Structure of materials ultrasonically consolidated from coarse-grained and nanostructured plates of commercially pure copper

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Abstract. Ultrasonic consolidation of commercially pure copper plates with coarse-grained and ultrafine grained structures was carried out. Copper plates in both states were joined by ultrasonic welding using the same route. Consolidated samples were studied in a cross section parallel to the oscillation direction. The compressive strain value and the joint quality in relation to the initial structure of the material were studied. It is shown that the ultrasonic consolidation is a promising method of additive manufacturing using bulk nanostructured materials.

1. Introduction

Ultrasonic welding (USW) is a technique of solid state joining based on applying ultrasonic vibrations to sheet materials under a static compressive load. It is successfully used in the technology for joining different materials including metals [1]. Generally, ultrasonic welding has been used for welding of samples such as thin wires and foils. However, due to the availability of high-power USW equipment, this technique is currently becoming promising for additive manufacturing technologies, especially for ultrasonic consolidation of large metal plates and foils into parts [1-3]. The quality of ultrasonically consolidated materials strongly depends on the conditions of USW. Thus, it is necessary to establish regularities of the formation of joints during USW, including the welding of layered structures.

USW can also be considered as a promising way of application of ultra-fine grained (UFG) materials in additive manufacturing technologies, since it is a relatively low temperature process and is expected to allow one to keep the average grain size of materials in the submicron scale as in the case of bulk ultrasonic treatment [4,5]. Improvement and optimization of the USW routes for ultra-fine grained materials may help to increase the area of their applications and increase the efficiency of manufacturing of complex shaped parts from these materials. In the present paper, the consolidation of UFG copper plates is studied and compared with the consolidation of coarse-grained copper plates.

2. Materials and methods

For the studies of the ultrasonic consolidation process, samples of coarse-grained and UFG copper were used. Coarse-grained copper was produced by annealing of the copper billet at a temperature of 600 °C in a time interval of 1 h. Then the billet was cut into 0.7 mm thick plates using a spark cutting...
machine. Samples of UFG copper were processed using severe plastic deformation by high pressure torsion (HPT) applying 5 revolutions at a speed of 5 rpm under a pressure of 5 GPa. After deformation, the samples had an UFG structure and a disc shape with a diameter of 12 mm and a thickness of 0.8 mm. Both slices cut from coarse-grained copper and samples of UFG copper were polished with sandpaper, cleaned with isopropyl alcohol and dried before the consolidation.

The USW process is schematically presented in figure 1. Vibrations are transmitted to the sample by a steel sonotrode, the welding tip of which had a rectangular shape with sizes of $6 \times 7$ mm and a serrated surface comprised of parallel “teeth”.$^*$. The resonance frequency of the vibrating system was equal to 20.2 kHz. The amplitude of vibrations was controlled by changing the biasing current supplied to the magnetostrictive transducer and measured by the capacity amplitude detector. Consolidated samples were obtained by successive ultrasonic welding of five coarse-grained and UFG plates using the following regimes: static load of $P = 7$ kN, welding time of $t = 1$ s for coarse-grained samples and three static loads of $P = 3.5, 5$ and 7 kN with the same welding time for UFG samples. When welding the UFG samples, the center of the welding tip of the sonotrode was located at a distance of about half the radius from the centers of the discs, where a more uniform and finer structure is formed during the process of HPT.

As a result of the above treatment, two consolidated samples with sizes equal to those of the welding tip were obtained. These samples were cut by spark cutting along the direction of ultrasonic vibrations. For the scanning electron microscopy (SEM) studies, the surface was polished with sandpaper, diamond paste and Struers OP-S colloidal silica suspension in order to reduce the size of abrasive grits. BSE SEM images were acquired on a Tescan Mira electron microscope at an accelerating voltage of 20 kV.

![Figure 1](image_url). Schematics of ultrasonic consolidation: welding of a sample (left side) and the sonotrode tip (right side).

3. Results and discussion

3.1. Consolidation process

Some text. During the ultrasonic consolidation of copper plates with the same parameters of the ultrasonic vibration system (frequency and biasing current supplied to the magnetostrictive transducer), the vibration amplitude of the sonotrode tip depended on the numbers of sequentially welded plates both in the cases of coarse-grained and ultrafine grained initial structures. Presented in figure 2 are the dependences of the vibration amplitude on the number of sequential welds. During the consolidation of all coarse-grained plates, the vibration amplitude was fairly constant during the period of welding, while in the case of consolidation of UFG samples, significant changes in the amplitude
during welding time were observed at all static forces $P = 3.5$, 5, and 7 kN. The range of these changes are indicated in figure 2 by error bars. This difference in welding behavior can be caused by the difference in the mechanical properties of UFG and coarse-grained copper under ultrasonic vibrations.

![Figure 2](image)

**Figure 2.** Dependence of vibration amplitude of sonotrode on the sequence number of welding joints during ultrasonic consolidation.

The USW led to high compression deformation of the consolidated plates. The compressive strain depends both on the initial structure of the plates and the static compression load. The coarse-grained sample after USW under the static load $P = 7$ kN underwent a compressive strain of about $\varepsilon = 30\%$. The values of the compressive strain of UFG samples welded under $P = 3.5$, 5 and 7 kN were equal to about $\varepsilon = 13$, 15 and 80%, respectively. It should be pointed out that in the sample welded under $P = 3.5$ kN, the last plate was not joined properly. Therefore, this static pressure was found to be not sufficient for consolidation with the sonotrode used in the present work.

The higher $\varepsilon$ value of the UFG plates is obviously caused by the increased plasticity of the UFG copper samples under ultrasonic vibrations in a comparison to the coarse-grained state [6] and the specific deformation behavior of UFG Cu, which exhibits no strain hardening during compression at room temperature [7].

3.2. **Welding joint quality of consolidated samples**

Scanning electron microscopic images of the cross sections of the consolidated samples along the direction of ultrasonic vibrations for different conditions of USW and initial structures are presented in figure 3. In most of the samples, the welding joints are clearly identified visually as thin lines with cracks and pores along the samples. However, in the sample consolidated from UFG plates under a static load of $P = 7$ kN, only one welding joint was identified. Joints between other plates are not visible on the SEM image of the cross-section of the sample. In this sample, there are more areas of well joined material and less macroscopic defects than in the other samples. Thus, USW under the static pressure $P = 7$ kN resulted in the best consolidation of UFG copper plates.
Figure 3. Macrostructure of consolidated samples along the direction of ultrasonic vibrations: (a) coarse-grained Cu, $P = 7$ kN; (b) ultrafine grained Cu, $P = 3.5$ kN; (c) ultrafine grained Cu, $P = 5$ kN; (d) ultrafine-grained Cu, $P = 7$ kN. Visible welding joints are marked by arrows.

4. Conclusions

The present study shows that the ultrasonic consolidation of UFG copper can be carried out at a lower static pressure than the consolidation of coarse-grained materials. Welding of UFG samples under a static load of $P = 7$ kN led to the formation of a bulk sample with the minimum amount of visible welding defects. At the same time, the UFG samples undergo higher compressive strain during the consolidation with the same static pressure than the ones with the coarse-grained structure. These differences can be explained by the different deformation behaviors of copper with the two types of structures: the presence of work hardening of coarse-grained copper and its absence for the UFG copper [7]. In order to better understand the advantage of UFG materials in the process of ultrasonic consolidation, detailed studies of the microstructure evolution during welding are needed.

Acknowledgments

The present work was supported by the Russian Science Foundation (grant # 16-19-10126). Experimental studies were carried out on the facilities of shared services center of IMSP RAS “Structural and Physical-Mechanical Studies of Materials”.

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