Studying Interaction of Multi-Motor Forming System for Double Curvature Items

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Abstract. Large double curvature panels are widely used in manufacture of modern aircraft bodies. One of the possible ways to manufacture such parts is to form a workpiece using the method of high temperature multi-point forming by means of a set of moving cores. The paper considers workpiece forming process using different core unit configurations and presents the results of workpiece behaviour study during forming, obtained by means of a finite element method. Conclusions are made on the existing interconnections between forming cores during the forming process.

1. Double Curvature Parts Manufacture Methods
Large load-bearing structural members, forming complex aero- and hydrodynamic circuits of air- and watercrafts, are usually very thick parts made of extra-strong materials (aluminium, steel, titanium) and having a complex spatial form. Mechanical treatment methods are widely used in their manufacture when a part of required shape is milled from large workpieces (forgings). This process is relatively simple, it can have many transitions, including heat treatment, a low material utilization rate, a large amount of material goes into chips, and as a result, the process is long and expensive. Another method of manufacturing large parts of complex spatial form is a deformation process. However, ensuring high forming accuracy of large and thick double curvature parts using traditional methods is a difficult and, sometimes, even impossible task. Existing solutions for forming large plates from high-strength alloys based on multiple step forming and/or multiple die punching have their limitations on press equipment, dimensions and loads as well as high cost of dies. One of the most promising solutions is deforming workpieces using multi-point forming by means of a reconfigurable core punch (matrix).

2. Existing Solutions
Reconfigurable core equipment predominantly has fixed matrix and punch forms. Constant and equal speeds of cores make it impossible to ensure optimal deforming speed, which means that double curvature parts need to be formed in several steps.

There is another approach to reconfigurable systems based not on the geometrical versatility of equipment but on the optimization of deformation modes, which includes deforming speed control and process intensification by heating the part. Many technical solutions implementing this approach [1-9] try to preserve physical and mechanical properties of formed material, minimize residual stress and avoid ductile fractures.
For this, forming is performed in creep mode where it is possible to maintain constant forming speed at each point. Various technical devices are suggested to provide required forming modes: individual core electric drives, differential motors based on hydraulic cylinders, load equalizing devices, etc.

Core unit composition and structure are determined by a set of process steps required to form large plates, their sequence and peculiarities.

The unit consists of three subsystems:

Workpiece treatment subsystem. It includes main functional parts, which actually perform process steps on a workpiece (preheating chamber, forming chamber, prequenching heating chamber, quenching chamber).

Support subsystem. It contains auxiliary functional parts, which ensure uninterrupted operation of main parts.

Monitoring and control subsystem. It contains hardware and software controlling all workpiece treatment and support processes.

Forming cores are two sets of opposing blocks. Core moving drive is based on autonomous variable-frequency electric drives. Rotational to linear motion conversion is performed by actuator that is an electric cylinder with a standard ball screw. Reduction gearbox is used to coordinate operation of electric motor and actuator.

The forming chamber is a system of two prefabricated sections, partially welded and partially assembled using bolt joints. Each section consists of two bearing plates: upper and lower. Upper and lower bearing plates are connected by the main basic frame members. Blocks are secured to the upper and lower bearing plates with bolt joints.

The main task is studying workpiece behaviour during multi-point forming to determine the optimal mode of forming core drive which ensures high item quality.

3. Forming Process Study
First, let us take three-point bend as a base part to study forming process. Three-point bend process is schematically shown in figure 1.

![Figure 1. Bending Process Illustration](image)

Designations in figure 1 correspond to the following: \( R_0 \) is assumed central radius; \( \varphi \) is bend central angle; \( h \) is deflexion value (linear forming cores movement); \( P \) is force affecting a workpiece; \( R_a, R_b \) are reactions at the opposing cores.

Let us determine the forming force with the following expression [10], \( H \):

\[
\Delta P = \frac{\sigma_s B s^2}{4} + \frac{1}{12} \frac{B s^3}{R_0} \left( 1 + \frac{\Delta h}{4} \frac{tg\left( \frac{\varphi}{2} \right) - \mu}{1 + \mu tg\left( \frac{\varphi}{2} \right)} \right)
\]
where \( s \) is workpiece thickness, \( m \); \( B \) is workpiece width, \( m \); \( R_0 \) is bend central radius, \( m \); \( l \) is distance between opposing cores axes, \( m \); \( \sigma_S \) is creep limit, \( Pa \); \( \Pi \) is material hardening modulus, \( Pa \); \( \mu \) is friction factor between core and workpiece.

Bend angle \( \phi \) changes during workpiece forming from zero to some final value determined by linear movement. At a first approximation, \( \tan \frac{\phi}{2} \) can be expressed through forming part parameters \( \tan \frac{\phi}{2} = \frac{2\Delta h}{l} \) [11].

\[
\Delta P = \frac{\sigma_S B s^2}{4 \left( \frac{l}{4} + \frac{\Delta h}{2} \right) - \mu}.
\]

Forming force can also be decreased by heating the workpiece which allows lowering creep limit and reducing hardening to zero. It should be noted that bending accuracy increases in this case due to reduced springback effect.

Now let us determine workpiece behaviour during forming. Finite element method is used for this. Workpiece bending process is simulated in Femap [12]. Let us consider two cases: during operation of the central core (figure 2) and one of the side ones (figure 3). It should be noted that when one core moves, others are still.

**Figure 2.** Workpiece behavior during central core operation

**Figure 3.** Forming force and support reactions during central core operation

Figure 3 shows the values of non-moving cores support reactions when central core moves. Meaning, that if central core presses down on the workpiece with force \( P \), then the workpiece applies force \( Q \) = \( P/2 \) to each of the side cores.

**Figure 4.** Workpiece behaviour during operation of one of the side cores

**Figure 5.** Forming force and support reactions during operation of one of the side cores

Figure 5 shows the values of non-moving cores support reactions when one of the side cores moves. Meaning, that if a side core presses down on the workpiece with force \( P \), then the workpiece applies force \( Q_1 = 2P \) to the central core and \( Q_2 = P \) to another (non-operating) side core.

When cores move simultaneously, each of them is affected by adjacent cores movement and affects them in turn. Central core takes most of the load in this bending scheme. If cores operate separately, there is no significant interaction.

The effect of deformation speed on forming process should also be taken into account. If the selected deformation speed is too high, there may be indentations on the workpiece from forming cores, ductile fractures due to stress in the workpiece which exceed yield limit [13]. If deformation speed is too low,
it unjustifiably lengthens the process. Too high deformation speed also increases the load on the forming rod.

When hot-forming method is used, two processes occur simultaneously and affect deformation resistance in opposite directions: hardening (cold work) and softening (recrystallization). Both processes take place in time. Hardening speed is determined by deformation speed and softening speed — by recrystallization speed, which depends on metal temperature. Depending on the ratio of deformation and recrystallization speeds (hardening and softening), deformation resistance at this temperature changes: the faster the deformation speed, the higher the deformation resistance. Deformation resistance at this speed and temperature is affected by deformation degree: the higher the deformation degree, the greater the cold work and deformation resistance [14, 15].

Therefore, deformation speed and degree directly increase deformation resistance and indirectly decrease it. When hot-forming method is used and heat output is small, hardening effect of both factors prevails, and deformation resistance rises with the increase of deformation speed and degree [16, 17].

Differentiation of thermal power load modes by deformation speed allowed to empirically establish that deforming at deformation speeds with order $10^3 \ldots 10^4 \text{s}^{-1}$ has certain advantages compared to fast (“instant”) elastoplastic deformation: forming force is reduced significantly, material deformation index increases. Moreover, during bending and relaxation calculations, area of elastoplastic stresses has to be monitored for active or unloading processes at the points of workpiece elements, as irreversible deformations of plasticity have to be taken into account, which significantly complicates the calculations [18, 19].

In view of the above, control object model in Simulink can be presented as shown in figure 6 [20].

![Figure 6. Control Object Model](image)

Three-point bending part is basic. Most important is the possibility of forming sheet materials. Reconfigurable forming core matrix may be used for this. Let us study workpiece behaviour at different quantities of forming cores.

Figure 7 shows force distribution by core with matrix 3x3 layout. Central core presses down with $P = 1$ force, and outer cores experience $0.384*P$ reaction.

Figure 8 shows Matrix 5x5 where adjacent cores experience $0.35*P$ reaction during central core operation.
Figure 7. Matrix 3x3

Figure 8. Matrix 5x5

Figure 9 shows Matrix 11x11 where adjacent cores experience 0.351*P reaction during central core operation.

Further increase of matrix size does not lead to significant force change. Matrix 5x5 is selected for study as it has sufficient accuracy and processing obtained results will not take a lot of time.

Figure 9. Matrix 11x11

Figure 10. Force Distribution in Matrix 5x5

During the study, it was established that during operation of one of the cores, the highest load falls on adjacent cores; in particular, ones located at matrix row and column lines (figure 10). Cores located in red area experience the highest load during core 33 operation, cores in blue area — the lowest. Other cores are in intermediate positions.

Now let us determine how movement of one core affects other adjacent cores. For this, we simulate each core operation using finite element method and estimate its impact on other cores. It should be noted, that operating core moves during simulation, others stay in place.

As the result of simulation, special points under positions 11 and 33 were determined, i.e. outer and central. Let us study matrix core movement in these cases as they are extreme and other cases are transient.

What distinguishes the outer point is that maximum force impacting adjacent cores is 0.94*P which is similar to bending force. Maximum force of operating core under position 33 is 0.35*P which is almost one third of bending force.

As in the case of three-point bending, core interaction and, consequently, drive interaction manifests only for simultaneous core operation. Meaning, that load moment for core drive is composed not only from the required bending force (moment) but from load moments occurring due to adjacent core drive operation (support reaction).

In general, if each core drive develops forming force,
\[
P = \begin{bmatrix}
P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\
P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\
P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \\
P_{41} & P_{42} & P_{43} & P_{44} & P_{45} \\
P_{51} & P_{52} & P_{53} & P_{54} & P_{55}
\end{bmatrix},
\]

then for each core force is as follows:
\[
P_{ROD} = \sum_{i=1}^{5} \left(P_{1,i} + P_{2,i} + P_{3,i} + P_{4,i} + P_{5,i}\right)
\]

For example, for core 33 (central), load force is determined as follows:
\[
P_{ROD3} = P_{33} + 0.35 \cdot P_{32} + 0.35 \cdot P_{34} + 0.35 \cdot P_{23} + 0.35 \cdot P_{43} + \\
0.2 \cdot P_{13} + 0.2 \cdot P_{13} + 0.2 \cdot P_{13} + 0.2 \cdot P_{13} + \\
0.03 \cdot P_{15} + 0.03 \cdot P_{15} + 0.03 \cdot P_{53} + 0.03 \cdot P_{53} + \\
0.008 \cdot P_{24} + 0.008 \cdot P_{42} + 0.008 \cdot P_{44} + 0.008 \cdot P_{22} + \\
0.082 \cdot P_{21} + 0.082 \cdot P_{21} + 0.082 \cdot P_{14} + 0.082 \cdot P_{41} + \\
0.082 \cdot P_{25} + 0.082 \cdot P_{25} + 0.082 \cdot P_{45} + 0.082 \cdot P_{45}.
\]

Here force \(P_{33}\) is forming force during separate core operation, other constituents manifest only when all cores move together. These expressions can be obtained for each core. All cores will not necessarily move. If one core is still, its force \(P_{ij}\) is taken as zero.

In view of the above, a conclusion can be made that in case of simultaneous movement of all cores, their drives need to be ready to process higher load than in case of separate operation. Simultaneous movement of all cores allows giving workpiece the required form right away instead of doing it in stages (as in case of separate operation). The results obtained using finite element method are approximate but adequate.

If we suppose that each core develops the same forming force \(P\), then each core will experience the following force during their simultaneous operation:
\[
P_{0} = \begin{bmatrix}
P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\
P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\
P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \\
P_{41} & P_{42} & P_{43} & P_{44} & P_{45} \\
P_{51} & P_{52} & P_{53} & P_{54} & P_{55}
\end{bmatrix} = P.
\]

This way, simultaneous operation of all cores leads to increased load on electric drive. Central core drives are most affected. This is why electric drive system should be designed, taking into account possible load increase during simultaneous operation of all cores.

4. Conclusion
Multi-point forming by means of a reconfigurable core punch (matrix) is the most promising existing solution to manufacturing large double curvature parts. This method provides high accuracy and quality of manufactured parts.

Finite element method was used to study forming process. It was established that in case of simultaneous (parallel) movement of each core, additional reaction impacts adjacent cores which manifests as increased load on core drive. However, in case of separate (sequential) movement of cores, additional load does not affect electric drives of adjacent cores.
In other words, interaction between cores by workpiece manifests only when they move simultaneously. This fact should be taken into account during core unit design.

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