Ultrasonic welding of ultrafine grained nickel

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Abstract. Solid state joints were obtained for the first time by ultrasonic welding (USW) of ultrafine-grained (UFG) thin disks of Ni processed by high pressure torsion (HPT). Samples of two types were studied: the ones for lap shear mechanical tests were prepared by joining two disks superimposed on each other under static loads of 4.5 and 6.0 kN, and the other type samples for structural characterization were obtained by sequential welding (consolidation) of four disks. The welding time for both type samples was equal to 1 s. The structure of consolidated samples was studied in their cross section by SEM, EBSD analysis, and also their Vickers microhardness was measured.

1. Introduction
Ultrasonic welding (USW) is a relatively new method of joining metallic materials and now is widely used to weld foils, sheets and wires [1-5]. USW is based on the use of the energy of mechanical vibrations generated in materials to be welded by a welding tool of an oscillatory system that performs reciprocating movements with an ultrasonic frequency (19-25 Hz). These vibrations cause the friction of surfaces to be welded, destruction of oxide layers, the plastic deformation and heating of materials in the welding area followed by their seizure. The welding temperature is lower than the melting temperature of the metals, therefore, USW is a method of solid-state joining.

Many studies in the literature have been devoted to elucidate the influence of parameters of the USW process, such as clamping force, vibration amplitude, welding time and welding power, on the quality of joints and lap shear and tensile strengths of welded samples [1-5].

Recently, it has been demonstrated that USW is a promising technology underlying one of the methods of additive manufacturing, ultrasonic consolidation, thus its development is of a considerable interest [6, 7]. The goal of ultrasonic additive technology, like any other metal forming technology, is to obtain parts and structures with high strength characteristics, which depend on both the process parameters and the characteristics of the starting material. From this point of view, it is of great interest to use ultrafine grained (UFG) sheets as a starting material for consolidation, since materials with the UFG structure have increased strength, hardness, and fatigue properties and can have better weldability than coarse-grained (CG) materials.

To date, the literature contains mainly data on the USW of aluminum alloys, copper, copper with aluminum, titanium with aluminum etc. [4,5,8-10]. To the authors’ knowledge, there have been practically no works on welding of nickel except for one paper [11]. There is also no data on the welding of metals in the UFG state.

Thus, the main goal of this study is to elucidate the role of the UFG state of nickel in the evolution of
of its microstructure during USW and to determine the strength of the joints of UFG sheets of nickel obtained by USW.

2. Materials and experimental procedure
Commercially pure nickel with the following composition: Ni ≥ 99.3, Co ≤ 0.2, Si ≤ 0.15, Fe, Mg, Cu, C ≤ 0.10, Mn ≤ 0.05, Zn ≤ 0.007, S ≤ 0.005, Pb, Ph, Bi, As, Sb, Cd, Sn ≤ 0.002 wt% (grade NP2 according to the Russian classification), was used as a material for the study.

Samples in the form of disks with a thickness of 1.2 mm and a diameter of 12 mm were subjected to high pressure torsion (HPT) under the pressure of 6 GPa on Bridgman anvils at room temperature up to the number of evolutions equal to five. As a result, discs with a thickness of 0.75 mm were obtained. The disks processed by HPT were ultrasonically welded in two ways as follows. Specimens for lap shear tests were obtained by spot welding of two disks superimposed on each other. Ultrasonic consolidation was carried out by sequential welding of four specimens, the lower specimen being welded to a substrate of the same material with the thickness of about 1 mm. The welding sonotrode tip had the shape of a rectangle with sizes 4.5 mm × 6 mm and a serrated surface comprised of seven parallel teeth perpendicular to the axis of the oscillatory system. The amplitude of vibrations of the sonotrode tip was equal to 20 µm, and the static load during USW 4.5 and 6 kN.

To determine the strength of welds made by ultrasonic welding, lap shear tests were carried out. The weld spots on the samples for these tests were located near the middle of their radius, since the microstructure formed during HPT is normally nonhomogeneous and the UFG structure is less developed at the centers of disks [12]. Locating the weld spot near the middle of their radius ensures a reasonable uniformity of the UFG structure. The lap shear tests were carried out at room temperature, with a deformation rate of 0.5 mm/min on an Instron 8862 universal testing machine. The ends of the welded sheets were fixed in grips of the machine maintaining the vertical axis of the entire system. At least three specimens were tested and the average value of lap shear strength was calculated for each type of welding conditions.

The structure of weld interfaces and bulk regions of the layers was characterized by scanning electron microscopy (SEM) on a TESCAN VEGA 3 microscope. The EBSD analysis was performed by a TESCAN MIRA 3 LMH FEG scanning electron microscope equipped with a CHANNEL 5 EBSD analyzer. The scanning was carried out with steps of 100 nm from square grids with side sizes of 2 mm. The specimens for EBSD analysis were prepared by mechanical polishing with a subsequent electromechanical polishing. The obtained EBSD maps were subjected to a clean-up procedure involving a grain tolerance angle of 5° and a minimum grain size of 3 pixels.

The Vickers microhardness of the samples was measured by an AFFRI DM8A testing instrument with a load on the indenter of 10 g and an exposure time of 10 s.

3. Experimental results
The initial structure of UFG nickel processed by HPT in a cross section of the disk sample near the middle of its radius studied by EBSD is shown in figure 1. From the inverse pole figure (IPF) map one can see that in the cross section the grains have an elongated shape, which corresponds to the scheme of deformation of the samples during HPT. The average grain size is about 200 nm along the short axis and 1.5 µm along the long one. An analysis of the misorientation distribution has shown that most of the grain boundaries have high-angle misorientations.

The values of lap shear strength obtained from mechanical tests are presented in table 1. From these data, one can see that for both conditions of welding, the joints of UFG nickel have similar values of strength. A fairly large scatter of the strength values was observed for the load of 6 kN and the failure modes of the samples of this type were different: sample No. 3 failed in the weld nugget pullout mode, while the others in the interface mode like all samples welded under the load of 4.5 kN.

The structural studies have shown that fairly good solid state joints are formed by the USW in both regimes. Only some weld interfaces can be seen at low magnification, most joints are clearly seen only at high magnifications. Typical microstructures of the weld joints formed by USW in the two regimes
are presented in figure 2. Figure 2a shows the structure of a joint in the sample processed by USW at a static load of 4.5 kN and the region where EBSD mapping has been done, and figure 2b presents the corresponding map. From this map, one can see that the microstructures of the upper and lower layers are different. In the lower layer, due to the action of deformation at increased temperature during ultrasonic welding, a significant grain growth occurred, while there is a thin layer of UFG structure directly in the joint region. The grain size in the upper layer also increases in comparison to the initial UFG state. To clarify the dependence of the grain size on the layer number, additional studies are required using the EBSD analysis method.

![Figure 1](image-url)

**Figure 1.** The initial structure of UFG nickel processed by HPT in the cross section of disk samples studied by EBSD analysis.

**Table 1.** Values of the lap shear strength of samples made by USW of UFG nickel under static loads of 4.5 and 6 kN

| Sample number | P=4.5 kN | P=6 kN |
|---------------|----------|--------|
| 1             | 98.1     | 81.2   |
| 2             | 91.6     | 98.3   |
| 3             | 89.5     | 111.1  |
| Mean          | 93.1     | 96.9   |

The microstructure of a joint of the sample consolidated under the static load of 6 kN is shown in figure 2d, and the location of the area where EBSD mapping has been carried out is shown in figure 2c. It can be seen that in this case the grain size in the layers also increased up to about 4-5 μm, and the grains have an almost equiaxed shape. In the interface area an UFG layer was preserved too.

Presented in table 2 are the results of measurements of the microhardness in specimens consolidated under the loads of 4.5 and 6 kN. Measurements were carried out in the cross-section near the center of weld spot. “Bulk” values correspond to the middles of layers and the interface microhardness to the regions of joints between two layers. The layers are numbered from the bottom to the top. For each bulk and interface region, the results were averaged over measurements at five points. As one can see from the table, both the bulks of the layers and the joint regions are characterized by high values of microhardness (more than 3000 MPa), and in the interface regions the microhardness is noticeably higher. This fact is consistent with the microstructural studies reported above. The values of microhardness in the bulks of layers correspond to the one of nickel polycrystal having the grain size about 1 μm, and in the weld regions the values are slightly lower than the ones.
corresponding to the UFG structure with the grain size of 200-300 nm. Evidently, the latter fact is due to the presence of micropores in the joints.

![Image](a)

![Image](b)

![Image](c)

![Image](d)

**Figure 2.** Microstructure of welded joint of UFG nickel at loads of 4.5 and 6.0 kN (b, d). Photos with overlaid EBSD map of the areas from which the survey was made (a, c)

**Table 2.** Microhardness values (in megapaskals) in the bulk and interface zones of layers in the samples consolidated by USW under the static loads of 4.5 and 6 kN

| Layer number | P = 4.5 kN | 1       | 2       | 3       | 4       |
|--------------|------------|---------|---------|---------|---------|
|              | Bulk zone  | 3052±32 | 3046±24 | 3060±20 | 3050±21 |
|              | Interface zone | 3156±15 | 3140±14 | 3148±18 |         |
| P = 6.0 kN   | Bulk zone  | 3132±30 | 3146±15 | 3160±20 | 3150±18 |
|              | Interface zone | 3266±10 | 3290±10 | 3302±12 |         |

**Conclusions**
In this study, we succeeded to obtain for the first time fairly good solid state joints of nickel sheets with an UFG structure processed by severe plastic deformation using ultrasonic welding. The lap shear strength of the samples obtained ranged from about 90 to about 110 MPa. The scatter of the results of mechanical tests was less significant for the case of static load 4.5 kN and more pronounced for the load of 6.0 kN, and in the latter case one of the specimens failed in the nugget pullout mode. Study of the microstructure of the consolidated samples has shown that during welding process a significant, up
to the sizes of 4-5 μm, grain growth in the bulk of the sheets occur and the UFG structure is preserved at interfaces. It has been shown that, nevertheless, the consolidated samples have a fairly high microhardness, which amounted about 3000 MPa in the bulk of layers and 200 MPa higher at interfaces. This demonstrates that the use of UFG samples for consolidation can have a potential in obtaining stronger bulk materials by means of ultrasonic additive manufacturing.

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