Design, study and development of new equipment for sheet-metal forming

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Abstract. A new facility for sheet-metal forming ensuring forming with heating of a workpiece to the temperature interval of warm or hot machining is designed and developed. The facility contains a case connected to a die where a working cylinder and a combustion chamber, separated from each other by the piston, are placed. Heating and deformation of a stamped workpiece is made under the influence of combustion products of fuel mixes in a working cylinder and dies. The distinctive feature of this unit is that the final forming stage ensures considerable increase of deforming effort that considerably enhances its technological capacity. Practical testing of the designed unit was performed. High quality products were obtained, which makes it possible to recommend this facility for use in small-scale production.

1. Introduction

Sheet-metal forming is widely spread throughout the world due to high quality of its products. The traditional forming equipment has high cost, and hence its application is only profitable in large-scale and bulk production. In various industries [1] of small-scale production it is more efficient to use hydroexplosive [2, 3], electrohydraulic [4], gas-detonation [5] and gas [6–8] forming units ensuring cost reduction for the production of stampings. However, these units fail to achieve the optimum forming effect for complex workpieces especially made of low-ductile alloys. It is advisable to form them through heating. In this respect, it is critical to develop new types of sheet-metal forming equipment for small-scale production.

2. Problem statement

The purpose of this study is to develop new equipment for sheet-metal forming ensuring stamping with workpiece heating.

To achieve this, we developed a gas forming unit with piston hydraulic amplifier [9], which scheme is shown in figure 1. The unit contains a case 1 and a die holder 2 connected to each other via bolts 3 and nuts 4. Inside a die holder 2 the die 5 is placed. Case 1 includes a working cylinder 6 with a piston 7 and a combustion chamber 8 equipped with inlet valves 9, 10, exhaust valves 11, 12 and spark plugs 13, 14. Die 5 is also equipped with an inlet valve 15, an exhaust valve 16 and spark plugs 17. A ring void 18 with a ring piston 19 serving a clamp of workpiece pressing 20 is installed at the end face of a case 1.

The unit operates as follows. Combustible gas is supplied via inlet valves 9, 10, 15 to a working cylinder 6, combustion chamber 8 and a die cavity 5, and then the compressed air, thus forming fuel stoichiometric mixtures. Equal pressure of a fuel mixture is set in a working cylinder 6 and a combustion chamber 7, and in a matrix cavity 5 the pressure is 2-3 times lower. Fuel mixtures in a working cylinder
6 and a die 5 are fired simultaneously via spark plugs 13, 17. As a result of their combustion the pressure in a working cylinder 6 and a die 5 increases manifold, at the same time the pressure in a working cylinder exceeds the pressure in a matrix 5 by 2…3 times. Under the influence of this pressure difference, the workpiece 20 is subject to drawdown in a die cavity 5. At a certain depth of a die, the drawdown stops due to gas compression in it. In this case, a workpiece is intensively heated within 0.5…1 s under the influence of combustion products. Then via a spark plug 14 the fuel mixture is fired in a combustion chamber 8 thus increasing the pressure manifold. Under the influence of this pressure a piston 7 moves and compresses gas in a working cylinder 6. At the same time, the pressure and temperature of gas intensively increase. This ensures further heating of a workpiece to achieve the set temperature interval. Then, the exhaust valve 12 is opened, and gas is released from a die cavity 5. Under the influence of gas pressure in a working cylinder 6 a workpiece, being deformed, fills the entire die cavity 5 thus completing a forming process. Then, the exhaust valves 11, 12 are opened and combustion products are released from a working cylinder 6 and a combustion chamber 7. Then having disconnected a die 5 from a case 1, the stamped workpiece is retrieved.

Figure 1. Scheme of gas forming unit with piston hydraulic amplifier: 1 – case; 2 – die holder; 3 – bolt; 4 – nut; 5 – die; 6 – working cylinder; 7 – piston; 8 – combustion chamber; 9, 10, 15 – inlet valves; 11, 12, 16 – exhaust valves; 13, 14, 17 – spark plugs; 18 – ring void; 19 – ring piston, 20 – workpiece.

Unlike known gas forming units at the final forming stage of this unit the gas pressure and temperature affecting the surface of a workpiece increase intensively. By increasing the developed deformation effort and a workpiece temperature, this expands the technological capacities of this unit. The maximum expansion of technological capacities of the unit can be reached at the optimum ratio of geometric parameters. Let us define these ratios. For this purpose, let us consider the heating of a workpiece.

3. Problem solving

On both sides the workpiece is influenced by combustion products, which temperature makes 2000…2200 °C. Under their influence the workpiece is heated intensively. Heat is transferred to the workpiece from combustion products generally due to convective heat transfer. Heat transfer conditions between gas and workpiece from a die and a working cylinder are almost equal, therefore the heat-transfer coefficients on both sides of the workpiece can be considered identical. Then, on the basis of the convection heat transfer equation of Newton-Rikhman [10] it is possible to write the following:

\[ dQ_w = dQ_{w1} + dQ_{w2} = 2\alpha F_w (t_g - t_w) d\tau \]  \hspace{1cm} (1)

where \( Q_w \) – total heat perceived by a workpiece; \( Q_{w1}, Q_{w2} \) – amount of heat transferred to a workpiece from a die and a working cylinder; \( \alpha \) – heat-transfer coefficient, \( W/(m^2 K) \); \( F_w \) – area of heat-absorbing surface of a workpiece, \( m^2 \); \( t_g \) – gas temperature, °C; \( \tau \) – time.
Heat from gas is also transferred to the walls of a die and a working cylinder. Let us assume that the heat-transfer coefficient is the same along the entire heat transfer surface. Besides, let us assume that the surface temperature of walls equals a workpiece temperature. Then the amount of heat transferred to walls of a die and a working cylinder may be defined by the following equation:

\[ dQ_s = dQ_{s1} + dQ_{s2} = \alpha(F_m + F_c)(t_g - t_w) \ dt \]  \tag{2}

where \( F_m, F_c \) – areas of heat-absorbing surface of a die and a working cylinder, \( m^2 \). From equations (1) and (2) we will receive:

\[ dQ_s = \frac{F_m + F_c}{2F_w} dQ_w \]  \tag{3}

A workpiece and walls of a die and a working cylinder are heated due to decrease of gas temperature. Hence, it is possible to write down the following:

\[ dQ_w + dQ_s = -m_g c_g dt_g \]  \tag{4}

where \( m_g \) – gas weight, \( kg; c_g \) – gas specific heat at constant volume, \( J/(kg\cdot K) \). From the equations (3) and (4) we will receive:

\[ dQ_w = -\frac{2F_w}{F_m + F_c + 2F_w} m_g c_g dt_g \]  \tag{5}

The gas weight in equation (5) may be defined by the following dependences:

\[ m_g = \rho_g V_c + \rho_{g_1} V_m = \rho_g (V_c + \beta_b V_m) \]  \tag{6}

\[ \frac{\rho_{g_1}}{\rho_g} = \frac{\rho_{b_1}}{\rho_b} = \beta_b \]  \tag{7}

where \( \rho_g, \rho_{g_1} \) – gas density in a cylinder and a die respectively, \( kg/m^3 \); \( V_c, V_m \) – volumes of a cylinder and a die, \( m^3 \); \( P_b, P_{b_1} \) – pressure of a fuel mixture in a cylinder and a die, \( Pa \); \( \beta_b \) – correlation of fuel mixture pressure.

Considering the dependence (6), from the equation (5) we will get:

\[ dQ_w = -\frac{2F_w}{F_m + F_c + 2F_w} \rho_g (V_c + \beta_b V_m) c_g dt_g \]  \tag{8}

Heat transferred from gas to a workpiece ensures the increase in its temperature, therefore:

\[ dQ_w = m_w c_w dt_w, \]  \tag{9}

where \( m_w \) – weight of heat-absorbing part of a workpiece, \( kg; c_w \) – specific heat of a workpiece material, \( J/(kg\cdot K) \). The weight of heat-absorbing part of a workpiece equals:

\[ m_w = \rho_w F_w \delta, \]  \tag{10}

where \( \rho_w \) – density of workpiece material, \( kg/m^3 \); \( \delta \) – workpiece thickness.

From the equations (8) – (10) after the corresponding transformations we will get:

\[ \rho_w c_w F_w \delta dt_w = -\frac{2F_w}{F_m + F_c + 2F_w} \rho_g c_g (V_c + \beta_b V_m) dt_g \]  \tag{11}

Let us define:

\[ f_w = \frac{2F_w}{F_m + F_c + 2F_w} \]  \tag{12}

\[ \xi = \frac{1}{F_w \rho_g c_g (V_c + \beta_b V_m)} \]  \tag{13}
where \( f_w \) – relative area of heat-absorbing surface of a workpiece; \( \xi \) – relative heat capacity of a workpiece. Then the equation (11) will be as follows:
\[
\xi dt_w = -dt_g. \tag{14}
\]

This equation shows that the increase of workpiece temperature in inversely proportion to \( \xi \), which, in turn, depends on the correlation of diameter and height of a working cylinder. In this respect, let us define the optimum values of their correlations. For this purpose, let us calculate \( f_w \) and \( \xi \) using dependences (12) and (13). Let us assume that the die is cylindrical and its diameter is equal to the diameter of a working cylinder, and the depth of a die is equal to a half of its diameter. Then the area of heat-absorbing surface of a die is equal to the sum of the area of a bottom of a die and its lateral area:
\[
F_m = \frac{\pi}{4} d_c^2 + \pi d_c \frac{1}{2} d_c = \frac{3}{4} \pi d_c^2, \tag{15}
\]
where \( d_c \) – diameter of a working cylinder, \( m \).

Similarly, the area of heat-absorbing surfaces of a working cylinder is defined as follows:
\[
F_c = \frac{\pi}{4} d_c^2 + \pi d_c h_c, \tag{16}
\]
where \( h_c \) – height of a working cylinder, \( m \). The heat-absorbing surface of a workpiece will be defined assuming that the workpiece is flat, i.e.:
\[
F_c = \frac{\pi}{4} d_c^2 \tag{17}
\]

From dependences (12), (15)-(17) we get the expression for the calculation of the relative heat-absorbing surface of a workpiece:
\[
f_w = \frac{d_c}{3d_c + 2h_c} = \frac{1}{3d_c + 2h_c} \tag{18}
\]

Let us calculate the volumes of a working cylinder and a die assuming that \( \beta_c=0.5 \):
\[
V_c = \frac{\pi}{4} d_c^2 h_c, \quad V_m = \frac{\pi}{4} d_c^2 \frac{1}{2} d_c = \frac{\pi}{8} d_c^3. \tag{19}
\]

Then from dependences (13), (18) and (19) we get:
\[
\xi = \psi \frac{f_w}{d_c \rho_g \gamma_g} \tag{20}
\]
\[
\psi = \left( 3 + 2 \frac{h_c}{d_c} \right) \frac{1}{h_c/d_c + 0.25} \tag{21}
\]

It follows from dependence (20) that \( \xi \) is proportional to \( \psi \), which only depends on the correlation of height and diameter of a working cylinder. Figure 2 shows the diagram of this dependence. The diagram shows that with the decrease of \( h_c/d_c \) below 0.5 the value \( \psi \) sharply increases. At the same time, according to dependence (20), \( \xi \) increases in proportion to \( \psi \), and the dependence (14) shows that the increase of \( \xi \) leads to the decrease of a workpiece temperature increment. Therefore, the decrease of \( h_c/d_c \) below 0.5 is not advisable. With the increase of \( h_c/d_c \) by more than 1.5 times the value \( \psi \) does not decrease sharply, hence, the value \( \xi \) does not decrease considerably, and the temperature of a workpiece slightly increases. However, the height of a working cylinder significantly increases. Therefore, it is possible to consider the optimum \( h_c/d_c \) ranging from 0.5 to 1.5, i.e. the optimum ratio of height of a working cylinder to its diameter falling within the limits of 0.5...1.5. At the same time, smaller \( h_c/d_c \) values refer to greater \( d_c \) values.
Figure 2. Dependence $\psi$ on the correlation of height and diameter of a working cylinder.

At the final forming stage, the gas pressure in a working cylinder is multiplied, which is transferred to a surface of a workpiece. The degree of pressure multiplication significantly depends on the ratio of volumes of a combustion chamber and a working cylinder. Work [9] shows that the best values of this ratio fall within the limits of 1.5…2, i.e. the *volume of the combustion chamber shall 1.5…2 times exceed the volume of a working cylinder*.

Using the above optimum ratios, the sheet-metal forming unit shown in figure 3 is designed, manufactured and assembled according to the scheme shown in figure 1.

*Specification summary of a unit:*
- Maximum diameter of workpieces, mm……………………………………………………………. 250
- Maximum thickness of workpieces, mm……………………………………………………………. 2
- Dimensional specifications, mm………………………………………………………………… 1250x600x300
- Diameter of a working cylinder, mm……………………………………………………………. 160
- Height of a working cylinder, mm……………………………………………………………. 240
- Volume of a working cylinder, m$^3$……………………………………………………………… 0.0046
- Volume of a combustion chamber, m$^3$………………………………………………………… 0.0069
- Maximum pressure of the energy carrier, MPa………………………………………………… 0.9

Figure 3. Photo of a sheet-metal forming unit.

Experimental studies were conducted for practical approbation of the designed unit and establishment of its operating patterns. The operating process was studied by oscillographic testing of pressure change in a working cylinder. Figure 4 shows one of the received oscillograms. It has two maxima. The first one refers to the completion of the combustion process in a working cylinder, while the second maximum corresponds to the completion of the combustion products compression caused by the piston movement under the influence of combustion chamber pressure. The obtained oscillograms showed that due to compression of combustion products the pressure in a working cylinder increases by
1.5…2 times depending on the heating time of a workpiece. At the same time, the deformation effort of a workpiece increases similarly at the final forming stage thus ensuring considerable expansion of technological capacity of a unit.

During experiments the sheet workpieces 1 mm thick made from steel 3 (GOST 380-2005) were formed using a cylindrical matrix with a diameter of 160 mm. Spheroidal bottoms were thus obtained. Figure 5 shows one of the bottoms formed under 0.7 MPa of a fuel mixture. The obtained bottoms had smooth surface without edge fins and corrugations.

4. Conclusions
1. The sheet-metal forming unit ensuring the production of complex parts per one technological operation due to heating of a machined workpiece is created.
2. The final forming stage ensures the considerable increase of the deformation effort of a workpiece, which is confirmed experimentally. This considerably expands the technological capacity of this unit.
3. Practical approbation of the designed unit is carried out. High quality of thus obtained items makes it possible to recommend this unit for use in small-scale production.

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