Ultrasonic welding of metals: instruments, process parameters, and prospects of welding of ultrafine grained materials

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Abstract. The results of studies on the development of instruments for ultrasonic welding (USW) of metals, which is the basic process for ultrasonic additive manufacturing, are presented. The influence of process parameters (static loading and welding time) on the microstructure and strength of joints produced by USW of commercially pure copper, nickel and titanium is studied. Preliminary results of the first studies on the USW of metals in an ultrafine grained (UFG) state are presented and the prospects of using UFG metals in the ultrasonic additive manufacturing are evaluated.

1. Introduction

Ultrasonic welding (USW) is a relatively new method of the solid state joining of metals and now is widely used in electrical engineering, electronics, automobile industry etc. for joining foils, plates and wires [1-5]. The interest to USW has increased in the recent years due to an invention of ultrasonic consolidation as one of the methods of additive manufacturing [6-8]. The ultrasonic additive manufacturing is based on successive welding of metallic foils to produce bulk articles. For research needs, this process can also be modeled by means of successive welding of metal sheets using a spot ultrasonic welder. This paper reports the results on the development of instruments for this goal and studies of the structure and properties of joints of three metals, copper, nickel, and titanium, processed by USW with an emphasis on the welding of metals having an ultrafine grained (UFG) microstructure. Finally, the prospects of using metals with UFG structures in ultrasonic additive manufacturing are outlined.

2. Instruments for ultrasonic welding

Ultrasonic horn is a key part of ultrasonic welding equipment, which imparts the ultrasonic energy into the samples of metals under welding. This part must satisfy two main requirements: achieving a sufficient amplitude of vibrations of the welding tip during the welding process, when a significant static load is applied, and the possibility of applying the static load with the least increase of the acoustic resistance. In order to satisfy the former, the horn is made as a kind of ultrasonic concentrator, while the latter condition is satisfied, if the static load is applied at a node. The common way of designing the horns is an analytic calculation (if possible) followed by finite element simulations [9,10].
We have considered three types of horns: 1) a half-wave horn, which has a conical input part and a cylindrical output part which is cut from two sides by vertical surfaces having radial transitions (figure 1 a); 2) a half-wave stepped horn with a radial transition (figure 1 b) and 3) one-wave horn with two radially smoothed steps (figure 1 c). All horns have flattened surfaces for applying a static force and/or for spanners. As shown by Merkulov [11], a composite horn consisting of a conical input part and cylindrical output part and a stepped horn with an exponential transition section have the highest values of the amplification coefficient. Additional cuts by two vertical surfaces further increases this coefficient for the first type horn. The presence of two stepped transitions provides the third horn also a high amplification coefficient. Khemelev et al. [9] have shown that exponential transition for stepped concentrator can be replaced by a radial one and obtained the correction factors for the lengths of the parts of horns in this case.

![Figure 1](image)

**Figure 1.** Schemes for design of horns for ultrasonic spot welding: (a) half-wave composite horn consisting of conical input and cylindrical output cut by radial surfaces (type 1); (b) half-wave stepped horn with radial transition (type 2); (c) one-wave stepped with radial transitions (type 3).

The analytic calculations do not allow for a sufficiently accurate prediction of the geometrical parameters of horns, since they are valid for the case of lateral dimensions of horns much less than the longitudinal ones. Also, only numerical calculations of real welding horns having weld tips, flattened surfaces for spanners or static load application, is possible.

Starting from the analytically predicted starting configurations obtained for concentrators without weld tips and flattened surfaces, finite element calculations were done for each type horn. The simulations were carried out for Steel 45, which is widely used for making ultrasonic waveguides. The steel bar to fabricate horns had the following properties: density $\rho = 7826 \text{ kg/m}^3$, Young’s modulus $E = 204.25 \text{ GPa}$ and Poisson’s ratio $\nu = 0.33$. The calculations were done for the target resonance frequency $f$ in the range of 20.0 – 20.1 kHz. The modal analysis of the horn models was performed using ANSYS Workbench Mechanical 19.1.

For the type 1 horn we have considered a horn with the following geometric parameters: $r_1 = 31.25 \text{ mm}$, $r_2 = 15 \text{ mm}$, $l_1 = 82 \text{ mm}$, $l_2 = 52.5 \text{ mm}$ and different positions of the beginning of radial cuts on the output part of the horn, $b$. The modal analysis has shown that this type of horn has two neighbor eigenfrequencies, one of which corresponds to torsional vibrations around the waveguide axis and the other to longitudinal oscillations. Figures 2 a,b present the dependences of these frequencies, $f$, and the
amplification coefficient for longitudinal oscillations, $M$, of the horns on the values of $b$. As one can see from the figures, the amplification of the waveguide is very high at small values of $b$ and it decreases with $b$. However, the use of a horn with an elongated narrow output part would result in a worse transmission of vibrations to the welding tip under static load, and it is better to choose a larger value of $b$ at a reasonable amplification. Also, close frequencies of the two vibration modes should be avoided, otherwise torsional vibrations can be excited along with the longitudinal ones leading to lowering of the resulting amplitude. The choice of $b = 106$ mm can be considered reasonable. Figure 3 represents the displacement map of the horn for this case. One can see that the node of displacements is nicely located on the flattened surface that facilitates applying a static load during USW.

The horn fabricated according to this design, had slightly different sizes (input end diameter 62.5 mm instead of 65 mm, $b = 104$ mm) and the resonance frequency of 20.20 kHz. Recalculation with these parameters yield the frequency 20.22 kHz, i.e. a value very close to the experimental one.

For the case of type 2 horn, it is important to place the displacement node near the end of the input part, prior to the radial transition. Recently, Khmlev et al. [12] have considered a stepped concentrator with a mounting flange located at the end of the input part and obtained corrected formulae for the lengths of the parts of the concentrator. In the present case, we looked for a configuration, in which the node is located in the middle of flattened surfaces for spanners and the amplification coefficient is reasonably high. The displacement field for the fitted geometrical parameters, $l_1 = 73.5$ mm, $l_2 = 29$ mm, $l_3 = 37$ mm for $r_1 = 31.25$ mm and $r_2 = 14$ mm is presented in

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**Figure 2.** Dependencies of the characteristics of horns of Type 1 on the positions of radial cuts of cylindric parts, $b$: (a) frequency of longitudinal (1) and neighbor torsional (2) oscillations; (b) amplification ratio for longitudinal vibrations.

**Figure 3.** Displacement map of type 1 ultrasonic welding horn with geometrical parameters adjusted for the target frequency.
figure 4. One can see that the resonance frequency is in the target interval and the node is located at a place well suited for applying a static load.

Figure 4. Displacement map of type 2 ultrasonic welding horn with geometrical parameters adjusted for the target frequency.

Figure 5 presents the displacement field map for the type 3 horn designed with the geometric parameters $r_1 = d_1/2 = 31.25 \text{ mm}$, $r_2 = d_2/2 = 25 \text{ mm}$, $l_1 = l_3 = 64 \text{ mm}$, $l_2 = l_4 = 62 \text{ mm}$. Again, one can see that the displacement node is located at the flattened surfaces near the end of the second large-diameter cylinder where the static load can be applied. Despite the smaller ratio between the diameters of the input and output parts, this horn provides the highest amplification coefficient of $M \approx 4.6$.

Figure 5. Displacement map of type 3 ultrasonic welding horn with geometrical parameters adjusted for the target frequency.

3. Ultrasonic welding of coarse-grained and ultrafine-grained metals

Samples of metals (commercially pure copper, nickel, and titanium) with the thickness of 0.5 and 0.7 mm were ultrasonically welded using different regimes of welding given by the values of static load and welding time at the amplitude of vibrations of the welding tip of about 20 $\mu$m. Two types of joint samples were obtained. By welding of two overlapped sheets, samples for lap shear tests were prepared. By successive welding of sheets, which imitated the process of ultrasonic additive manufacturing, consolidated samples were obtained for a structural characterization. Putting thermal couples between the sheets under welding, the temperature rise during welding was evaluated.
As coarse-grained materials, strips cut from as-received commercial sheets of Cu, Ni and Ti with thickness of 0.5 mm were used. To study the role of UFG structure, samples of UFG copper and nickel were processed by high-pressure torsion (HPT). For this, disks of copper and nickel with diameter of 12 mm and thickness of 10 mm were placed between Bridgman anvils with hollows and subjected to torsion straining up to 5 revolutions under the pressure of 6 GPa [13]. As a result of this treatment, disk samples with diameters 12 mm and thickness of 0.7 mm were obtained. This allows one to obtain UFG structures with grain sizes less than 0.5 μm in copper and nickel [14].

Studies have shown that during the USW process a significant increase of the temperature occurs. The maximum temperature increases with static load $P$ and welding time $t$ and can amount from 450°C in copper during welding for 1 s in copper up to more than 700°C during welding for 2 s in titanium.

With an increase of $P$ and $t$ the lap shear strength of USW-processed joints increases. Studies of the microstructure of the joints shows that this is caused by an enhancement of the quality of joints, i.e. the decrease of the density of pores remained in joint interfaces. At the same time, there are optimum values of the static load and above these values the strength of joints decreases due to a significant deformation of the sheets and a change in the failure mode from the interface one to the weld nugget pullout (figure 6).

![Figure 6. Samples of titanium weld joints processed by USW for 1 s under the static load of 6 (a) and 7 (b) kN after lap shear tests. The left figure indicates the interface failure and the right weld nugget pullout mode of failure.](image)

With an increase of the initial hardness and strength of a material the requirements to the welding parameters providing satisfactory joint quality become more severe: the optimum static load increases and the welding time decreases. This is due to the fact that a higher temperature is required for hard materials to decrease their yield stress and undergo local plastic deformation in the welding zone. For welding of titanium, welding time of 2 s and more was necessary under the load of 5 to 7 kN for the welding tip area of about 30 mm², whereas copper and nicked were well welded at lower loads and in time of 1 s.

The most important preliminary result, which was obtained in the studies is that copper and nickel are ultrasonically welded better in the UFG state than in the coarse-grained one. The joints of UFG copper obtained by USW at static load of 3.5 kN had the same strength of about 33 MPa as the joint obtained by welding of commercial copper sheets under the load of 5 kN. The lap shear strength of the joints processed by USW under the load of 6 kN amounted nearly 100 MPa for UFG nickel versus 70 MPa for commercial nickel.

On the other hand, measurements of the microhardness distribution in the cross section of consolidated samples of nickel show that the minimum microhardness is approximately higher in the material consolidated from UFG samples than in the one processed from commercial sheets. This
occurs despite the fact that for the regimes used a significant grain growth occurred in the interface regions during welding of UFG materials (figure 7). Nevertheless, the grain size after consolidation is still in the range of a few micrometers that allows the material to retain its high strength and hardness.

![Microstructure of the cross section of a joint of initially ultrafine-grained sheets of copper processed by USW. One can see a significant grain growth near the welding interface.](image)

Figure 7. Microstructure of the cross section of a joint of initially ultrafine-grained sheets of copper processed by USW. One can see a significant grain growth near the welding interface.

Thus, the preliminary studies demonstrate that by successive welding, i.e. consolidation of sheets or foils with an UFG structure it is potentially possible to obtain bulk materials, which can have higher strength characteristics than the ones obtained by a consolidation from conventional commercial sheets or foils. In order to make better use of this potential, it is important to look further for regimes of USW, which would provide good joint quality at a less significant grain growth.

A considerable grain growth occurs even in the commercial sheets of titanium, although their initial grain size was out of the ultrafine range. The fact that intensive grain growth occurs in UFG copper and nickel and commercial titanium during the very short time intervals during USW is unusual and calls for more careful studies. Most probably, this is due to an effect of not only the enhanced temperature, but also of an intensive cyclic deformation during the process of ultrasonic welding.

4. Conclusions
Modal analysis of three types of horns for ultrasonic welding had been performed using finite-element method based ANSYS software. The results show that in same cases (type 1 horn, for example), torsion vibrations modes with very close frequencies can be excited along with the desired longitudinal vibrations and such modes should be avoided in designing the horns.

Experiments have been carried out on USW of the sheets of commercially pure copper, nickel, and titanium. Copper and nickel with an ultrafine grained microstructure were welded ultrasonically for the first time. These preliminary results demonstrate that, despite a significant grain growth in UFG metals due to the effect of high temperature and intensive oscillatory straining, ultrasonically consolidated samples retain a higher microhardness that the samples consolidated from coarse grained metals. This leads to an important conclusion that ultrasonic additive manufacturing based on USW can have a potential in processing bulk articles with higher strength when using materials with an UFG structure.

Acknowledgments
The present work was supported by the Russian Science Foundation (grant No. 16-19-10126). Electron microscopic studies and mechanical tests were carried out on the facilities of shared services center of IMSP RAS "Structural and Physical-Mechanical Studies of Materials".
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