Study of the influence of cross section sizes of the rod shock system on the efficiency of shock pulse energy transfer to the deformation center

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Abstract. Using the finite element model of the shock system, the efficiency of the shock pulse energy transfer to the deformation zone under wave strain hardening is studied. It was established, that conducting research from the point of view of the efficiency of transferring the shock pulse energy to the deformation zone, and from the point of view of the design of the shock pulse generator, is advisable on shock systems in which the contacting ends of the striker and the waveguide have equal diameters. Studies showed that with ratios $1<\frac{L_1}{L_2}<10; 5<\frac{L_1}{d_1}<10$, an increase in the fraction of the shock pulse energy transmitted to the deformation zone $n$ exceeds 80\% for the striker and waveguide with diameters of 30, 48, 60, 90 mm. According to the adopted optimization criteria, the geometrical dimensions of the striker and the waveguide are determined, which ensure the transfer of the largest amount of shock pulse energy to the deformation zone.

1. Introduction

The use of dynamic effects on the deformation zone is energetically more profitable than its static loading. The principle of dynamic effects on the treated zone is laid down in modern methods of strain hardening [1-3].

The problem of increasing the fraction of the shock pulse energy transmitted to the deformation zone is relevant for all methods based on shock [1, 9]. There are several ways to increase the fraction of energy transmitted to the deformation zone. Thus, an increase in the striking force of the striker, on the one hand, can increase the strike system efficiency, and on the other, lead either to an increase in the strength requirements for the elements of the strike system, or to an increase in their size and, consequently, cost. Another method that contributes to an increase in the fraction of energy transmitted to the deformation zone is the use of an intermediate link in the shock system — the waveguide. This solution, due to the action of the reflected deformation waves, makes it possible to generate a prolonged shock pulse, consisting of not only the head but also the tail. A prolonged shock pulse is characterized by the highest energy.

The impact through the intermediate link - the waveguide, is laid down in the principle of the wave strain hardening method (WSH). The development of the wave strain hardening method (WSH) began in the 90s of the last century, in 1997 the first patent was obtained [1]. The basis of wave strain hardening (WSH), as in the two previous SPD methods, is the use of the energy of wave processes (Figure 1). The generation of shock pulses occurs in a shock system with an intermediate link. It
allows us to form shock pulses, consisting of the head and tail. The tail part of the pulse is formed due to the energy of recovery of the deformation waves and depends on the loaded medium properties. The use of the tail part makes it possible to prolong the shock pulse impact on the loaded medium, intensifying the elastoplastic deformation and increasing the efficiency of the process. The process of loading a material with a deformation wave is characterized by an expanded set of control factors, which provides wide possibilities for controlling the parameters of pulses, expands the possibilities of deformation processing, as well as allows us to create a layer with a given uniformity of hardening and depth. The hardened layer is formed as a result of repeated pulse actions. The foci of these actions have a relative displacement. The multiplicity and strength of the pulsed action, the dimensions of the deformation zone, determined from the contact problem solution, the pattern of change in the material properties along the depth of the surface layer as a result of a single pulsed action determine the nature of the diagram of the gradient hardened surface layer properties [1]. The high (acoustic) speed of the propagation of the deformation wave in the material (about 5000 m/s), the ability to control the intensity and duration of the force action on the surface layer fragments, allow us to attribute this processing method to the methods of intense plastic deformation of the material.

Figure 1. Scheme of the hardened surface loading during WSH: 1 - pulse generator, 2 - striker, 3 - waveguide, 4 - tool, 5 - hardened surface; $A$ - impact energy, $P_{st}$ - static load, $S$ - part feed relative to the tool, $L_1$, $L_2$ - length of the striker and the waveguide, respectively, $d_1$, $d_2$ - diameter of the striker and the waveguide, respectively [1].
In the process of studying the possibilities of the WSH method, the influence of the geometric dimensions of the shock system elements on the efficiency of energy transfer to the deformation zone was noted. Previously conducted series of experiments, in a rather narrow range, revealed rational geometric relationships of the shock system that contribute to the greatest transfer of the shock pulse energy to the deformation zone: $d_1/d_2 = 1.3$, $L_1/L_2 = 3.5$, $L_1/d_1 > 3$, where $L_1$, $d_1$, and $L_2$, $d_2$, respectively, the length and diameter of the striker and waveguide. When using shock systems with such parameters, the depth of the hardened layer is 6-8 mm, and the degree of hardening reaches 150% [1].

The process of wave strain hardening can be controlled by a large number of technological factors in a wide range of values [3]. On the one hand, this allows a rather fine WSH control, on the other hand, due to a large amount of experimental data, difficulties in establishing interrelations between technological factors that ensure the formation of the required hardening parameters arise.

The study of the influence of a large number of controlled technological factors of WSH hardening efficiency is easiest to carry out in the modeling process. The existing analytical model of pulse formation in the deformation zone, wave transformation at the boundaries of sections with various acoustic properties, as well as a computer program created on its basis, require rather cumbersome calculations and are based on assumptions that must be clarified in case of a FEM [1]. So, the physical-mechanical properties of the processed material are taken into account in an experimental manner, without taking into account hardening curves; hardening is carried out with only one tool; hardness (stress, strain) formed in the loading medium as a result of the calculation can be determined only at one point, under the imprint from the impact of the tool, and not by the equidistant surface of the material. Though, finite-element models proposed later by A. Afonin [4], allow us to identify the nature of the relationship between the fields of stresses, strains, design and technological parameters of the thread rolling process with static and static-pulse loading of the deforming tool, they have a narrow focus and are intended only for solving problems related to thread rolling. Therefore, the task of developing a comprehensive model of the process of a modified layer wave strain hardening, which allows us to get rid of the limitations of earlier models, is relevant. Due to the fact, that the method of wave strain hardening has been developed quite recently, most of its features are not fully disclosed. So, the issue of choosing the dimensions of the cross section for the shock system elements during WSH is relevant. This is due to the search for the effective cross-sectional size of the elements of the shock system during WSH, which can ensure the transfer of the maximum possible energy fraction of the shock pulse at the minimum possible mass and dimensions of the striker and waveguide.

The aim of this work is to study the influence of the dimensions of the cross sections of the rod shock system on the efficiency of shock pulse energy transfer to the deformation zone during wave strain hardening.

2. Materials and methods

Please For research, the rod type of the shock system was used. The striker with a flat end struck the flat end of the waveguide, statically pressed against the loading medium. The diameter of the striker $d_1$ is equal to the diameter of the waveguide $d_2$. To carry out the studies designated for the purpose of the work, shock systems with a range of diameters $d_1 = d_2 = 16, 32, 48, 60, 90$ mm were taken. For a comprehensive assessment in the study, it is also necessary to take into account the influence of the striker lengths $L_1$ and the waveguide $L_2$, as well as the ratio of the striker length $L_1$ to its diameter $d_1$ in the range: $1 < L_1/L_2 < 10; 1 < L_1/d_1 < 10$.

For the planned research, it is necessary to conduct about 64 experiments and produce 128 elements of shock systems, with a total mass of finished products of about 4 tons (3960 kg).

Due to the high complexity, metal consumption and duration of research, work on the search for effective cross-sectional dimensions of shock systems must be carried out using simulation.
The creation of a model of the process of the WSH shock pulse formation, taking into account the shortcomings of the previously created ones, was carried out using modern engineering analysis based on the finite element method [5-8,10]. The leader in the simulation of fast processes (about $10^5$ s) is the LS-DYNA software package.

The development of a model of a shock pulse in a deformation zone during wave strain hardening is divided into four stages (Figure 2) [2].

At the first stage, in the Workbench section of the Ansys program, model elements are created in the graphics module: a striker, a waveguide and a loading medium. The striker and the waveguide are rods with flat ends, and the loading medium has the form of a rectangle. Then they are positioned relative to each other, according to Figure 1. To significantly speed up the calculation using the Split Body element, the model is cut along the symmetry axis and only half of the model is left for calculation.

Then, in the Engineering Data module, models of the shock system materials and the loading medium are created. The basis for this is the values of the physical-mechanical properties of real materials obtained as a result of preliminary laboratory studies conducted with the help of appropriate equipment. In the Symmetry Region section, the boundary of the passage of the symmetry plane of the model is indicated. The breakdown of the created model into finite elements - tetrahedrons, is performed in the Mesh section. There, the type of grid is selected and its size is set. In the Contacts section, the type of Frictional contact between model elements is set and the value of the friction coefficient is indicated. Using the Contact Tool, contact interactions between model elements are generated.

At the second stage, the Static Structural module sets the preliminary static compression of the loading medium by the waveguide. In the beginning, in order to limit the displacement of the loading medium under load, the boundary condition Fixed Support is applied to its lower end. The boundary condition Displacement introduces a ban on the waveguide movement along the z axis, which helps to avoid its displacement under load from the symmetry axis. To account for the effect of gravitational forces on model elements, the Standard Earth Gravity module is added to the calculation. To set the
value of the static load, in the Force section, the waveguide is assigned the value of the force of its preload to the loading medium in Newtons. The final setup of this stage is completed in the Analysis Settings section by setting the static loading process duration.

At the third stage, the simulation of fleeting shock loading in the LS-DYNA module takes place. As in the previous stage, the model setup begins with the boundary conditions: Fixed Support - a ban on moving the lower end of the loading medium and Displacement - a ban on the displacement of the striker and waveguide relative to the axis of symmetry. The effect of gravitational forces on model elements is taken into account by adding the Standard Earth Gravity module to the calculation. The addition of the Dynamic Relaxation function is necessary to take into account in the calculation the effect of the preliminary static load on the loading medium calculated in the Static Structural module. The action of the shock load of the striker is realized through speed in the Velocity section, which is more correct from the energy point of view than through the force parameter. In the Analysis Settings section, the value of the End Time parameter is configured. It includes the sum of the time of static loading, impact and unloading after impact.

At the fourth stage, in the Solution module, processing and visualization of simulation results takes place. The module enables us to visualize the action of various types of deformations, stresses, etc. in the model.

The calculation time was determined taking into account preliminary static loading and applying one impact with an energy of 35 J. When developing a model for the shock pulse formation, it was possible to take into account all the features of the WSH method in it.

To identify the parameters of the shock system that provides the largest share of the shock pulse energy transferred to the deformation zone, various shock systems with geometric parameters in the ranges $1 < L_1 / L_2 < 10$ were simulated; $1 < L_1 / d_1 < 10$; $d_1 = d_2 = 16, 32, 48, 60, 90$ mm. To study the effect of the diametrical difference between the striker and the waveguide on the efficiency of shock pulse energy transfer to the deformation zone, their ratios of $0.5 < d_1 / d_2 < 2$ were used. The elements of the shock system: the striker and the waveguide are assigned the physical-mechanical properties of hardened 90CrSi steel, and the loading medium - 41Cr4 steel in the delivery state.

Using the shock pulse diagram (Figure 2) obtained as a result of the impact, the fraction of the energy transferred to the deformation zone was estimated using the method described in [1]. The reliability of the developed finite element model was evaluated by comparing the obtained values of the shapes, duration, amplitude and energy of the shock pulses with the data revealed under the same conditions on the experimental bench. The simulation results correspond to experimental data with a confidence level of 0.95.

3. Results and discussion

3.1. Study of the influence of the diametrical difference between the striker and the waveguide on the efficiency of shock pulse energy transferred to the deformation zone

The simulation results are graphically presented in Figure 3 and 4.

When using a striker and a waveguide in the shock system, with the ratio of their diameters $d_1 / d_2 = 2/1$, the lowest transmitted energy efficiency was 73-78%, obtained with the values $L_1 / L_1 = 1, (1 \leq L_1 / L_2 \leq 10)$ The rest of the shock systems with $5 \leq L_1 / d_1 \leq 10, (1 \leq L_1 / L_2 \leq 10)$ with $d_1 / d_2 = 2/1$, showed the efficiency of the transmitted energy share of more than 80%.

In the case of using shock systems with the ratio of the diameters of the striker and waveguide $d_1 / d_2 = 1.5/1$, the range $L_1 / d_1 = 1, (1 \leq L_1 / L_2 \leq 10)$, also provided a low n 41-60%, which means significantly less than with $d_1 / d_2 = 2/1$. Shock systems with $5 \leq L_1 / d_1 \leq 10, (1 \leq L_1 / L_2 \leq 10)$ transmitted n more than 80%. Compared with $d_1 / d_2 = 2/1$, the change in the energy transfer efficiency of the shock pulse of these shock systems was 1-2%.
The use of shock systems with a ratio of the diameters of the striker and waveguide $d_1/d_2 = 1/1$ revealed that the smallest efficiency of energy transfer of the shock pulse to the deformation zone was 36-46% at $L_1/d_1 = 1$, $(1 \leq L_1/L_2 \leq 10)$. Impact systems with $5 \leq L_1/d_1 \leq 10$, $(1 \leq L_1/L_2 \leq 10)$ compared with $d_1/d_2 = 1.5/1$, on average reduced $n$ by 8-10%. A value of $n$ greater than 80% is set at $L_1/d_1 = 10$, $(1 \leq L_1/L_2 \leq 10)$.

The use of shock systems with the ratio of the diameters of the striker and waveguide $d_1/d_2 = 1/1.5$ led to a decrease in $n$ to 29-44% at $L_1/d_1 = 1$, $(1 \leq L_1/L_2 \leq 10)$. In shock systems with parameters $5 \leq L_1/d_1 \leq 10$, $(1 \leq L_1/L_2 \leq 10)$ compared with $d_1/d_2 = 1/1$ $n$ decreased from 6 to 16%. Values of $n$ more than 80% are set only in shock systems with $L_1/d_1 = 10$, $(5 \leq L_1/L_2 \leq 10)$.

**Figure 3.** Diagram of the proportion of the shock pulse energy transmitted to the deformation zone on the diametrical difference of the striker and the waveguide.

**Figure 4.** Diagram of the dependence of the fraction of the shock pulse energy transmitted to the deformation zone on the diametrical difference of the striker and the waveguide.
If a striker and a waveguide are used in shock systems, with the ratio of their diameters \( \frac{d_1}{d_2} = 1/2 \), with \( L_1 / d_1 = 1 \), \( 1 \leq L_1 / L_2 \leq 10 \), the shock pulse energy transfer efficiency constituted only 30-36%. Compared with \( \frac{d_1}{d_2} = 1/1.5 \), in shock systems with \( 5 \leq L_1 / d_1 \leq 10 \), \( 1 \leq L_1 / L_2 \leq 10 \), the shock pulse energy transfer efficiency decreased by 1-7%. Values of \( n \leq 80 \% \) are achieved in only one shock system with \( L_1 / d_1 = 10 \), \( L_1 / L_2 = 10 \) parameters.

Based on the analysis of the data obtained for further studies, shock systems with equal diameters of the striker and waveguide are used. This is connected, firstly, with a small difference of 8-10% of the shock pulse energy efficiency transmitted to the deformation zone, as compared with \( d_1 / d_2 > 1 \), and secondly, the use of shock systems in which the diameters of the striker and the waveguides are not equal, significantly complicate the design of devices (shock pulse generators), where they are installed, thus increasing their overall metal consumption and mass.

3.2. Study of the influence of the dimensions of the rod shock system cross sections on the efficiency of shock pulse energy transferred to the deformation zone

The simulation results are graphically presented in Figure 5 and 6.

![Figure 5: Diagram of dependence of the fraction of the shock pulse energy transmitted to the deformation zone on the dimensions of the cross sections of the rod shock system.](image)

With the ratio \( L_1 / L_2 = 1 \), the change in the diameter of the striker and the waveguide from 15 to 90 mm: with \( L_1 / d_1 = 1 \) the fraction of the shock pulse energy transmitted to the deformation zone \( n \) (efficiency) increased from 15 to 59%; with \( L_1 / d_1 = 5 \), \( n \) increased from 48 to 91%; with \( L_1 / d_1 = 10 \), the efficiency of the shock system increased from 66 to 91%. With the ratio \( L_1 / d_1 = 10 \), an increase in efficiency of more than 87% was observed for all sections under consideration except for \( \Omega 15 \) mm.

In the case when \( L_1 / L_2 = 3 \), a change in the diameters of the shock system elements from 15 to 90 mm: with \( L_1 / d_1 = 1 \), the proportion of the shock pulse energy transmitted to the deformation zone \( n \) increased from 21 to 59%; with \( L_1 / d_1 = 5 \), \( n \) increased from 39 to 80%; with \( L_1 / d_1 = 10 \) \( n \) increased from 58 to 89%. 

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With the ratio $L_1 / L_2 = 5$, a change in the diameter of the striker and waveguide from 15 to 90 mm was noted, with $L_1 / d_1 = 1$, a fraction of the shock pulse energy transmitted to the deformation zone $n$ increased from 18 to 57%; with $L_1 / d_1 = 5$, $n$ increased from 41 to 83%; with $L_1 / d_1 = 10$, the efficiency of the shock system increased from 56 to 88%.

In the case when $L_1 / L_2 = 10$, a change in the diameters of the shock system elements from 15 to 90 mm, with $L_1 / d_1 = 1$, increased a fraction of the shock pulse energy transmitted to the deformation zone $n$ from 12 to 56%; with $L_1 / d_1 = 5$, $n$ increased from 38 to 87%; with $L_1 / d_1 = 10$, $n$ increased from 61 to 90%.

To determine the boundaries of the growth range $n$, in the case of a further increase in the diameter of the shock system elements to Ø 120, 180, 270 mm, it was decided to conduct four more experiments with one of the more effective ratios $L_1 / d_1 = 10$; $L_1 / L_2 = 1$. As a result, it was found that an increase in the diameter of the striker and waveguide to 120, 180, 270 mm did not significantly change the fraction of the energy transmitted to the deformation zone, which amounted, respectively, to 93; 96; 96%, but the mass of the shock systems was 212, 718 and 2425 kg. Studies have shown that it is inappropriate to use shock systems with a diameter of more than 90 mm, since the level of overall dimensions grows faster than the efficiency of the fraction of the shock pulse energy transmitted to the deformation zone.

To optimize the obtained values, the efficiency of shock pulse energy transferred to the deformation zone (see Figure 5, 6), it is proposed to introduce the following criteria:

1. The range of $n$ is more than 80%.
2. The waveguide diameter is not less than 30 mm. This is the smallest possible size for its future fastening on the waveguide of the tool.
3. The total length of the striker and waveguide must not exceed 1000 mm. As a rule, shock systems of more than 700 mm cause difficulties with their placement in the body of the shock device due to the increase of the center of gravity, the stiffness and weight requirements. All this provides
additional difficulties in the design of shock systems. So, with a diameter range from 15 mm to 90 mm and a total length of the striker and waveguide of 1000 mm, the shock system mass varies from 1.4 to 50 kg.

4. The total mass (m) of the striker and waveguide must not exceed 15 kg. 
Thus, as result of optimization, the following rational layout dimensions of shock systems are presented in Table 1.

Table 1. Relationship of the shock system mass and its effectiveness (n) with the ratio of the geometric parameters of the elements of the shock system of the striker and the waveguide.

| No in Figure 5 and 6 | \( d_1 = d_2 \), mm | \( L_1 / L_2 \) | \( L_1 / d_1 \), mm | \( L_2 \), mm | m, kg | n, % |
|----------------------|-------------------|----------------|-----------------|--------------|------|------|
| 12                   | 30                | 1              | 10              | 300          | 300  | 3.3  | 88   |
| 27                   | 30                | 3              | 10              | 300          | 100  | 2.2  | 87   |
| 8                    | 48                | 1              | 5               | 240          | 240  | 6.8  | 81   |
| 13                   | 48                | 3              | 10              | 480          | 480  | 13.6 | 90   |
| 28                   | 48                | 3              | 10              | 480          | 160  | 9    | 81   |
| 9                    | 60                | 1              | 5               | 300          | 300  | 13.3 | 85   |
| 24                   | 60                | 3              | 3               | 300          | 100  | 8.8  | 81   |

4. Conclusion
1. It was established that the use of shock systems in which the ratio of the diameters of the striker and the waveguide more than \( d_1 / d_2 = 2 \) is impractical, since in comparison with \( d_1 / d_2 = 1.5 \), an increase in the fraction of the transmitted energy in the deformation zone is possible only in the range of 1-2%.

2. It was established that the use of shock systems with a ratio of the diameters of the striker and the waveguide \( d_1 / d_2 < 1 \) is also impractical due to the limited number of the parameters of the shock systems providing more than 80% of the shock pulse energy transfer to the deformation zone and the complexity of the shock pulse generator design.

3. It was established that to conduct studies from the point of view of the efficiency of transferring the energy of the shock pulse to the deformation zone, and from the point of view of the design of the generator of shock pulses, it is advisable on shock systems in which the contacting ends of the striker and the waveguide have equal diameters.

4. It was found that with an increase in the diameter of the striker and waveguide from 15 to 90 mm, the share of the shock pulse energy transmitted to the deformation zone increased by 38%.

5. It was established that for ratios \( 1 \leq L_1 / L_2 \leq 10 ; 5 \leq L_1 / L_2 \leq 10 \), there is an increase in the fraction of the shock pulse energy transmitted to the deformation zone of more than 80% for the striker and waveguide with diameters of 30, 48, 60, 90 mm.

6. It was established that it is impractical to use impact systems with a diameter of more than 90 mm, since in the considered ranges of ratios of sizes of shock systems elements \( 1 \leq L_1 / L_2 \leq 10 ; 1 \leq L_1 / d_1 \leq 10 \) the level of technical complexity is growing faster than the energy efficiency of this system.

7. It was established that according to the accepted criteria for optimizing the shock system parameters (its length is not more than 1000 mm; its mass is not more than 15 kg; the waveguide length is not less than 100 mm; n more than 80%), the following dimensions of the striker and waveguide are considered the most energy-efficient: 1) \( d_1 = d_2 = 30 \) mm \( 1 \leq L_1 / L_2 \leq 3 ; L_1 / d_1 = 10 \); 2) \( d_1 = d_2 = 48 \) mm \( 1 \leq L_1 / L_2 \leq 3 , 5 \leq L_1 / d_1 \leq 10 \); 3) \( d_1 = d_2 = 60 \) mm \( 1 \leq L_1 / L_2 \leq 3, L_1 / d_1 = 5 \).

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