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Improved compromise between the electrical conductivity and hardness of the thermo-mechanically treated CuCrZr alloy

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ABSTRACT

The study was concerned with improving the thermo-plastic treatment of the CuCrZr alloy so as to achieve a better compromise between its electrical conductivity and hardness. The experiments included severe plastic deformation (SPD), such as hydrostatic extrusion (HE), equal channel angular pressing (ECAP), and a combination of these processes, all followed by a precipitation hardening stage (solution treatment before the deformation and post-deformation ageing). The aim was to produce a material with a strongly refined microstructure (which is a factor promoting high hardness and high mechanical strength of the material) with the preservation of its high electrical conductivity. The material obtained had an ultrafinegrained structure (d_2 = 200 nm) and a high ultimate tensile strength UTS = 630 MPa, values which are much higher than those of the reference commercial material used for the fabrication of the spot-welding electrodes. The optimization of the process parameters also permitted achieving a high electrical conductivity of 78% IACS. The CuCrZr alloy is commonly used as the material for the tips of the spot-welding electrodes, especially in the transportation industry. Therefore, the properties of the material obtained in the present study were verified from the applicative point of view i.e. some standardized spot-welding electrodes were fabricated of it and subjected to lifetime tests. The lifetime of the electrodes made of the material subjected to HE + post-deformation ageing appeared to be more than 6 times as long as that of the reference commercial electrodes. In the material treated by ECAP + HE, the result was much less advantageous which was because of the weaker morphological texture compared to that formed characteristically in the materials treated by HE alone.

1. Introduction

The CuCrzr alloys show advantageous mechanical properties and high electrical conductivity and, thus, they are widely used in the welding- and electrical engineering industries [1,2], e.g. in the manufacture of plasma-facing parts of the devices intended for fusion energy research [3]. Unfortunately, these two advantageous parameters are in opposition to one another, i.e. the higher the hardness related with the higher degree of plastic deformation, the lower the electrical conductivity [4]. Therefore, the problem to be solved is how to improve the mechanical properties of the CuCrZr alloy without any significant loss of its electrical conductivity. One of the methods used for improving the mechanical properties of materials is the refinement of their structure to the ultrafinegrained (UFG) or nanocrystalline (NC) level by subjecting them to severe plastic deformation (SPD) [5]. This is the preferred method in the case of the CuCrZr alloy since this material shows the susceptibility to work hardening during cold deformation and to the Cr and Cu-Zr precipitation hardening during the ageing treatment [4,6–8]. In the recent time, several SPD methods have been extensively tested, with the equal channel angular pressing (ECAP) being the most often used method [6,7,9] in which the trials were mostly concentrated on strengthening the material by multiplying the number of pressing passes (usually above 8) and by precipitation ageing before [10] or after [9,11] the ECAP. The post-ECAP ageing gave a better strengthening effect and a better improvement of the electrical conductivity [9,11]. Certain untypical processes have also been tested, such as dynamic plastic deformation conducted at the temperature of liquid nitrogen (DPD-LNT) without ageing [8]. This method gave a high ultimate tensile strength (UTS) of 700 MPa (the highest value achieved up to date) with electrical conductivity of 78.5% IACS, and the microstructure composed of nanotwins and about 50 nm nanograins. Although this result is very impressive, this technique cannot be easily employed in bulk production.

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In the present study attempts were made to avoid cryogenic deformation but to achieve a comparable tensile strength of the CuCrZr alloy together with a high homogeneity of deformation and the preferred longitudinal texturization by using only a limited number of process steps conducted at high strain rates. It was believed that the significant grain refinement together with well developed grain texture would permit achieving a good compromise between the strength of the CuCrZr alloy and its electrical conductivity, such that would be acceptable to the potential manufacturers. Therefore our experiments included the two alternative versions: one-pass hydrostatic extrusion (HE) and a combination of two ECAP steps followed by HE, both with a post-deformation ageing. Beyond any doubt, it appeared that the hydrostatic extrusion promoted the grain refinement with a higher efficiency than other SPD techniques, which was so thanks to the higher strain rates applied, among other factors [12–15]. The combination of ECAP and HE has already been successfully used in various sequences for processing nickel and copper where it yielded UFG and NC structures with the grain size close to or below 100 nm [16]. A solution treatment (ST) followed by HE to the true strain $\varepsilon = 4$ applied to the CuCrZr alloy gave an average grain size of 200 nm and the yield stress (YS) above 500 MPa, whereas the ST plus ageing resulted in a grain size of 50 µm and YS = 280 MPa. Hence it was concluded that HE is much more effective in hardening the alloy than precipitation strengthening [17]. Another experiment was conducted with a 3 mm diam. CuCrZr wire subjected to ST followed by ECAP B_c route and then by HE conducted to a total true strain of 11.5 which gave a smaller grain size of 140 nm and the YS increase to 635 MPa [18]. Both results were only achieved after many hydrostatic extrusion passes and with the final product in the form of thin wires. Unfortunately, none of these papers reports on processing bulk forms and post-deformation ageing and none of them presents the measured values of the electrical conductivity which is the crucial parameter in many commercial applications. In the present study, a novel route was proposed. The CuCrZr rods 16 mm in diameter were processed by a single HE pass or, alternatively, by HE combined with ECAP conducted to a moderate total strain, both followed by post-deformation ageing. Then the properties of the thus treated rods, such as the structure, hardness, the strength vs % IACS characteristic, were examined and compared with the properties of the spot welding electrodes made of them.

2. Experimental

The material examined was a CuCrZr copper alloy according to the Standard PN-EN 10204:2006P with the chemical composition (in wt%): 0.5–1.2 Cr, 0.03–0.3 Zr, max. 0.08 Fe, max. 0.1 Si, balance Cu. The material was solution-treated at a temperature of 1000 °C for 1 h and cooled in water.

The samples of the alloy were subjected to plastic working according to the two procedures:

1. Sample 50 mm in diameter was hydrostatically extruded in one pass at the true strain $\varepsilon = 2.28$ to a final diameter of 16 mm
2. Sample 30 mm in diameter was subjected to two passes of ECAP at the total true strain $\varepsilon = 2{,}3$ with a rotation of 180° between the successive passes (route C). Then the material was hydrostatically extruded in one pass with a true strain $\varepsilon = 1.27$ to obtain a final diameter of 16 mm. The cumulated total true strain was $\varepsilon = 3.57$.

Both processes were conducted at room temperature. During the hydrostatic extrusion, the samples were intensively cooled at the die exit with cold water just after they left the deformation zone. After the plastic deformation, the samples were subjected to post-deformation ageing within the temperature range from 420 to 480 °C for 1–3 h. The microstructure of the material in the starting state was analyzed in an optical microscope (Nicon Eclipse LV150), whereas after the plastic deformation – in a transmission electron microscope (Tecnai TF20). The observations were made on transverse and longitudinal cross-sections of the samples. The microstructure in terms of the grain size was evaluated using the 'Micrometer' software [19]. In each case, the data were based on the TEM images obtained. After the imaging, at least 200 grains selected randomly from the population were outlined and the software calculated the equivalent grain diameter d_2 (defined as the diameter of the circle with the surface area equal to that of the given grain).

The mechanical properties of the samples were examined in a Zwick/Roell Z250 kN machine using the static tensile test at room temperature, the straining rate of $0.008\,s^{-1}$ on the standard round samples with length to diameter ratio 5:1 machined along the extrusion axis. The hardness of the material was measured by the Vickers HV10 method with the use of an automated KB 250 BVRZ hardness tester under a load of 1 kG within a test period of 15 s. The electrical conductivity (% IACS) was measured in a SIGMATEST 2.069 Forester device. The material was then used for the fabrication of spot-welding electrodes according to the DIN 44750 Standard. The parameters of these electrodes were compared with those of a commercial CuCrZr electrode of the same geometry. The spot welding tests were performed using an automated stand (Fig. 1) constructed at the Faculty of Production Engineering, Warsaw University of Technology, according to the PN-EN ISO 8166:2007 Standard [20]. The stand permits maintaining constant values of the: (i) electric current, (ii) cooling parameters and efficiency, (iii) load force, and (iv) distance between the successive welds. The parts to be welded were zinc coated sheets 1 mm thick. The durability of the electrodes was examined using the peel-off test according to the PN-EN ISO 10447:2007 Standard.

3. Results

3.1. Compromise between hardness and electrical conductivity

The most important parameters of the electrodes intended for spot welding are their hardness and electrical conductivity. The high hardness itself is not sufficient for the long lifetime of the electrodes to be achieved. When their electrical conductivity is low, the intensity of the electric current must be high which enhances thermal effects thereby contributing to quick degradation of the electrode material. Fig. 2

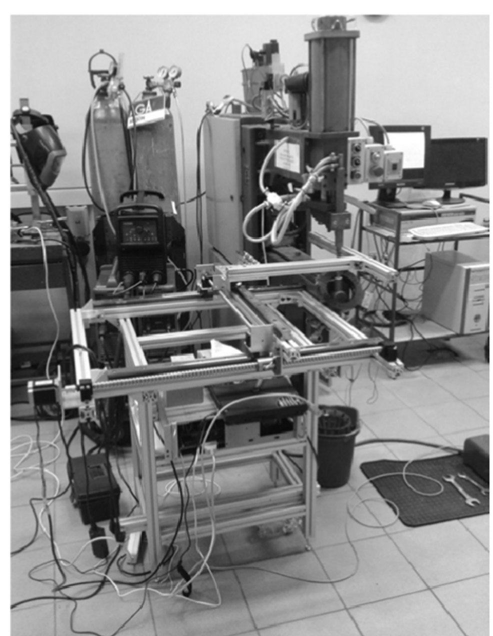

Fig. 1. An automated stand for spot welding according to PN-EN ISO 8166:2007 standard.