Assessment of the mechanical properties of welded joints after wave strain hardening

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Abstract. The purpose of this work is to establish the relationship between the modes of wave strain hardening (WSH) and changes in the ultimate strength, microhardness, impact strength of welded joints. The need for these studies is associated with the prevention of destruction of welded joints with the help of their subsequent WSH. The uniqueness of the WSH method lies in the wave loading of the processed material by shock pulses with a given duty cycle, energy and duration. This makes it possible to increase microhardness and form compressive residual stresses at a depth of more than 10 mm, which makes the use of the method promising for increasing the strength of welded seams. These studies have not previously been conducted. Materials 10ХСНД, 30ХГСА and 40Х were taken as objects of research, from which important welded products are often made in industry. As a result of the research, based on the conditions for increasing the strength of welded joints of the selected materials, rational modes of strengthening and the direction of processing have been determined.

1. Introduction

Welding is one of the most common technological processes for assembling products of varying complexity, such as body elements, pipelines, pressure vessels, etc. In this case, the share of destruction of welded structures is approximately 30% of the total number of reasons for their failures [1]. Prevention of destruction of welded joints is an urgent task for modern mechanical engineering. The requirements for the strength of the weld are such that it should not be lower than that of the base metal. To increase metal strength in the heat-affected zone and reduce the residual stresses both in the base metal and in welds, various technological methods such as heat treatment, aging, surface plastic deformation (SPD), etc. are used [2-7].

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 welded joints and near-weld zones, ultrasonic and vibro-shock treatment, rolling, etc. are used [13-20].

A fairly effective method for processing welded joints and near-weld zones, in order to increase their strength properties, is the SPD method - wave strain hardening (WSH). This method, due to a number of additional design and technological parameters, makes it possible to act on the surface to be hardened with controlled shock pulses and to form in it the required hardness distribution at a depth of 15 mm and create compressive residual stresses [8-12]. However, studies on the use of WSH, to
increase the strength properties, were carried out only in fragments, using welded samples made from 09Г2C steel.

The purpose of this work is to study the influence of WSH modes on the mechanical properties of welded products.

2. Research methodology

As a material for research, we used steel widely used in industry for the manufacture of welded products, such as: 10ХСНД, 30ХГСА and 40X. Workpieces with dimensions of 600 * 100 * 7 mm were made from each material and then welded into a plate of 600 * 200 * 7 mm. Welding was carried out in a semi-automatic mode.

To prepare for WSH, the leg of the welded seams was cut off to the height of the protrusion above the plane of the plate of 0.1 mm. Strengthening by a deformation wave was carried out with an energy of 150 J with a shock frequency of 10 Hz and with modes corresponding to a change in the overlap coefficient K: 0; 0.3 and 0.6. The overlap coefficient K is a value that makes it possible to evaluate the uniformity of overlapping of the plastic imprints of the tool impacts during WSH. The range of change for K 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 prints [8-12]. A rod roller with a diameter of 10 mm and a width of 40 mm was used as a tool for strengthening.

In order to identify the most effective direction of hardening, WSH of the welded seams was carried out both in the longitudinal and transverse directions relative to the axis of the welded joint (figure 1).

![Figure 1. Welded joints: 1) samples with welded joints; 2) area of the welded joint; 3) axis of the welded joint; 4) direction of longitudinal strengthening of the welded joint; 5) the direction of the transverse hardening of the welded joint.](image)

After WSH, samples for research were cut out of the welded plates on a band saw:
1) microhardness maps in the welded product;
2) strength properties of welded joints by static tensile strength test;
3) impact strength.

To study the microhardness map after different modes of WSH, hardened samples were cut along the weld axis. Microhardness studies were carried out using a KB 30S hardness tester. Static tensile resistance tests were carried out on a WDW-100E universal electromechanical computer-controlled machine. The determination of the values of the impact strength of the material was carried out on an impact driver.

3. Investigation of the influence of WSH modes on the mechanical properties of welded joints

The values of microhardness, strength, impact toughness obtained as a result of research at various modes of WSH are shown in figure 2-4.
Figure 2. Change in ultimate strength, microhardness and impact toughness of welded seams made of 40X steel as a result of WSH: 1) unselected seam; 2) K=0 transverse hardening of the seam; 3) K=0.3 transverse hardening of the seam; 4) K=0.3 longitudinal hardening of the seam 5) K=0.6 transverse hardening of the seam; 6) K=0.6 longitudinal strengthening of the seam; 7) initial material.

Thus, with WSH of the welded seams of the 40X steel plate, based on the analysis of the obtained tensile diagram (figure 2), it was possible to establish that, in general, strengthening led to a significant increase in the yield strength and the tensile strength. With transverse hardening with K = 0.3, it was possible to increase the ultimate strength by 3% while maintaining the plasticity at the level of that of the unhardened welded joint material. An increase in the yield point and ultimate strength, without a significant decrease in the plasticity of the material, has a positive effect on the performance properties of the part, including the fatigue resistance.

WSH of plates made of steel 40X led to strengthening of the weld along its entire thickness. Thus, the transverse strengthening of the welded seam with K = 0.3 and K = 0.6 led to an increase in microhardness, on average over the entire thickness of the welded seam and the heat-affected zone, by 21 and 16.5%, respectively. Longitudinal hardening of the weld area led to an increase in microhardness only by 13 and 9.5%, respectively, at K = 0.3 and K = 0.6.

The impact toughness of the welded joint formed in 40X steel decreased by 5.8%. WSH with K = 0 practically does not change the impact toughness of unreinforced weld material. WSH with K = 0.3 is accompanied by a decrease in impact toughness upon strengthening in the transverse direction by 21%, and upon strengthening in the longitudinal direction - by 24%. WSH with K = 0.6 is accompanied by a decrease in impact toughness with strengthening in the transverse direction by 33.7%, and with strengthening in the longitudinal direction - by 39.5%.
Figure 3. Changes in microhardness, ultimate strength and impact toughness of welded joints made from 30 ХГСА steel as a result of WSH: 1) unselected seam; 2) K=0 transverse hardening of the seam; 3) K=0.3 transverse hardening of the seam; 4) K=0.3 longitudinal hardening of the seam; 5) K=0.6 transverse hardening of the seam; 6) K=0.6 longitudinal strengthening of the seam; 7) initial material.

When welding plates made of 30 ХГСА steel, an increase in the microhardness of the welded seam by 50% compared to the parent metal was established (Fig. 3), which introduces serious restrictions on the possibility of a welded product hardening using WSH.

Thus, the WSH of a welded seam with K = 0 led to an increase in its microhardness by only 7% in comparison with an unreinforced seam. When hardening with K = 0.3 in the transverse direction, the microhardness increased by 7.1%, and in the longitudinal direction by 4%. Hardening with K = 0.6 in the transverse direction led to an increase in microhardness by 8.1%, and in the longitudinal direction by 6.9%.

As a result of the analysis of the static tension diagram, it was found that the ultimate strength of the welded joint material is 5.7% higher than that of the initial material. WSH of the weld with K = 0 led to an increase in the ultimate strength by 5.1%, with a decrease in the ductility of the material by 38.1%, compared with an unreinforced weld. WSH with K = 0.3 in the transverse direction is accompanied by an increase in the ultimate strength by 7% in comparison with unreinforced material, and hardening in the longitudinal direction is accompanied by an increase in the ultimate strength by only 2.4%. At the same time, plasticity decreases by 22.7 and 38.1%, respectively. WSH with K = 0.6 in the transverse direction is accompanied by an increase in the ultimate strength by 6.6%, and in hardening in the longitudinal direction - by an increase in the ultimate strength by 3% The value of plasticity decreased by 38.1 and 54.5%, respectively.

Due to the formation of a welded seam in 30 ХГСА steel impact strength decreased by 14.4%. Hardening with K = 0 practically did not change the impact strength in comparison with an unreinforced weld. WSH with K = 0.3 is accompanied by a decrease in impact strength upon strengthening in the transverse direction by 19.2%, and upon strengthening in the longitudinal...
direction - by 21.6%. Treatment with $K = 0.6$ leads to a decrease in impact strength during hardening in the transverse and longitudinal directions by 27.7%.

The microhardness of the material of the welded joints of plates made of 10 ХСНД steel is by 13% higher in comparison with the initial material. WSH with $K = 0$ leads to an increase in the microhardness of the weld by 4.2%. Strengthening in the transverse direction with $K = 0.3$ is accompanied by an increase in microhardness on average over the thickness of the weld and the heat-affected zone by 5.4%. WSH in the longitudinal direction with $K = 0.3$ provides an increase in the microhardness of the material by 4.2%. WSH in the transverse direction with $K = 0.6$ provides an increase in microhardness by 14.5%, and in the longitudinal direction - by 2.7%.

As a result of testing the samples under static tension, it was found that when compared with the original material, the presence of a weld did not affect the value of the ultimate strength, but the ductility decreased by 19%. Strengthening with $K = 0$ did not change the ultimate strength, and the ductility decreased by 12.5%. With WSH with $K = 0.3$ in the transverse direction, an increase by 15.3% in the ultimate strength was established, and in the longitudinal direction - by 5.8%. Compared with an unreinforced weld, the plasticity in the transverse and longitudinal directions decreased by 64.8 and 43%, respectively due to WSH. Strengthening with $K = 0.6$ in the transverse direction made it possible to increase the ultimate strength by 20%, and in the longitudinal direction by 9%. At the same time, the plasticity decreased by 58.5 and 49%, respectively.
Impact strength, due to the formation of a weld in 10 ХСНД steel, decreased by 22.6%. Hardening with K = 0 had little effect on the change in impact strength; in comparison with an unreinforced weld, it decreased by 4.5%. WSH with K = 0.3 reduces the impact strength during hardening in the transverse and longitudinal directions by 3.3%. WSH with K = 0.6 leads to a decrease in impact strength during hardening in the transverse direction by 16.8%, and in the longitudinal direction by 20.2%.

4. Conclusion
1. A significant influence of the direction of WSH processing of the welded joint on its microhardness, strength and impact strength has been established. The best complex of the above listed properties is provided by WSH with transverse hardening of welded joints, which is associated with the peculiarities of the implementation of the WSH process and the geometric parameters of the weld.
2. It has been established that with the WSH of welded seams of plates made of 40X steel, the rational mode is transverse strengthening of welded seams with an overlap coefficient K = 0.3, which ensures 21% increase in microhardness over the entire section of the welded seam, and preserves its plasticity at the level of unreinforced welded joint material.
3. It has been established that the rational modes for strengthening welds made of 30 ХГСА steel are those that provide hardening in the transverse direction with K = 0.3 and K = 0.6. This makes it possible to increase microhardness by 7-8% and the ultimate strength by 6.6-7%. It should be taken into account that hardening with K = 0.6 in comparison with K = 0.3 is accompanied by a more significant decrease in plasticity - by 40%.
4. It has been established that WSH of welded joints made of 10 ХСНД steel can significantly increase their ultimate strength. So, in the case of the longitudinal direction of hardening with K = 0.3 and K = 0.6, the ultimate strength increases by 15-20%, which is accompanied by a 58-64% decrease in plasticity. The optimal mode of WSH of welded joints on products made of 10 ХСНД steel is hardening in the transverse direction with K = 0.3, which provides an increase of 5.8% in ultimate strength, 5.4% of microhardness with a decrease in plasticity by 43%.

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