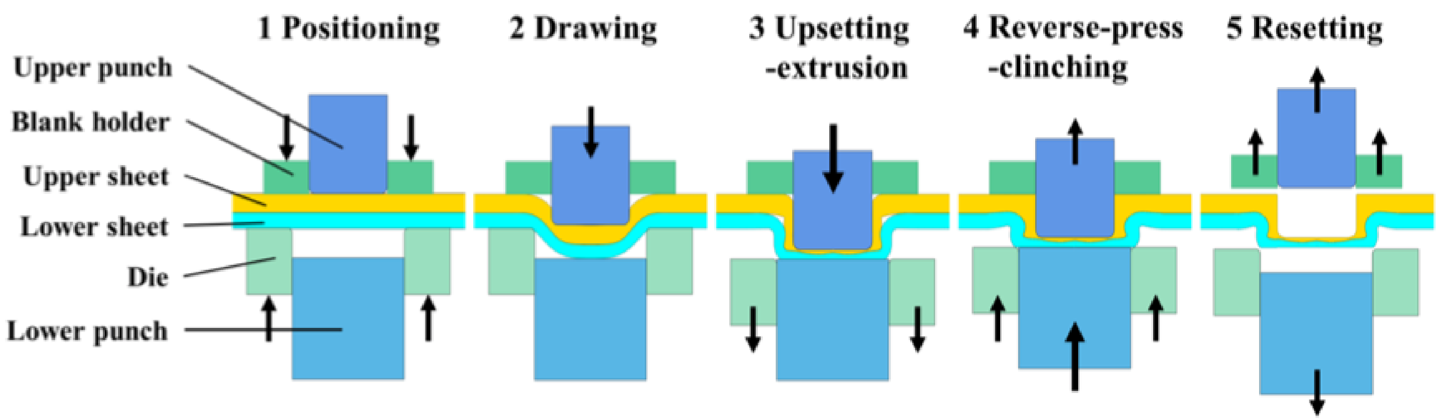

Figure 1

Schematic diagram of drawing-upsetting-extrusion-clinching process

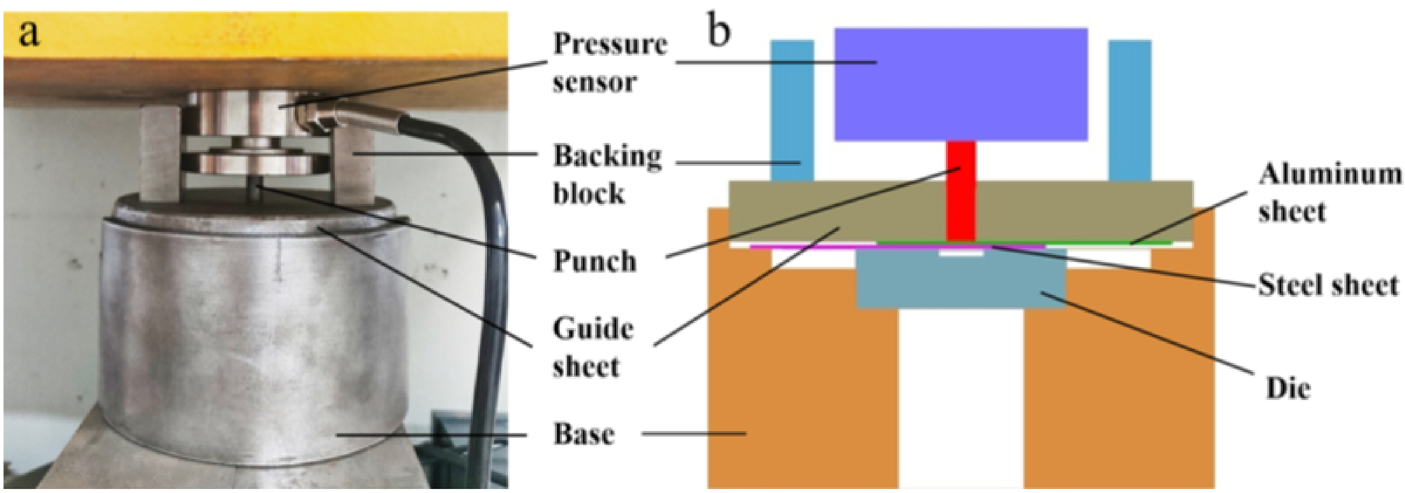

Figure 2

(a) setup (b) schematic of the drawing and upsetting-extrusion experiment

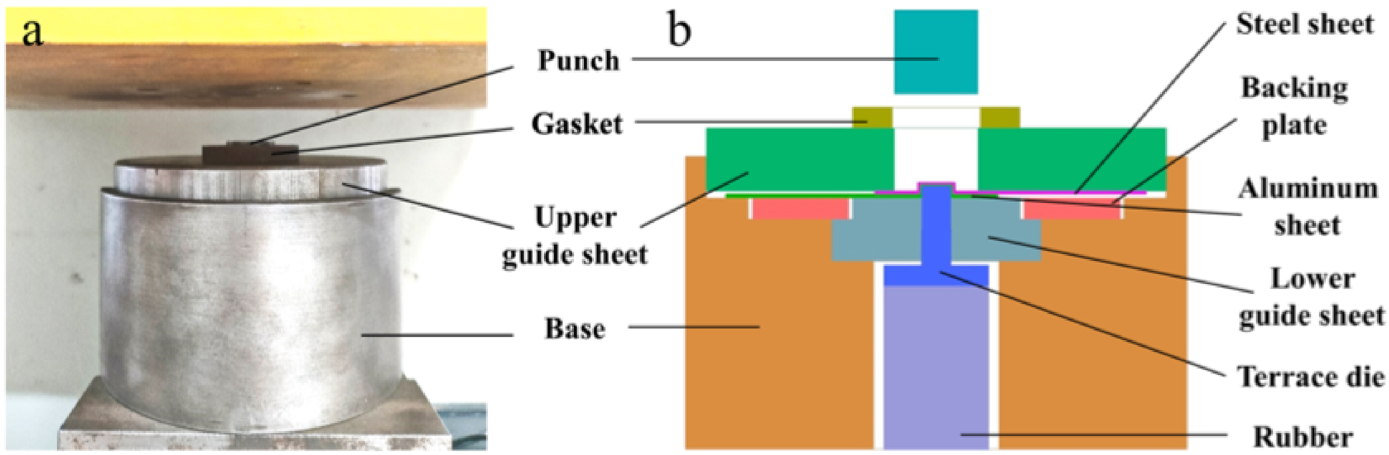

Figure 3

(a) setup (b) schematic of the reverse-press-clinching experiment

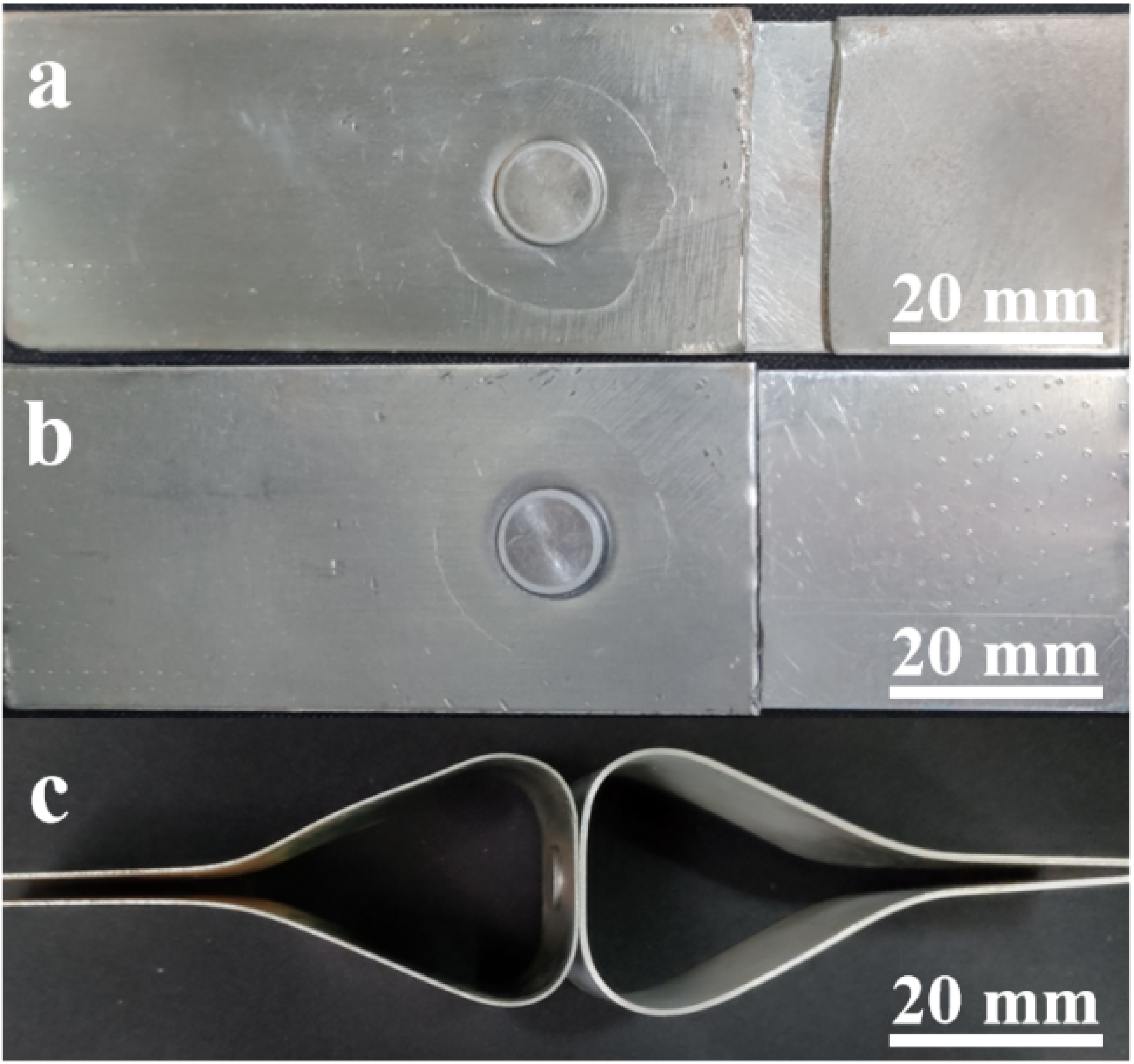

Figure 4

Test samples for mechanical properties:

(a) shear test sample, (b) fatigue test sample, and (c) peel test sample

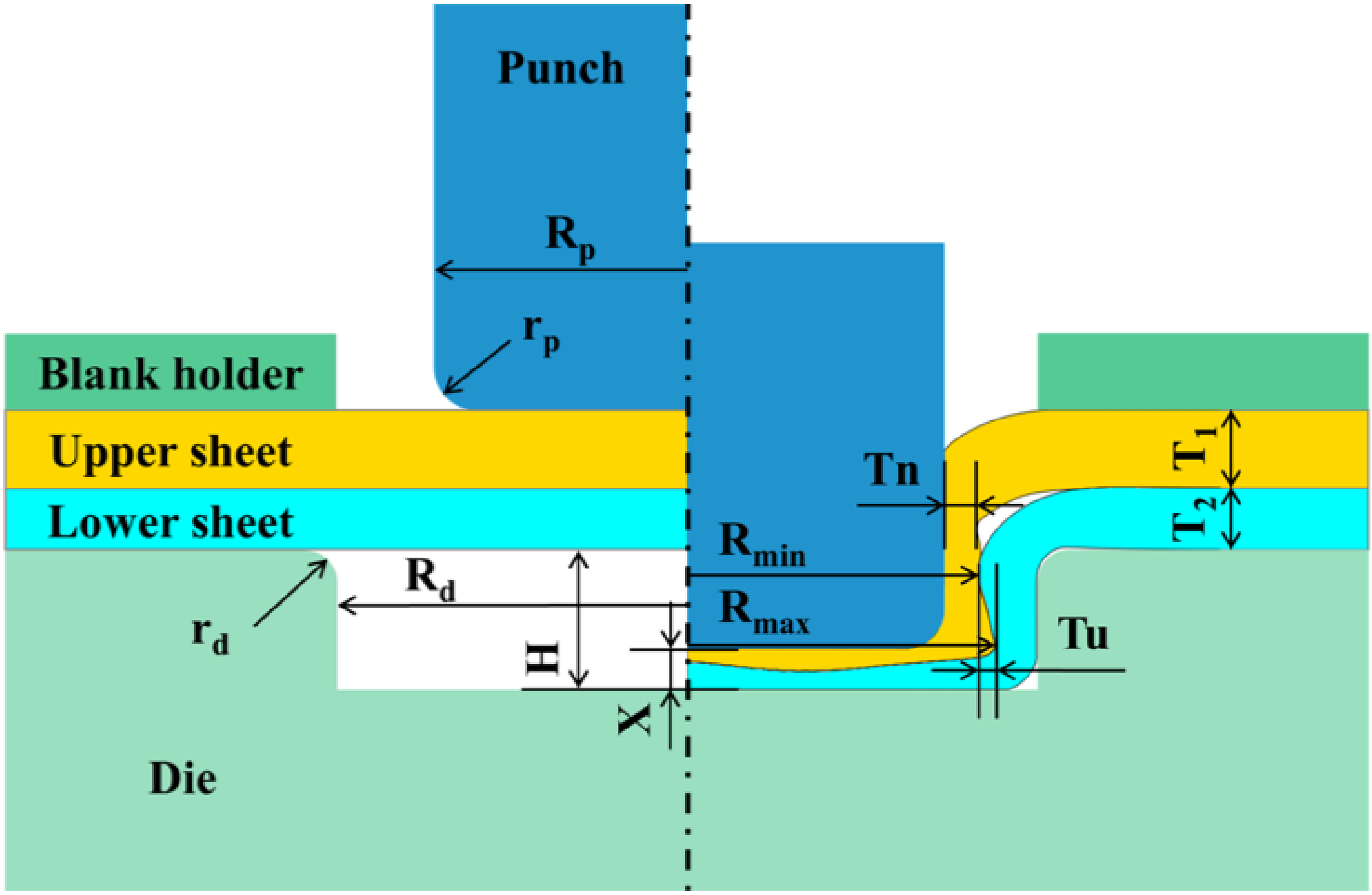

Figure 5

Schematic diagram of drawing-upsetting-extrusion stage

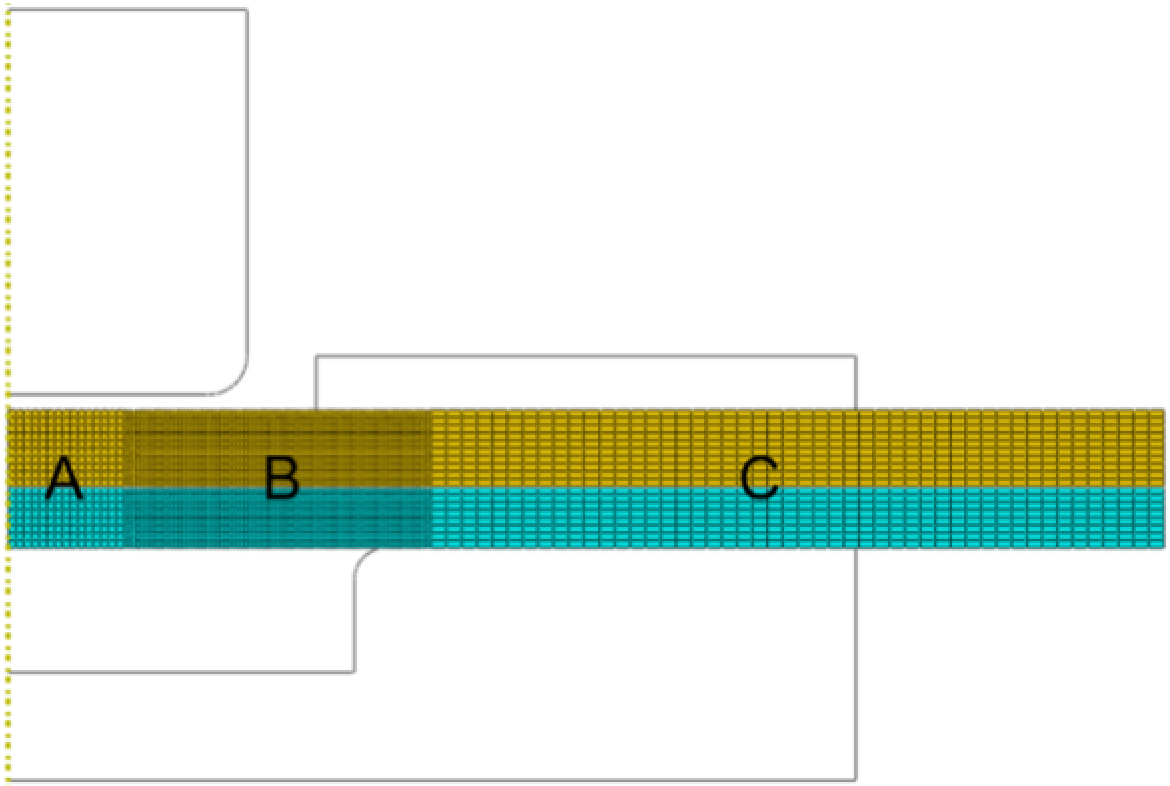

Figure 6

Finite element model of drawing-upsetting-extrusion stage

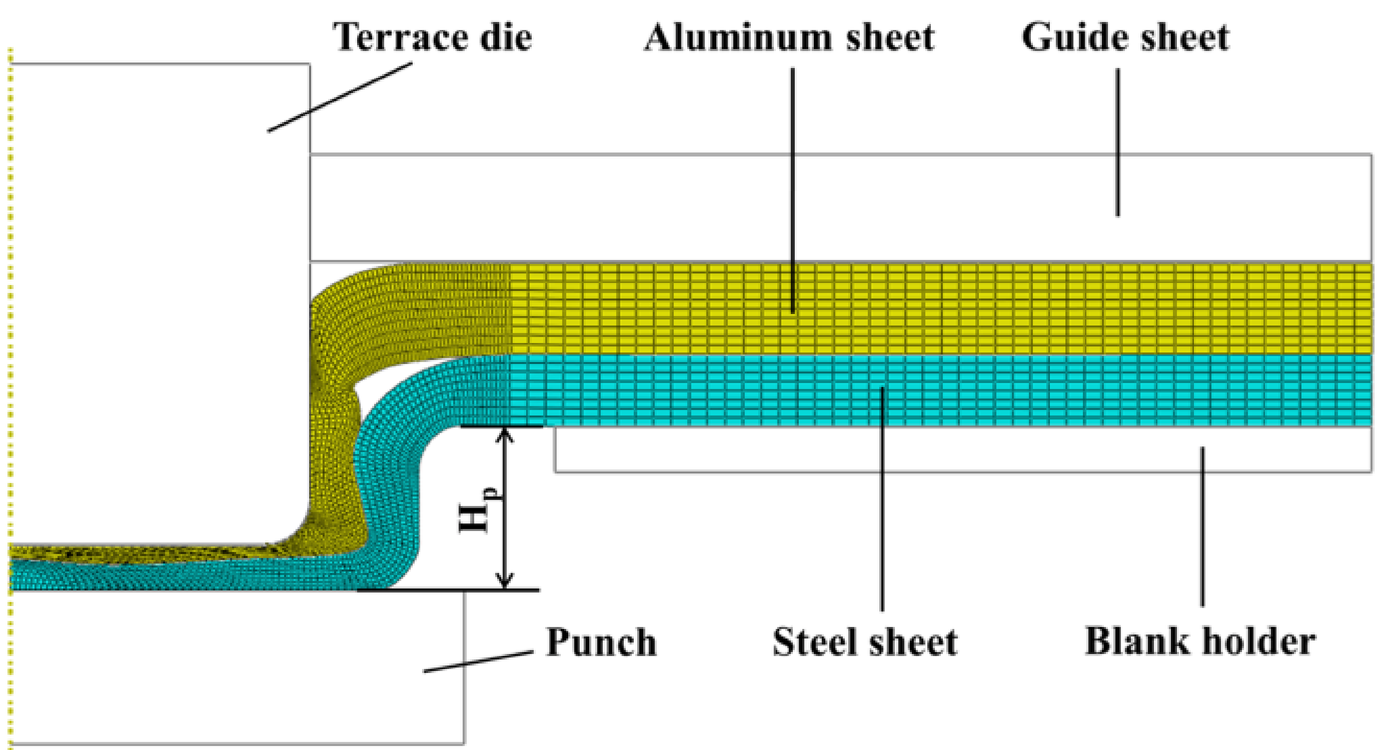

Figure 7

Finite element model of reverse-press-clinching stage

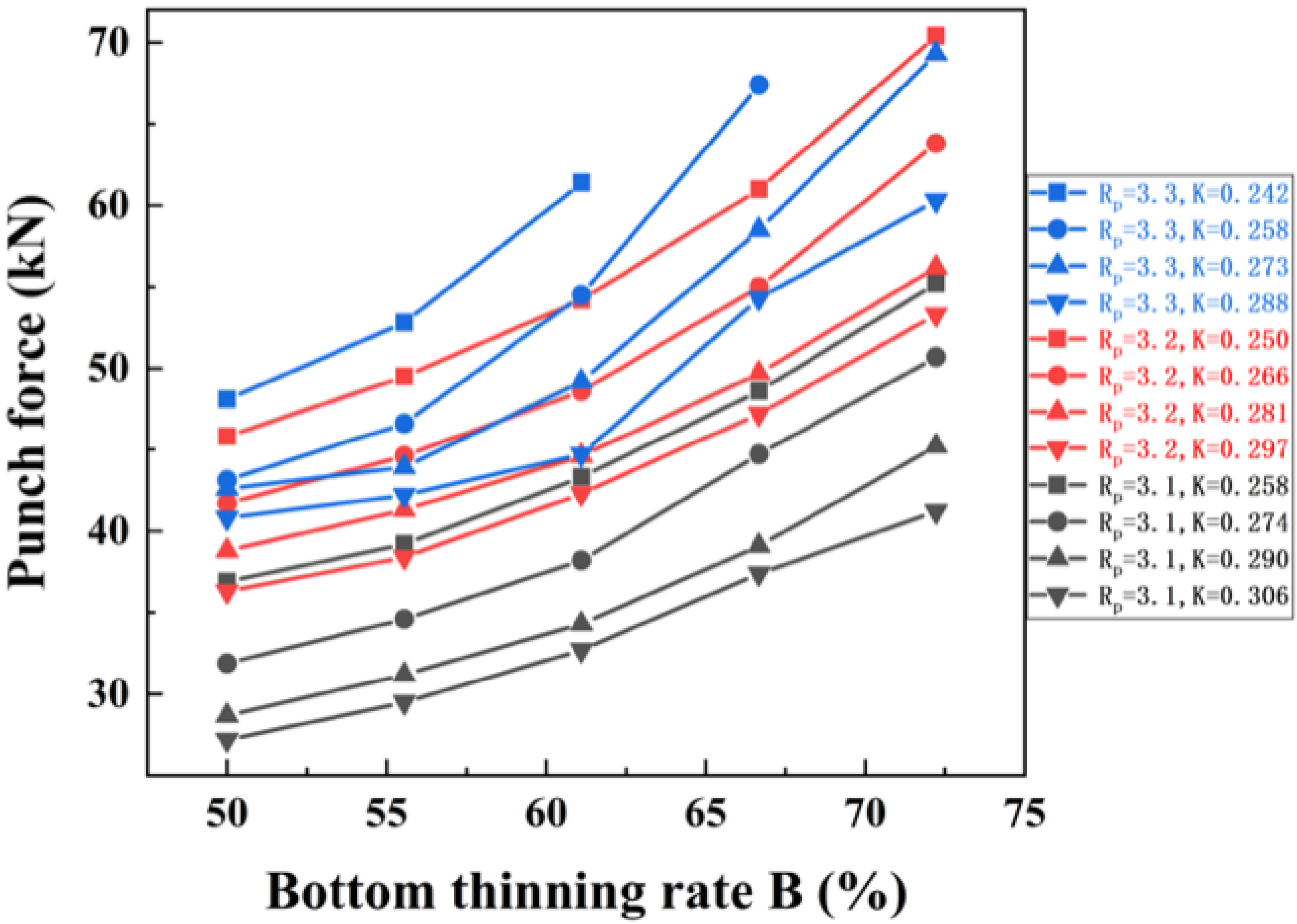

Figure 8

Relationship between forming force and bottom thinning rate

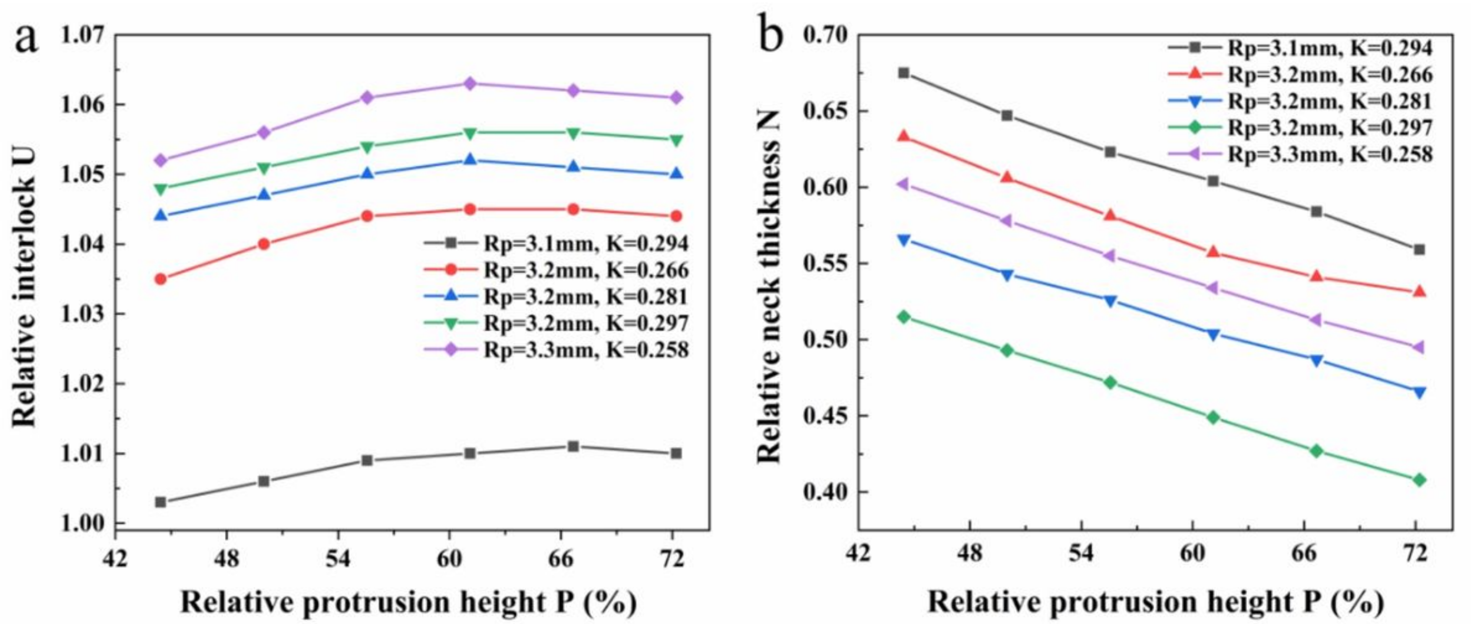

Figure 10

Relationship between interlock, neck thickness and protrusion height after reverse-press-clinching (a) relative interlock, (b) relative neck thickness

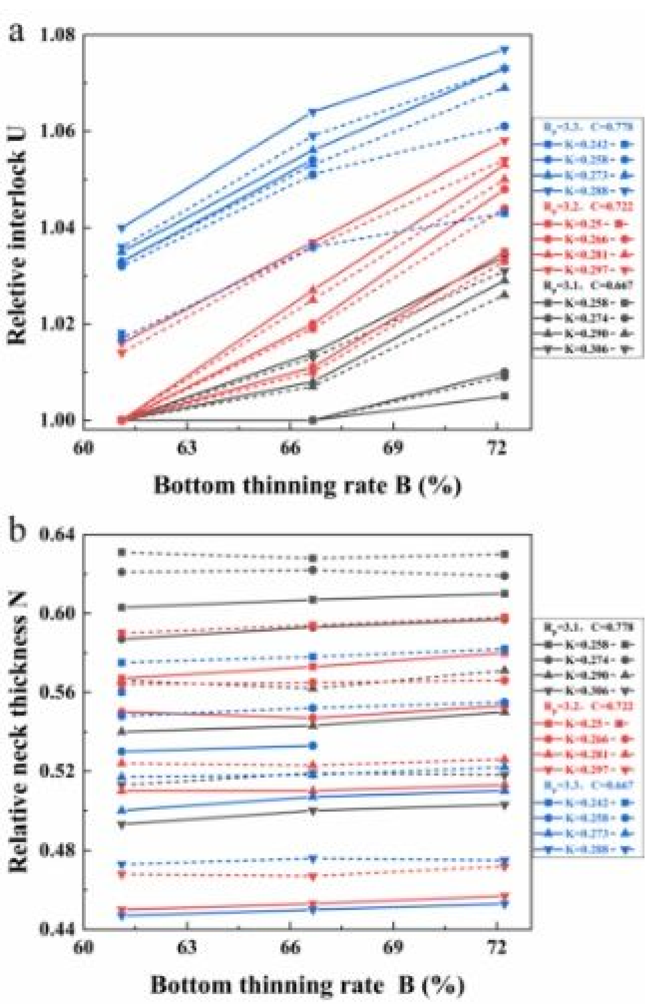

Figure 11

Relationship between relative interlock, relative neck thickness and bottom thinning rate after reverse-press-clinching

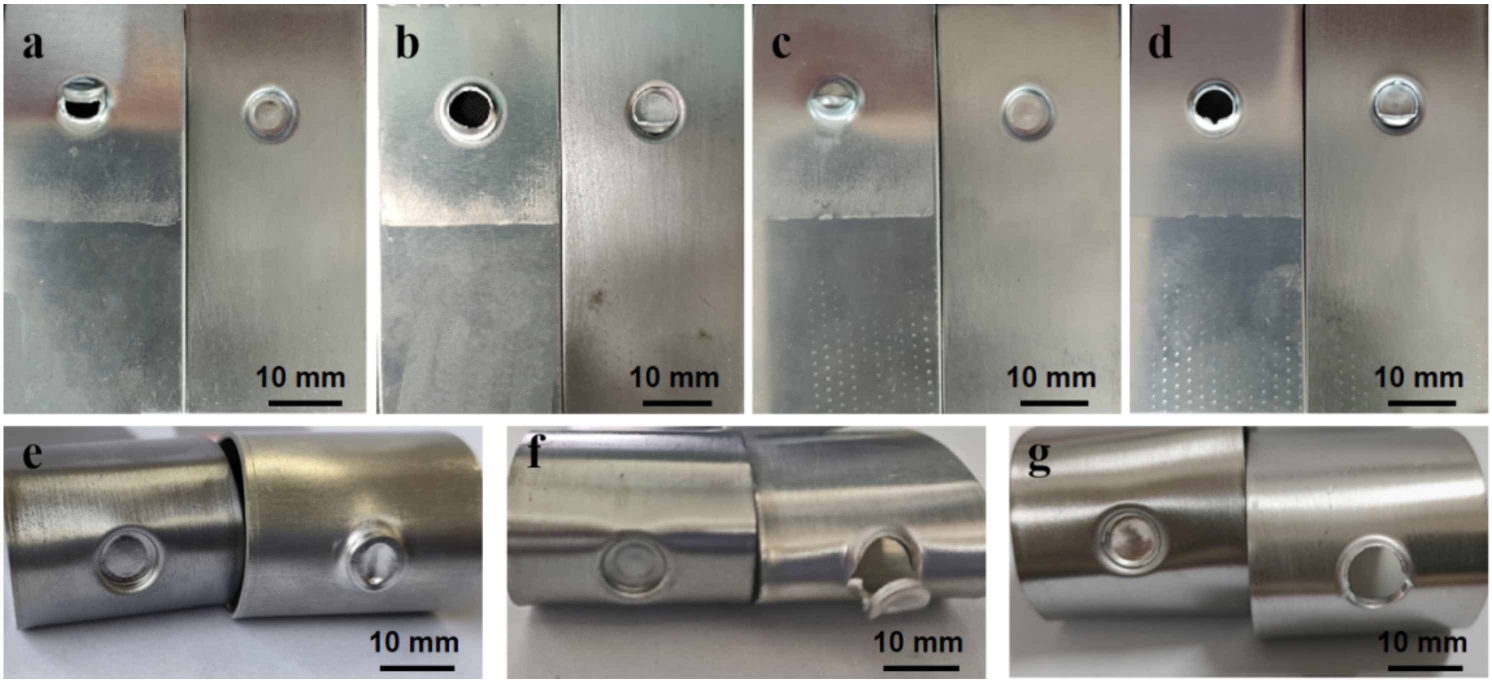

Figure 12

Failure form of (a) (b) shear tests, (c) (d) fatigue tests, (e) (f) (g) peel tests

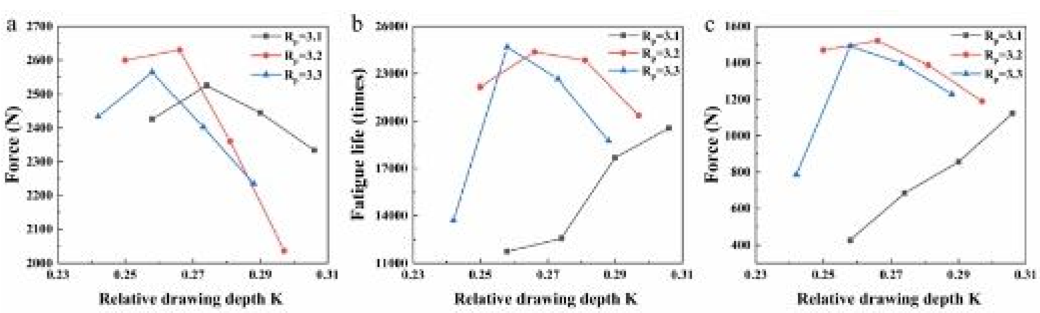

Figure 13

Test results of mechanical performance

(a) shear tests, (b) fatigue tests, (c) peel tests

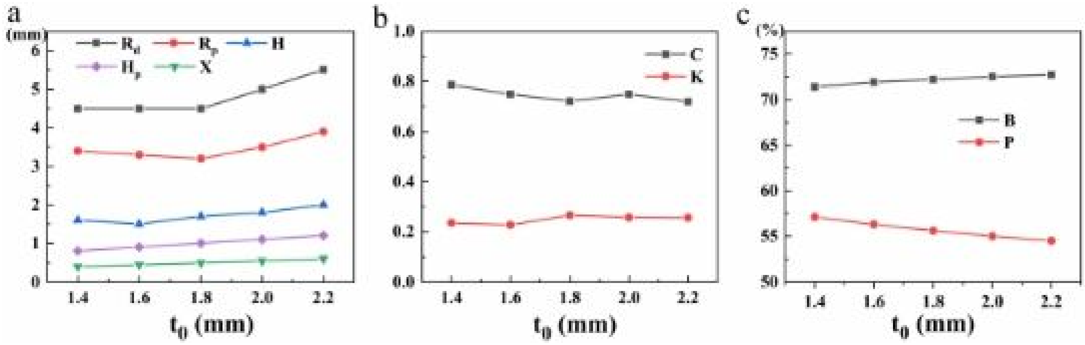

Figure 14

Optimal die parameters under different sheet thickness combinations

(a) die radius R_d, punch radius R_p, drawing depth H, bottom thickness X, protrusion height Hp, (b) the relative clearance between the punch and die C, the relative drawing depth K, (c) the bottom thinning rate B, the relative protrusion height P

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial.pdf