Enhance the Mechanical Strength of Metal Plates by Processing the Shape of the Bulge

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Abstract. The shape change of spherical bulge can affect the mechanical strength of sheet metal parts. The strength contrast experiment between the local bulge plate and the flat plate was designed to analyze the influence and mechanism on mechanical strength from local bulge shape change. The experiment took an approach measuring the combined displacement and stress of each unit on the stressed surface and the central axis under the same thickness and load to compare the difference of mechanical strength. The results show that the bulge plate brings maximum stress and maximum displacement less than 6% of the plate, smaller mean stress and displacement, lower content of strong stress and high deformation unit, and it is more obvious when the load direction is the same as the bulge direction. The method can provide a new idea for enhancing the mechanical strength of components and reducing the amount of material used in equipment manufacturing.

1. Introduction

With the increasing demand for high-strength construction machinery and the shortage of resources, the use of as little material as possible or to enhance the mechanical strength of parts through proper shape change is one of the optimization of mechanical design. Engineering Mechanics Theory shows that excessive stress and deformation of parts under load are the main cause of machine parts invalidity. Therefore, reducing the stress and deformation of the part generated by the force can significantly enhance its mechanical strength.

It is found that compared with a flat plate, the plate with local bulges can effectively reduce the deformation and stress values generated by the force, and the bulge direction also has a great influence. Therefore, two sets of comparative experiments with "stress" and "displacement" were designed to explore the influence of the shape change of "local bulge" on the mechanical strength of parts. The experiment is to research the deformation and interior stress for two kinds of parts through the method of controlling variables in SolidWorks environment.

2. Experimental modeling

2.1. Test subject

In order to control the variables in the comparison experiment, the plate parts were designed to be smooth plates of 100mm*100mm*5mm. One is a flat plate, and the other is a plate with a spherical bulge formed by pressing, bottom diameter of 40mm and 10mm height, hereinafter called as bulge plate(refer with:Figure 1). All materials are alloy steel with the summary of properties(refer with:Table 1). The parts are all fixed by four threaded holes at the corners. Apply a load perpendicular
to the surface on the parts, and set its pressure as 2.04 mpa, which can avoid the influence of different stressed area. This pressure is worth setting because the maximum stress value generated by the force-receiving surface of the plate under this pressure is close to the ultimate yield strength of the material used through repeated measurements.

Table 1. Properties summary of the alloy steel

| Attributes          | Quantity     | Unit   |
|---------------------|--------------|--------|
| Elastic Modulus     | 2.1e + 011   | N/m^2  |
| Poisson Ratio       | 0.28         |        |
| Shearing Modulus    | 7.9e + 010   | N/m^2  |
| Mass Density        | 7700         | Kg/m^3 |
| Tensile Strength    | 723825600    | N/m^2  |
| Yield Strength      | 620422000    | N/m^2  |

When an object is subjected to an external force, it will be deformed internally as a change in stress. Fracture and excessive deformation failure are main failure modes of parts generally, which mainly express insufficient strength (the received stress $\sigma$ exceeds the allowable stress $[\sigma]$) and insufficient stiffness (the deformation $\gamma$ exceeds the allowable shape variable $[\gamma]$). So reducing the shape variables and stress values generated by load, that is, increasing the ability to resist the action of load, which can effectively enhance the mechanical strength and prolong its service life.

Therefore, by comparing the deformation displacement and interior stress under the same load, to investigate the effect of the local bulge shape change on the mechanical strength of the part.

2.2. Test Program
Firstly, the load is applied perpendicularly to the 100*100 faces of the flat plate and the bulge plate 100*100, respectively, and the direction of load for bulge plate is identical or opposite with the bulge direction, hereinafter called as "I-bulge plate" and "O-bulge plate" (refer with:Figure 2).

Secondly, marked the central axis of the force surface (refer with:Figure 1), it contains all the bulge units. Then respectively test out the stress and displacement values of each unit on the central axis and on the stressed surface, then it will obtain a total of 12 groups of experimental data.

3. Data analysis

3.1. Test of Stress
Analyse 12 groups of experimental data. Firstly, based on the three groups of stress data of each unit on the central axis, three stress curves can be drawn (refer with:Figure 3), and a stress analysis table can be obtained (refer with:Table 1).

As shown in Figure 3, the stress curves of each unit on the central axis of two bulge plates have an obvious stress trough at the central bulge position, indicating that the existence of the bulge greatly weakens the generation of stress, with the maximum weakening amplitude reaching 95%. It is worth
noting that the upward fluctuation of the stress at the bottom edge of the bulge exceeds the stress at the same position of the plate and less than the maximum stress generated by the plate.

![Stress curves of each unit on the central axis of three plates](image)

Figure 3. Stress curves of each unit on the central axis of three plates

| Numerical analysis | Plate | I-bulge plate | O-bulge plate |
|--------------------|-------|---------------|---------------|
| Maximum            | 379.3 MPa | 345.3 MPa | 348.5 MPa |
| Average value      | 304.6234234 MPa | 223.8881197 MPa | 225.6517094 MPa |
| Percentage of 300-400 MPa | 0.324324324 | 0.188034188 | 0.256410256 |
| Percentage of 200-300 MPa | 0.675675676 | 0.547008547 | 0.478632479 |
| Percentage of below 200 MPa | 0 | 0.264957265 | 0.264957265 |

Table 2. Stress numerical analysis of each unit on the central axis of the stressed surface

In Table 2, the maximum and average of the stress values of the flat plate are greater and the percentage in the strong stress range of the plate is much higher than two bulge plates. These mean the bulge plate has a higher ability to avoid strong stress. What’s more, the bulge plate can manifest superior capability when received the load whose direction is identical with the bulge direction, that is, the percentage in the strong stress range is smaller, and concentrated in the weak stress range, which make the plate has better load resistance and strength.

Secondly, analyse the three groups of stress data. In this case, the corner threaded holes are used for the part fixing method, causing a sharply stress changing in the fixing holes domain, so these position values should be ignored, and a stress analysis table can be obtained(refer with:Table 3).

| Numerical analysis | Plate | I-bulge plate | O-bulge plate |
|--------------------|-------|---------------|---------------|
| Maximum            | 617.5 MPa | 461 MPa | 542.9 MPa |
| Average value      | 245.304694 MPa | 235.7682707 MPa | 247.3990859 MPa |
| Percentage of 500-600 MPa | 0.002317945 | 0 | 0.001351612 |
| Percentage of 400-500 MPa | 0.005988024 | 0.001930875 | 0.004441012 |
| Percentage of 300-400 MPa | 0.132122851 | 0.211237691 | 0.194632168 |
| Percentage of 200-300 MPa | 0.63299208 | 0.615755937 | 0.589109867 |
| Percentage of below 200 MPa | 0.2265791 | 0.171075497 | 0.210465341 |

Table 3. Stress numerical analysis of each unit on the stressed surface

In Table 3, the maximum and average of the stress values of the plate are greater than the stress values generated in the same position of two bulge plates, and the percentage in the strong stress range of the plate is much higher than the bulge plate. What’s more, the bulge plate can manifest superior capability when received the load whose direction is identical with the bulge direction.

3.2. Test of displacement

Based on the three groups of the displacement of each unit on the central axis, three displacement curves can be drawn(refer with:Figure 4), and a analysis table can be obtained(refer with:Table 4).
Figure 4. displacement curves of each unit on the central axis of three plates

Table 4. displacement numerical analysis of each unit on the central axis of the stressed surface

| Numerical analysis | Plate       | I-bulge plate | O-bulge plate |
|--------------------|-------------|---------------|---------------|
| Maximum            | 0.8439 mm   | 0.713 mm      | 0.74 mm       |
| Average value      | 0.509352126 mm | 0.475253951 mm | 0.490205058 mm |
| Percentage of 0.8-0.9 mm | 0.064801415 | 0             | 0             |
| Percentage of 0.7-0.8 mm | 0.153561666 | 0.100596359 | 0.156328715 |
| Percentage of 0.6-0.7 mm | 0.167229458 | 0.215630885 | 0.195056675 |
| Percentage of 0.5-0.6 mm | 0.191670687 | 0.211550534 | 0.205132242 |
| Percentage of below 0.5 mm | 0.422736774 | 0.472222222 | 0.443482368 |

As shown in Figure 4, the displacement curves of two bulge plates have obvious diminishing effect, indicating that the existence of the bulge weakens the deformation, with a weakening amplitude up to 26%. In Table 4, the maximum and average of the displacement values of the plate are greater than the deformation values generated in the same position of two bulge plates, and the percentage in the high displacement range of the plate is much higher. These mean the bulge plate has a higher ability to avoid high deformation. The bulge plate can manifest superior capability when received the load whose direction is identical with the bulge direction, that is, the percentage in the high deformation range is smaller, and concentrated in the small deformation range, which make the plate has better deformation resistance and rigidity.

Finally, based on the three groups of the displacement data of each unit on the stressed surface, three displacement curves can be drawn (refer with: Figure 5, 6, 7). Then analyse the three groups of displacement data, and a stress analysis table can be obtained (refer with: Table 5).
Figure 6. Displacement curves of each unit on the stressed surface of the I-bulge plate

Figure 7. Displacement curves of each unit on the stressed surface of the O-bulge plate

Table 5. Displacement numerical analysis of each unit on the stressed surface

| Numerical analysis         | Experiment       | Plate   | I-bulge plate | O-bulge plate |
|----------------------------|------------------|---------|---------------|---------------|
| Maximum                    |                  | 0.8439 mm | 0.713 mm      | 0.74 mm       |
| Average value              |                  | 0.701309009 mm | 0.63772906 mm | 0.657718803 mm |
| Percentage of 0.8-0.9 mm   |                  | 0.297297297 | 0             | 0             |
| Percentage of 0.7-0.8 mm   |                  | 0.252252252 | 0.384615385   | 0.47008547    |
| Percentage of 0.6-0.7 mm   |                  | 0.198198198 | 0.299145299   | 0.256410256   |
| Percentage of 0.5-0.6 mm   |                  | 0.216216216 | 0.230769231   | 0.205128205   |
| Percentage of below 0.5 mm |                  | 0.036036036 | 0.085470085   | 0.068376068   |

It can be seen from the comparison of the three figures that the displacements of two bulge plate unit are all below 0.74mm, while the displacement of the plate exceeding 0.8mm accounts for more than 29.7%. In Table 5, the maximum and average of the displacement values of the plate are greater than the displacement values generated in two bulge plates, and the percentage in the high displacement range of the plate is much higher. What’s more, the bulge plate can manifest superior capability when received the load whose direction is identical with the bulge direction.

4. Mechanism exploration

The plate with local bulges is subjected to less deformation and interior stress by the same load than the flat plate. The reason for this difference is that the existence of bulge shape can eliminate part of the effect of load. It can be seen from Figure 4 that the stress at the bulge portion is far less than that at the flat part, and the stress reduction value is above 6%. In the mechanical analysis for the bulge, due to the existence of spherical bulges, some interior stresses generated by the external force on the spherical bulges offset each other, that is, the existence of bulges improves the resistance of parts and enhances its strength.
The comparison of the displacements of the respective units, further indicates that the existence of the bulges can better resist the elastic deformation and reduce the fracture tendency of the parts. The farther away from the fixed position of the part, the larger the shape variable of the part is, and the existence of bulges can reduce this trend, especially in the bulge molding position. The shape variable of the bulge position is far less than that of the same position of the plate.

5. Summary
(1) The spherical bulge shape formed by pressing can improve the load resistance of parts. The results show that the plates with spherical bulges have higher load-resisting capacity, and the maximum interior stress and deformation amount are reduced, thereby improving the mechanical strength and rigidity of the parts. And this effect is more obvious in the bulge molding position.

(2) The enhancement effect of local bulges is more obvious when the direction of the bulge is the same as load’s direction, more difficult to reach the ultimate stress and ultimate deformation.

(3) Particularly, stress concentration occurs at the edge of the bulge due to the drastic shape change. It’s necessary to avoid excessively drastic measure changes and try to smooth the transition edge.

The research results in this paper have a strong guiding significance and reference value for the design and application of shape changes to enhance the strength and stiffness of the parts.

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