Evaluation of the effect of various types of tools on a weld joint during wave strain hardening

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Abstract. The article studies the problem of increasing the durability of weld joints using surface plastic deformation by the method of wave strain hardening (WSH). Earlier, WSH was not used for these purposes. The prospect of using WSH for increasing the durability of weld joints is associated with the possibility of increasing the microhardness and the formation of compressive residual stresses at a depth of more than 10 mm. To identify the most effective conditions for the use of various types of tools for WSH of weld joints and accelerate the search for rational modes and conditions of WSH, finite element modeling was used. As a result of the research, recommendations related to the use of various types of WSH tools, depending on the thickness of weld joints, changes in hardness and stress state of the near-weld zone after welding, were given.

1. Introduction

Increasing the strength of weld joints is an urgent problem in mechanical engineering. The need for additional impact on the weld joint after it is obtained is associated with a decrease in the strength properties of the heat-affected zone (weld and heat-affected zone) due to the burnout of metal chemical elements, rapid local heating and metal cooling, and as a consequence, the appearance of significant tensile stresses [1, 2].

To increase metal durability in the heat-affected zone and reduce the residual stresses in the base metal and in joints, various technological methods such as heat treatment, aging, surface plastic deformation (SPD), etc. are used.

The use of traditional methods to improve the strength properties of the heat-affected zone - heat treatment and aging, is characterized by significant time and energy costs and has certain limitations associated with the overall dimensions of the processed product.

Among the SPD methods, for the treatment of weld joints and near-weld zones, ultrasonic and vibro-shock treatment, rolling, etc. are used.

A sufficiently effective method for processing weld joints and heat-affected zones is the SPD method is wave strain hardening (WSH). Compared to other SPD methods, wave strain hardening has wider technological capabilities for the formation of a hardened surface layer, allows a high degree (up to 150%) and a large depth of hardening (more than 6 ... 10 mm) [3]. A feature of the method is the generation of deformation waves in a shock system with an intermediate link and their communication.
to the deformation zone, in order to strengthen the critical surfaces of machine parts. The effectiveness of the method is provided due to the almost complete use of the deformation wave energy generated in the shock system for the elastoplastic deformation of the hardened material. Depending on the required parameters of the surface layer hardening, a shock pulse of the required amplitude and duration is formed, the material and geometric parameters of the shock system elements are selected. By controlling the parameters of the deformation wave, it becomes possible to obtain not only a uniformly hardened surface layer, but heterogeneously hardened zones as well. The uniformity of overlapping of plastic prints is estimated through the overlap coefficient $K$. The range of $K$ variation is from 0 to 1: at $K = 0$, the prints do not overlap, the edges of the prints border each other; at $K = 1$, there is a complete overlap of the prints, the strikes are applied to the same place [3].

WSH has a large number of controlled technological parameters, due to the use of various tools it can provide the required effect on the deformation zone. However, at the moment, theoretical and practical experience has been accumulated in the processing of solid materials, the development of the WSH technology of weld joints is at the initial stage, the necessary information is not available. Therefore, studies related to the choice of the type, shape of the tool for WSH of weld joints, parameters that provide the required effect on the deformation zone are relevant.

Carrying out a full-scale experiment is always associated with the difficulties of its implementation, material costs, requirements for the availability of appropriate equipment. Modeling the process using modern engineering analysis tools based on the finite element method significantly speeds up the procedure for obtaining the necessary information.

The purpose of this work is to study the result of the impact of various types of tools in the case of WSH of the weld joint by computer simulation by the finite element method.

2. Experimental technique
The development of a finite element model of the process of strengthening weld joints by the WSH method was carried out in the Ansys program, which is the world leader in the field of engineering analysis [4-7]. The modeling was carried out in four stages.

At the first stage, the geometry of the welded product, weld joint and WSH tool was formed.

At the second stage, a model of the material of the welded product was created. For this, its thermophysical and mechanical properties were set. The data were taken from the reference literature and the results of the corresponding tests of the material used.

At the third stage, the thermal problem of heating the weld was solved. As a result residual stresses in the welded workpiece that arise in the product after welding was obtained.

At the fourth stage, the resulting weld was subjected to WSH with different processing modes with different types of tools. The result of modeling the fourth stage is the determination of the residual stresses and microhardness values obtained in the weld joint after WSH.

To assess the adequacy of the developed finite element model, a preliminary field experiment was carried out. For research, we used plates with dimensions of 600 * 100 * 7 mm, made of 40X steel. With the help of a semi-automatic welding machine, these plates were butt welded and had a final size of 600 * 200 * 7 mm. WSH of weld joints was carried out with an energy of 150 J with a shock frequency of 10 Hz and with modes corresponding to the overlap coefficients $K = 0.3$ and $K = 0.6$. A rod roller with a diameter of 10 mm and a width of 40 mm was used as a tool for strengthening. After processing the WSH joints, the welded plate was cut on a band saw along the joint and the microhardness was measured in the resulting section using a KB30S hardness tester. Comparison of the simulation data and the values obtained as a result of a full-scale experiment, under the same initial conditions, was carried out according to the microhardness map in the weld joint section. The comparison results are shown in Figure 1.
Figure 1. Distribution of microhardness (HV, MPa) over the depth (h, mm) of the weld joint: 1) unreinforced (experimental data); 2) unreinforced (simulation results); 3) hardened with $K = 0.3$ (experimental data); 4) hardened with $K = 0.3$ (simulation results); 5) hardened with $K = 0.6$ (experimental data); 6) hardened with $K = 0.6$ (simulation results).

The obtained theoretical data on the distribution of microhardness in the surface layer with a satisfactory probability (92%) correspond to the experimental values. The results obtained can be considered significant.

To study the effect of various types of tools for WSH on weld joints of plates made of 40X steel, we simulated the problems in which the following were used as tools: 1) rod rollers 40 mm wide and 10, 18 and 27 mm in diameter; 2) balls with diameters of 18 and 27 mm; 3) rods with a spherical end, 12 mm in diameter and 18 mm high. In the case of obtaining deep imprints of tool impacts in the workpiece being processed and the impossibility of further processing because of this, work was carried out to compose combinations of several simultaneously operating tools according to the multi-contact WSH scheme [8, 9].

3. Assessment of the effect of various types of tools on the weld joint during wave strain hardening

As a result of the conducted studies, it was established that the heat-affected zone in the welded workpiece made of 40X steel is the areas located to the left and right of the axis of the weld at a distance of 18 mm. Thus, in order to influence this heat-affected zone, it is necessary to expose a 40 mm wide section to the WSH. Another condition for conducting WSH is the need to perform machining in one pass of the tool. The fulfillment of this condition is necessary to increase the processing productivity, reduce the risk of edge effects and the overlapping of the edges of the hardened tracks (excluding over-hardening) in the case of WSH of a heat-affected zone for several tool passes.

As a result of studies of the welded seam without hardening, it was found that the average hardness along the thickness was 3000 MPa. On the hardened surface, there are residual tensile stresses of 370 MPa, which at a depth of 6.5 mm begin to transform into compressive ones, and at a depth of 9.5 mm, reach a maximum of -210 MPa (Fig. 2, 4, 5).

As a result, WSH with $K = 0.3$ rollers with diameters of 10, 18, 27 mm, in comparison with unreinforced weld joints, the microhardness increased by 46, 32, 31%, respectively, and a depth of hardening of 6.3, 5.3 and 5 mm was obtained (Fig. 2, 3). As a result of WSH with $K = 0.3$, the values of residual stresses on the weld hardening surface changed from tensile +370 MPa to compressive -310 MPa (Fig. 4, 5). The use of rollers of the considered diametrical dimensions did not change the value of the obtained compressive stresses on the hardened joint surface. The transition of compressive stresses to tensile stresses for rollers with diameters of 10 and 27 mm is set at a depth of 7
mm, and for 18 mm rollers - 8.2 mm. The maximum tensile residual stresses $+50..70$ MPa, installed on the side opposite to the hardening, is also the same for all rollers of the considered diametrical dimensions.

Figure 2. The maximum values of microhardness (HV, MPa) obtained on the surface of the weld joint at its WSH with $-K = 0.3$; and with $-K = 0.6$ using: 1) 10 mm roller; 2) 18 mm roller; 3) 27 mm roller; 4) rods with a spherical end of 12 mm; 5) 18 mm balls; 6) 27 mm balls; 7) weld joint without hardening.

Figure 3. The maximum values of the depths of hardening (HV, MPa) of the welded layer at its WSH with $-K = 0.3$; and $-K = 0.6$: using 1) 10 mm roller; 2) 18 mm roller; 3) 27 mm roller; 4) rods with a spherical end of 12 mm; 5) 18 mm balls; 6) 27 mm balls; 7) weld joint without hardening.

Figure 4. Distribution of residual stresses ($\sigma$, MPa) over the thickness of the welded layer (h, mm) at its WSH with $K = 0.3$ using: 1) 10 mm roller; 2) 18 mm roller; 3) 27 mm roller; 4) rods with a spherical end of 12 mm; 5) 18 mm balls; 6) 27 mm balls; 7) weld joint without hardening.
In case of WSH weld joints with $K = 0.6$ rollers with diameters of 10, 18, 27 mm, compared with $K = 0.3$, the microhardness increased by 1.6, 9.5, 2%, respectively, and the depth of hardening for a roller with a diameter of 10 mm remained unchanged, and for other cases it increased by 17 and 12%, respectively. The influence of the considered diametrical dimensions of the rollers with WSH with $K = 0.6$ on the residual stresses is practically indistinguishable and merged into one line on the graph (Fig. 5). On the hardened side, the value of residual compressive stresses was $-250 \ldots -270$ MPa, which is comparable to the values obtained at $K = 0.3$. The transition to tensile stresses is located at a depth of 7.5 mm, and the maximum of their values $+40, 50$ MPa is located on the surface opposite to the one being hardened. These values practically coincided with the values of the residual stresses obtained with WSH with $K = 0.3$ by a roller 18 mm in diameter.

Under the given WSH modes using one tool with a spherical end with a diameter of 12 mm, its deep penetration into the hardened surface is established, which makes it impossible to implement the process. Proceeding from this, to achieve the adopted hardening width of the heat-affected zone equal to 40 mm, tools with a spherical end with a diameter of 12 mm were installed in two rows staggered in a special mandrel, in the amount of 10 pieces. Due to this technical solution, as a result of WSH with specified modes, with $K = 0.3$, it was possible to increase the microhardness by 51% compared to unreinforced welded joints, and to achieve a hardening depth of 2.8 mm (Fig. 2, 3). The values of the residual stresses on the hardened weld surface changed from tensile $+370$ MPa to compressive $-250$ MPa (Fig. 4, 5). The maximum residual stresses of $-300$ MPa were at a depth of 1 ... 1.5 mm. Unlike rod rollers, tools with a spherical end at a depth of 4 and 8.5 mm show two transitions of compressive stresses into tensile stresses. The value of the residual compressive stresses on the surface opposite to the one being hardened was $-40$ MPa. The maximum tensile residual stresses are set at a depth of 6 mm and are $+130$ MPa.

With WSH of weld joints with $K = 0.6$ (compared with $K = 0.3$), using tools with a spherical end with a diameter of 12 mm, the microhardness increased by 1.8% respectively and the hardening depth by 18%. The distribution of residual stresses in case of WSH with $K = 0.6$ in comparison with $K = 0.3$ differs only near the surface to be hardened. With WSH with $K = 0.6$ compared with $K = 0.3$, the residual compressive stresses decreased from $-250$ MPa to $-210$ MPa, and their maximum ($-300$ MPa) shifted from a depth of 1..1.5 mm to a depth of 1.5 ... 2.2 mm.

When using tools for WSH – balls, as in the case of tools with a spherical end, to ensure the required width of hardening of the heat-affected zone of the weld joint, they were installed in a checkerboard pattern in a special mandrel. Balls with diameters of 18 and 27 mm were used in an amount of 10 pieces. So, with WSH with $K = 0.3$ balls with diameters of 18 and 27 mm, in
comparison with unreinforced welded seams, it was possible to increase the microhardness by 49 and 39% and to achieve the hardening depth of 2.7 and 2.1 mm, respectively (Fig. 2, 3).

Thanks to the use of balls with diameters of 18 and 27 mm as WSH tools, it was possible to change the stress state: instead of tensile residual stresses of +300 MPa, compressive stresses of 260 MPa and 220 MPa, respectively, are formed on the hardened surface (Fig. 4, 5). As in the case of the use of tools with a spherical end, the use of balls as tools also led to a double transition of compressive stresses into tensile stresses in the weld section. Such a transition for balls with a diameter of 18 mm occurred at depths of 4.3 and 9 mm, and for balls with a diameter of 27 mm – 3.3 and 8 mm. The value of the residual compressive stresses on the surface opposite to the one to be hardened was -45 and -95 MPa, respectively, for the balls of 18 and 27 mm. The maximum tensile residual stresses of 180 MPa were set for balls of 18 mm and 27 mm at a depth of 6.3 and 5.2 mm, respectively.

With WSH of weld joints with $K = 0.6$ using balls with diameters of 18 and 27 mm, compared with $K = 0.3$, the microhardness increased by 1.1 and 3.7%, respectively, and the hardening depth increased by 28.6% only for balls with a diameter of 27 mm. When passing from $K = 0.3$ to $K = 0.6$, the character of the curve of the distribution of residual stresses along the depth of the weld became the same for the considered standard sizes of balls. On the hardening surface, the residual compressive stresses amounted to 460 MPa. A double transition of compressive stresses into tensile stresses in the section of the welded seam occurred at a depth of 3.9 and 8.7 mm. The value of the residual compressive stresses on the surface opposite to the hardened surface was 45 and 55 MPa, respectively, for balls of 18 and 27 mm. The maximum tensile residual stresses of + 140 MPa were found for balls of 18 mm and 27 mm at a depth of 6.4 mm.

4. Conclusion
1) The prospects of using WSH for increasing hardness, hardening depth and ensuring the transition of tensile stresses to compressive ones in weld joints and the heat-affected zone have been confirmed.
2) It was found that if it is necessary to increase the hardness to 50% of the heat-affected zone of weld joints with a thickness of up to 5 mm, it is necessary to use balls with a diameter of 18 mm as a tool and carry out WSH according to a multi-contact scheme with $K = 0.6$.
3) It has been established that to increase the strength of weld joints up to 10 mm thick without a significant decrease in hardness (up to 20%) after welding, it is promising to use rod rollers with a diameter of 10 mm and to carry out WSH with $K = 0.3$-0.6.
4) It has been established that if the priority is not increasing the hardness, but obtaining residual compressive stresses in the surface layer of the weld with a thickness of up to 10 mm, it is necessary to use a roller with a diameter of 18-27 mm and WSH with $K = 0.3$.

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