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Issue Article

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RESULTANT FORCE ESTIMATION IN SQUARE SHEET METAL DRAWING

Abstract: *The analysis of the resultant force graphs under the conditions of the sheet metal drawing process was performed. At the initial stage of drawing (0-4 mm), contact between the punch and the sheet occurs, the blank bends and plastic zones are formed. At a drawing depth of 4-8 mm, active drawing of the flange begins, accompanied by an increase in contact resistance and expansion of the plastic zone. At a drawing depth of 8-12 mm, the walls of the part are formed and the main part of the plastic work accumulates. With a further increase in the drawing depth to 16 mm, localization of strain develops in the radii and corners of the square part. At the final stage of drawing (16-20 mm), final forming, redistribution of strain and stabilization of contact interaction occur. Thus, the sequence of forming metal sheets is determined according to the increasing degree of complexity of the drawing process, taking into account the applied resultant force.*

Key words: *drawing, resultant force, curve, material, drawing depth.*

Language: *English*

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1. Introduction

Estimating the resultant force when drawing of square sheet metal blanks is a key step in die tooling design, determining the required press power and tool life.

Drawing of square parts is significantly more difficult than classic cylindrical drawing due to the unevenness of deformation. The main problems include:

- heterogeneity of the stress state;
- complexity of mathematical description;
- risk of defect formation;
- inaccurate assessment of friction forces;
- excess power reserves.

Some innovative approaches to calculating and optimizing plastic deformation forces in metal sheets were investigated experimentally and by finite element modeling.

Colgan and Monaghan [1] conducted an analysis and experimental study of the deep drawing process, identifying the key factors influencing product quality and deformation forces.

Padmanabhan et al. [2] studied the influence of process parameters on deep drawing of stainless steel, showing the importance of optimization to prevent defects.

Morozov [3] examined the force parameters of metal deformation during sheet drawing, proposing methods for estimating forces based on mechanical characteristics.

Venkateswarlu et al. [4] investigated the influence of process parameters on punch impact force and thickness variation, emphasizing the role of precise parameter control on product quality.

Gharib et al. [5] proposed a strategy to optimize the blank holder force to improve the deep drawing efficiency.

Dolinic and Grizelj [6] evaluated the distribution of drawing force and thickness under variable pressure, revealing the influence of dynamic control of the holder pressure.

Parsa et al. [7] compared forming loads of steel and brass laminated sheets, showing differences in forces due to the materials.

Guo et al. [8] developed a transfer learning method to predict deep drawing force, which improves the accuracy of process modeling.

Prabu and Senthil Kumar [9] investigated the variation of forces with friction coefficient and blank diameter, emphasizing the importance of these parameters in process control.

Hamza et al. [10] conducted an experimental study and numerical optimization of force parameters in sheet metal forming, improving the efficiency and quality of the process.

In this article, an analysis and comparison of the resultant drawing force of square sheet blanks made of various metallic materials (taking into account anisotropic properties) was performed to optimize the parameters of the technological process and reduce the metal consumption of stamping equipment.

2. Materials and methods

The initial and boundary conditions for modeling the drawing process of square metal sheets are described in detail in [11].

3. Results and discussion

The results of numerical simulation were processed and graphically presented in Figure 1.

On the graphs, the abscissa axis shows the drawing time equivalent to the drawing depth, i.e. 0.005 s is equal to a drawing depth of 1 mm, 0.01 s is equal to a drawing depth of 4 mm, and so on. The ordinate shows the resultant force in N.

The color dependencies represent the following force responses:

- the blue curve is the main resultant force of the drawing process;
- the red curve is a comparative/superimposed force curve showing the near or maximum contact force response;
- the black curve is the basic load trend, that is, a gradual increase in the average resistance level with increasing drawing depth.

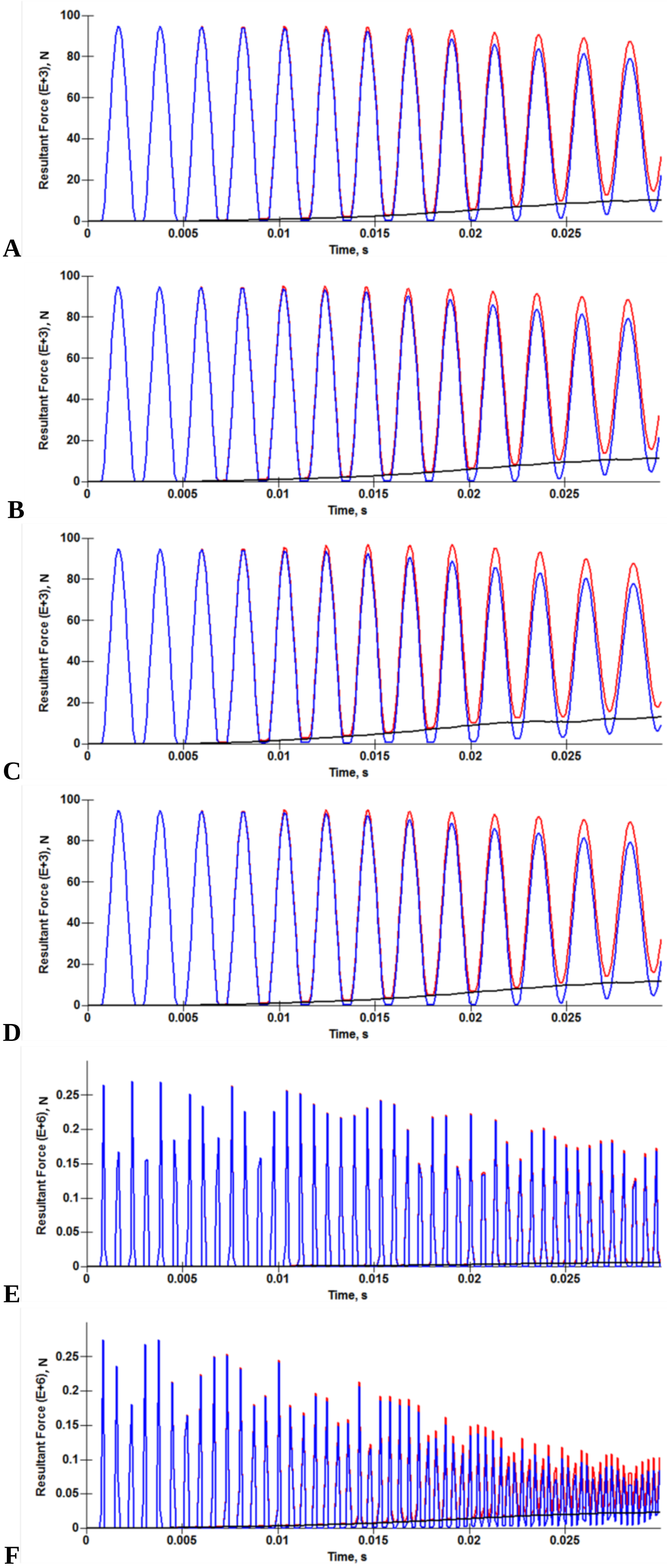

Figure 1. Dependencies of the resultant drawing force of a metal sheet on the drawing time: A – DC05 high-quality cold-rolled low-carbon steel; B – DC01 structural high-quality carbon steel; C – S355MC high-strength low-alloy steel; D – AISI 304 austenitic stainless steel; E – 5754 deformable aluminum alloy, and F – Ti Grade 4 commercially pure titanium.

DC05 high-quality cold-rolled low-carbon steel exhibits soft and stable force response. The peaks on the graph are regular, and the amplitude gradually decreases towards the end of the process.

The blue curve reflects the main drawing process. At the beginning and middle of the process it is quite stable.

The red curve appears mainly in the later stages, where it shows the comparative contact component.

The black curve grows moderately. This indicates a smooth increase in average resistance without sharp jumps.

DC01 structural high-quality carbon steel shows one of the most stable graphs among steels. Force peaks are regular, repetitive, without pronounced chaos.

The blue curve shows the steady-state basic force response.

The red curve is almost identical to the blue one at the beginning, and becomes slightly higher in the later stages. This indicates an increase in the local contact component during the development of the drawing.

The black curve gradually increases, reflecting the growth of the average resistance level due to the increase in contact area and the accumulation of plastic deformation.

S355MC high-strength low-alloy steel exhibits the most stress-strain behavior among steels. Force peaks remain high throughout all stages of the drawing. The red curve is significantly higher than the blue one in the late stage.

The blue curve shows the high basic resistance of the material.

The red curve indicates an increase in the local contact force response, especially after a drawing depth of 12 mm.

The black curve increases more noticeably than for mild steels. This is due to increased contact resistance and high levels of friction.

For AISI 304 austenitic stainless steel, the graph has a regular periodic character. The blue and red curves almost coincide in the first half of the process, and in the later stages the red curve becomes slightly higher than the blue one.

This shows that as the drawing depth increases, the contact component and material resistance become more pronounced.

The blue curve reflects the basic force response. The peaks are quite high and stable throughout the depth range.

The red curve shows the comparative or maximum force component. At a drawing depth of 12-20 mm, it becomes noticeably higher than the blue curve, which is associated with an increase in local contact loads and hardening of the material.

The black curve increases smoothly, indicating an increase in the average resistance of the drawing.

For the 5754 deformable aluminum alloy, the graph has a pronounced pulsed character. The blue curve is represented by frequent narrow peaks. This distinguishes the aluminum alloy from steels, which have more regular and smooth peaks.

The vertical scale is of the order of 10^6 N, meaning that the force peaks are on a larger scale. At the initial stage, sharp high pulses are observed, then as the drawing depth increases, the amplitude gradually decreases.

The blue curve shows the instantaneous force response. The high initial peaks are due to the rapid contact of the punch with the sheet metal blank and the dynamic reaction of the thin aluminum sheet.

The red curve appears predominantly in the peak areas and shows the comparative force response.

The black curve is almost at zero and gradually increases. This shows a gradual increase in the base contact resistance with increasing drawing depth.

Ti Grade 4 commercially pure titanium has a pulsed force curve similar in shape to that of 5754 deformable aluminum alloy, but the physical cause is different. In aluminum alloy, the impulse response is associated with the dynamic softness of the material, while in titanium it is associated with high resistance to plastic flow and strong anisotropy.

Peaks of dependencies are frequent and dense. In the later stages of the drawing process, the amplitude decreases, but the graph remains full of oscillations.

The blue curve shows the sharp instantaneous force response.

The red curve becomes increasingly visible as the drawing depth increases and indicates an increase in the local contact/comparative component.

The black curve rises smoothly, but remains low compared to the peaks. This shows that the main contribution is not due to friction, but to the internal resistance of the material.

4. Conclusion

Thus, the results of comparison of the drawing process of various materials were obtained based on the following factors:

- by force response

DC01, DC05, AISI 304 and S355MC steels have more regular force curves. This indicates a more stable drawing of the sheet and a periodic nature of the contact. 5754 deformable aluminum alloy (soft material and increased dynamic component) and Ti Grade 4 commercially pure titanium (high resistance to plastic deformation) have a more impulsive character.

- by plastic work

5754 deformable aluminum alloy is characterized by the lowest plastic work, DC01 structural high-quality carbon steel is the most technologically advanced steel, and the most loaded material is S355MC high-strength low-alloy steel.

In steels, the main part of the plastic work is formed already at a drawing depth of about 12 mm. In the 5754 deformable aluminum alloy, the accumulation of plastic strain is more distributed over the drawing depth, while in titanium, high plastic work develops from the very beginning of the process and is maintained until the end of the drawing process.

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