Hydropress assembling automation of interference fits with steel and titanium parts

A V Romanov, A V Shchenyatsky and A V Petrov

1Kalashnikov Izhevsk State Technical University, 7, Studencheskaya street, Izhevsk, 426069, Russia
2JSC "Kalashnikov Concern", 3, Deryabin driveway, Izhevsk, 426006, Russia

*ms_istu@mail.ru

Abstract. The main aspects of assembling automation of hydropress connections are considered – increasing the assembling performance, its stability and ensuring the quality of hydropress connections. A control system for the technological complex of hydropress assembling on a base of fuzzy logic methods has been developed, it provides the control of technological assembling modes, including: pressing speed, oil pressure, control of the force and pressing length, without identifying the parameters of assembling process, as well as the guaranteed presence of liquid friction in the non-linearity conditions of assembling process. The structure and control algorithm of automated hydropress assembling that ensure the maintenance of the working oil pressure during assembling are proposed. The algorithm is based on a set of feedbacks: pressure and position sensors, that provides a qualitative transition from boundary to liquid friction. A prototype of the technological complex of hydropress assembling of interference fits has been developed, that allows to assemble joints with a coupling diameter up to 50 mm in an automated mode. The results of experimental studies of automated assembling of steel and titanium joints are presented.

1. Introduction

One of the most advanced technologies for obtaining joints with tension is the hydropress assembling method, that is based on creating an oil layer under high pressure between the contacting surfaces of the assembled parts, as a result of which the relative displacement of the mating surfaces of the shaft and bush takes place fluid and boundary friction [1,2,3].

The process of hydropress assembling and the quality of the assembled couplings depends on many factors: pressure, flow rate and viscosity of the working fluid, speed of the assembling operation, technological scheme and pressing equipment, etc. The change of these parameters occurs to the limit values and is not regulated, that is negative affects on the stability of the pressing process and load capacity of the assembled fits with tension [4].

Improving the performance of assembling, its stability, as well as ensuring the quality of hydropress connections are possible on the basis of automation of assembling process, that allows to fully realize the advantages of this method.

Such schemes of oil supply as: with an oil distribution groove, with oil supply from the end of the joint, using a false piston, differential are widely used [5].

The most difficult from the point of view of ensuring the stability of assembling process is the technological scheme with oil supply from the connection end, due to the excessive amount of oil that
requires adjusting the assembling parameters to avoid plastic deformations (the oil pressure should not exceed maximum value). Improving the performance and quality of connections through automation using this scheme is a particular scientific interest.

2. **Automatic control system of hydropress assembling**

The process of assembling component joints using a hydropress method depends on many factors, most of which are not taken into account in the mathematical model of a hydraulic press assembling (effect the lead-in chamfer angle on the pressing force, condition of the surface layer of parts, mechanical properties of the material, oil viscosity, process speed, relative position accuracy of mating parts, etc.) [4].

In addition, the control object is non-linear, as a result, when solving the problem of ensuring the required oil pressure in the press-in zone using the methods of the theory of automatic control, certain problems of control of this process may arise [6].

The experience of investigating the hydropress assembling of joints with tension [4] shows that when pressing in when changing the friction mode, there is a sharp change in the magnitude of the pressing force, and in these extreme points compensation is required for the disturbances that occur during this.

Application of a fuzzy control appliance with low sensitivity to control object parameters changes, high performance on the error dynamics, the ability to work correctly when large disturbances occur and the control object is highly nonlinear, allows to solve the above problems [7].

2.1. **Fuzzy control system of hydropress assembling**

Consider the automatic control system of the hydropress assembling based on fuzzy logic, it is presented in Figure 1.

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**Figure 1.** Functional diagram of hydropress assembling control system.

SPSH – set point position and speed at hydropress assembling; ASM - axis synchronization module; q_op – operating oil pressure; FPR - fuzzy logic pressure regulator; FPC 1,2 – fuzzy logic position controllers of mechatronic press axes 1,2; DAC1,2 – channels of digital-to-analog converters; PLC – programmable logic controller; Axis 1,2 - linear mechatronic module of parallel axes 1,2; MP – mechatronic press; ADC1,2 – channels of analog-to-digital converter; PS1,2 – position sensors 1,2; PrS – pressure sensor; FS – force sensor; HPPS – high pressure pumping station; CO – control object – process of hydropress assembling.
The system contains two regulators that perform certain functions: a position controller and a pressure regulator, the structure of which is shown in Figure 2.

![Figure 2. Structure of pressure regulator](image)

SPSH – set point position and speed at hydropress assembling; ASM - axis synchronization module; FPR - fuzzy logic pressure regulator; PSC - pressing speed corrector; FPC 1,2 – fuzzy logic position controllers of mechatronic press axes 1,2.

The control system of hydropress assembling works as follows. The pressure regulator is activated at the semi-dry friction section when the operating oil pressure \(q_{OP}\) is reached and it is switched off at the braking section. The value of operating oil pressure \(q_{OP}\) is compared with the actual value of oil pressure \(q\) obtained from the pressure sensor after analog-digital conversion. The calculated pressure difference \(\Delta q = q_{OP} - q\), its first \(\Delta q'\) and second \(\Delta q''\) derivatives are input variables for the pressure regulator, that forms the control action \(U_{vp}\), which reduces the deviation of fluid pressure from the operating one.

The corrector of pressing speed limits the control action value on the basis of the calculated control action \(U_{vp}\) and speed reached at the site of operating pressure \(V_{opc}\).

The increment of the pressing speed is calculated as:

\[
U_{kVp} = k_{Vp}U_{vp} 
\]

where \(k_{Vp}\) - correction factor, \(U_{vp}\) - value of control action at pressure regulator output.

The calculated increment of the pressing speed is passed to the position and speed setting module, after this to the axis synchronization regulator and axis position regulators, thereby maintaining a pressure close to the operating pressure by reducing or increasing the speed at the control section.

The input parameters of pressure regulator are: pressure mismatch \(\Delta q\), the first \(\Delta q'\) and the second \(\Delta q''\) derivatives of mismatch \(\Delta q''\). Fuzzy input variables have three triangle terms: negative (N), neutral (NE), positive (P).

The fuzzy variable with triangle terms: negative large (NL), negative medium (NM), negative small (NS), neutral (NE), positive small (PS), positive medium (PM), positive large (PL) are used to the linguistic description of output variable, that provides a satisfactory sensitivity of the regulator to changes of system state [8].

The assumption that the greater pressure mismatch must comply with a greater control action was used when forming the rulebase. The linguistic rules are formulated on a base of this value.

Fuzzy logic system is designed for Mamdani type. Rules are formed by type of IF ... AND ... AND THEN...

As a result, the required increment of the \(dU_{vp}\) pressing speed is formed at the output of pressure regulator on the basis of fuzzy logic, depending on the values of the input variables in accordance with the linguistic rules.
The formulated pressure regulator based on fuzzy logic is the basis of the control system of the technological complex for hydropress assembling of interference fits. It maintains a given oil pressure and pressing speed that provides the required assembling modes.

2.2. Control algorithm of automated hydropress assembling
Assembling in automated mode is carried out in accordance with the algorithm shown in Figure 3.

It is necessary to regulate the pressing speed \( V_Z \), ensuring the constancy of operating oil pressure \( q \) and, thereby, the liquid friction mode, when using the technological scheme with the oil supply from the coupling end.

![Figure 3. Control algorithm of hydropress assembling (automatic mode).](image)

The following notation are used in the algorithm:
- \( a_p \) – pressing acceleration,
- \( a_d \) – deceleration,
- \( L_i \) – pressing length at \( i \) – time moment,
- \( L_p \) – pressing length,
- \( q_i \) – oil pressure at \( i \) – time moment,
- \( q_{\text{min}} \) – initial (starting) oil pressure,
- \( q_{\text{op}} \) – operating oil pressure,
- \( S_{\text{p}} \) – length of the pressure regulation section,
- \( S_{\text{opc}} \) – length of operating pressure creation section,
- \( t \) – time,
- \( V_p \) – pressing speed.

The control algorithm maintains the operating oil pressure \( q_{\text{op}} \) in the control section (semi-fluid friction section) by changing \( V_p \) that provides the required modes of hydropress assembling.
3. Technological complex of automated hydropress assembling

The mechatronic press [9] is additionally equipped with a pressure sensor (0–250 MPa) to realize the possibility of hydropress assembling. The oil is pumped into the interface zone by means of a controlled high-pressure pumping station \( (q_{\text{max}} = 600 \text{ MPa}) \).

The block diagram of the technological complex for the hydropress assembling, including the mechatronic press and the technological block, is presented in Figure 4.

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**Figure 4.** Structural diagram of the technological complex for hydropress assembling

PC – personal computer (top level control device); PLC – programmable logical controller (medium level control device); MP – mechatronic press; TU – technological unit; HPPS – high pressure pumping station; PrS – pressure sensor; FS – force sensor

The scheme of technological unit is shown in the Figure 5, technological equipment and assembling coupling is shown in the Figure 6.

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**Figure 5.** Scheme of the technological unit for hydraulic press assembling

1 - load module; 2 - shaft; 3 - bush; 4 - case of the technological block; 5 - pressure sensor; 6 - high pressure pumping station; 7 - press table

**Figure 6.** Technological equipment and assembling coupling

1 - technological unit; 2 - pressure sensor; 3 - supply pipe from the high-pressure pumping station; 4 - assembling coupling.
4. Results

Samples that drawings are shown in Figure 7 were used for the automated hydropress assembling.

The seating surfaces of the bush are obtained by electrical erosion processing, the shaft - by fine turning with subsequent grinding.

The material of coupling parts are:
shaft – steel 3140H (HRC 40...45);
bush – steel 1045 (230…260 HB), titanium ST-A90.

![Figure 7. Samples design of interference fit parts (shafts and bush).](image)

The initial acceleration of traverse motion during the pressing is determined taking into account the technological requirements for the assembling process of hydropress joints, as well as for the reasons of ensuring the performance of the assembling operation and depending on the tension varied within the limits of \( a_p = 50 \ldots 200 \text{ mm/s}^2 \).

For most of the joints with tension used in mechanical engineering, the ratios of the length and diameter of the landing vary within \( L = 0.5 \ldots 3d \), as a result, the length of the pressing in full-scale experiments was taken \( L = 30 \text{ mm} \).

The oil pressure operating value for the steel-steel connection was taken 100 MPa, steel-titanium - respectively 130 MPa, based on the condition of ensuring liquid friction and non-occurrence of plastic deformations.

The assembled sample of the hydropress fits is shown in Figure 8.

![Figure 8. Assembled experimental sample.](image)

Changes of pressing process parameters during the experiment are presented in diagrams (Figures 9,10) (connection "steel-steel, tightness 21 µm, \( a_p=70 \text{ mm/s}^2 \)).

The increase of oil pressure at the beginning of assembling process is due to the presence of a dry friction area on the inlet edge of bushing due to the fact that the gap required for the expiration of the oil is only beginning to form.
Figure 9. The dependence of oil pressure on the pressing length.

Figure 10. The dependence of pressing speed on the pressing length.

The oil pressure continues to increase on the semi-dry friction section and the pressure regulator starts to work when the operating pressure is reaching. The further change of pressure depends on the speed of pressing. The fuzzy logic controller maintains the oil pressure close to the operating one by reducing the speed or raising it by increasing the speed.

It was found that the pressing modes for couplings with smaller tightness changed more smoothly, while at the minimum tension at high accelerations of $a_P$ (up to 200 mm/s$^2$) the speed of pressing $V_P$ increased to 43 mm/s (Table 1).

| № of sample | Material of coupling | Tightness $\delta$ (µm) | $a_P$ (mm/s$^2$) | $V_P$ max, mm/s |
|-------------|----------------------|--------------------------|------------------|-----------------|
| 1           | steel-steel          | 6                        | 200              | 43              |
| 2           |                       | 15                       | 100              | 37              |
| 3           |                       | 21                       | 70               | 28              |
| 4           |                       | 6                        | 120              | 39              |
| 5           | steel-titanium       | 15                       | 80               | 31              |
| 6           |                       | 21                       | 50               | 22              |

The achieved assembling speeds significantly exceed the speed of pressing in the non-automatic mode (not exceeding 10 mm/sec) for samples with a coupling diameter of 10 mm.

The bearing capacity of the connection was determined after assembling. The test results are given
in Table 2.

Table 2. Axial force and torque values.

| № of sample | Samples, shaft-bush | Tightness δ (µm) | F_A (kN) | T (Nm) |
|-------------|---------------------|------------------|---------|--------|
| 1           | steel-steel         | 6                | 2,89    | 15,70  |
| 2           | 15                  | 15               | 7,46    | 34,93  |
| 3           | 21                  | 21               | 10,35   | 51,46  |
| 4           | steel-titanium      | 6                | 4,10    | 20,30  |
| 5           | 15                  | 15               | 10,50   | 52,15  |
| 6           | 21                  | 21               | 13,50   | 69,32  |

Thus, the results of experiments confirm the correctness and efficiency of proposed fuzzy control system and algorithms for controlling the technological complex during the assembling in automatic mode, as well as the quality of assembled fits by the criterion of bearing capacity.

5. Conclusion

The developed automatic control system provides control of technological modes, namely maintaining the oil pressure in a given range, and ensures the guaranteed presence of liquid friction. When the requirements for the oil pressure range are tightened, pressure sensors with a minimum response time, intelligent control systems based on neural networks or other technological schemes of the hydropress method should be used.

Using of fuzzy logic in nondeterministic build conditions allowed to achieve the required quality of connection; when the control range is narrowed, the knowledge base with a large number of terms and rules, as well as other types of membership functions should be used.

The pressing speed level of 43 mm/s achieved by this scheme is more than 4 times higher than the maximum assembling speed in non-automatic mode, but it does not fully realize the capabilities of the hydropress method, higher pressing speeds can be achieved by applying other assembling schemes, in particular the differential pressure pumping method or using oil flow regulators.

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