High strength and high conductive copper-based alloy produced by SPD for contact wires for high speed railway lines - A short review

B Ravisankar¹, K Sivaprasad¹, N Ramesh Babu¹, G I Raab² and R Z Valiev²

¹ Department of Metallurgical and Materials Engineering, National Institute of Technology, Tiruchirappalli – 620 015 INDIA
² Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, 12 K. Marx str., Ufa, 450008 Russia

E-mail: brs@nitt.edu

Abstract. The development of high-speed railway lines, the requirements for contact wires of catenary become more essential. The contact wire should be strong, wear resistant and fatigue resistant, and also possess good thermal stability along with high electrical conductivity. At present, copper wires alloyed with cadmium are used. The replacement is more of a necessity since cadmium is a material hazardous to environment, and it is already banned by several countries. Over the last several decades, growing attention has been focused on the development of copper-based alloys with high strength and good electrical conductivity. Novel severe plastic deformation (SPD) procedure, namely equal-channel angular pressing (ECAP), has been applied for obtaining ultrafine-grained (UFG) materials with high strength and good electrical conductivity. This overview mainly focuses on the suitability of ECAPed copper and its alloys for contact wires in high-speed railway lines.

1. Introduction

The development of high-speed railway lines, the requirements for contact wires of catenary becomes more essential. The contact wires are suspended from the catenary wires via dropper wires and are in direct contact with the pantograph, transmitting power from the rail overhead line system to the locomotive as shown in the figure 1.

The contact wire should be strong, wear resistant and fatigue resistant, and possess good thermal stability along with high electrical conductivity. The contact wires should be suitable for outdoor use in moist tropical climate and in areas subject to heavy rainfall, polluted due to industry and marine atmosphere and severe lightning.

Global practice shows that the real solution to the problem is to replace the material of contact wires with copper alloys with higher strength, high electrical conductivity and good thermal stability. At present, copper alloyed with cadmium and Cu-Mg wires are used. The replacement is more of a necessity since cadmium is a material hazardous to environment, and it is already banned by several countries. The properties of Cu-Mg alloys do not meet the requirements for high speed railway lines and, hence, replacement with another material becomes indispensable. Over the last several decades, growing attention has been focused on the development of copper-based alloys with high strength and good electrical conductivity. Strength can be increased by alloy addition, but as is well known, high strength
and good electrical conductivity are often mutually exclusive in copper alloys. In order to overcome the shortcoming, a novel severe plastic deformation (SPD) process, namely equal-channel angular pressing (ECAP), has been applied for obtaining ultrafine-grained (UFG) materials with high strength and good electrical conductivity. In the ECAP process, a well lubricated billet is pressed in a die that contains two channels, equal in cross section, intersecting at an angle called the die channel angle as shown in figure 2 (a). The material is subjected to shear deformation at the intersection plane. Since the process is capable of maintaining the net dimensions of the work piece, repetitive extrusion is possible and enables for imposing high strains in the materials subjected to ECAP. Thus during the ECAP processing, significant structural refinement can be achieved. Numerous studies have demonstrated that the severe plastic deformation processing enables achieving a drastically new level of properties due to the severe working of the structure and the change in the kinetics of phase transformations in alloys. The advanced version of ECAP, i.e. ECAP-Conform (figure 2 (b)) process is capable of producing long-length wire rods required for contact wires of catenary.

![Figure 1. Schematic representation of catenary.](image)

![Figure 2. Schematic representation of (a) ECAP and (b) ECAP - Conform processes.](image)
While going for the development of high strength and high conductivity copper based alloys, the retention of properties is a major technical challenge. Therefore, in the process of development it is necessary to determine precise amount of alloying elements that can provide high strength and preserve a satisfactory level of ductility. The task of the processing by ECAP-Conform is to ensure the maximally profound solid solution decomposition at the deformation stage for strain-hardening Cu alloys and at the aging stage for precipitation-hardening Cu alloys.

This overview mainly focuses on the suitability of copper and its alloys processed by SPD techniques for contact wires in high speed railway lines.

2. Copper and its alloys

The other best method, apart from strengthening by alloy addition, is grain refining. The desired combination is the tensile strength of 450 MPa with electrical conductivity of 90% International Annealed Copper Standard (IACS) in case of pure copper, and 600 MPa with electrical conductivity of 83 %IACS in case of Cu-Cr-Zr alloys, for contact wires in high speed railway lines. By traditional techniques such as rolling, drawing etc., the required properties are achieved by the primary 30% thickness reduction and intermediate aging and/or annealing followed by a secondary 60% thickness reduction. The combination of tensile strength and electrical conductivity were gained for the alloy with 95% reduction by conventional techniques [1]. The reduction in dimensions and cost involved in production restricts the use of conventional techniques. The other way to attain grain refinement without dimensional changes is through severe plastic deformation techniques. Also, the SPD techniques heavily alters the microstructure, precipitation kinetics which enables for attainment of the required level of properties in copper and its alloys for high speed railway lines. Hence, the paper discusses the review of development of high strength and high conductive catenary wires especially in pure copper, copper-chromium-zirconium and copper-titanium carbide in situ composites and its processing by various severe plastic deformation processes by various scientists and researchers.

In pure copper, a tensile strength of 430±20 MPa has been achieved in ECAP with three passes [2] with a ductility of 10%. In oxygen free high conductivity copper, a tensile strength of 440 MPa is achieved with a ductility of 28% and dephosphorised copper in four passes [3]. The conductivity of the samples decreased with increasing number of ECAP passes. After 7 passes, it was estimated to be 81% International Annealed Copper Standard (IACS). The electrolytic tough pitch (ETP) copper after 12 passes of ECAP the ultimate tensile strength was about 440 MPa [4]. The ETP copper in the initial state exhibits an electrical conductivity of 100.2% IACS. Grain refinement by ECAP caused a reduction to 93.1% IACS. Though the strength properties are achieved with little sacrifice in electrical conductivity and ductility, the thermal stability of the nanostructured ECAPed copper is maintained till 400 K only, which restricts the use of pure copper in contact wires.

The research is directed towards the controlled addition of alloying elements coupled with grain refinement by severe plastic deformation. The alloying elements, which are responsible for precipitation hardening, are chosen as against solid solution straighteners, as they are reducing the electrical conductivity to a greater extent.

Cu–Cr–Zr alloys have attracted considerable interest recently because of their high strength, as well as good formability, high thermal/electrical conductivity, good fatigue resistance, excellent stability at high temperatures (473 – 673 K) and low cost. Therefore, Cu–Cr–Zr alloys are widely used in high speed railway contact wire. Cu–0.71%Cr–0.08%Zr alloy when ECAPed in Route Bc attains a tensile strength of 450 MPa with an elongation of about 20% [5]. Based on the results of high pressure torsion (HPT) of Cu-0.1%Cr-0.06%Zr, Cu-0.5% Cr-0.08%Zr, Cu-1%Cr-0.1%Zr, and Cu-0.3%Cr-0.5%Zr alloys, it is concluded that alloying with chromium in concentration above the solubility limit does not result in additional hardening both after HPT and after subsequent aging. However, excessive alloying with zirconium allows obtaining a structure with a smaller grain size (113 nm), enhances structure stability during heat treatment and noticeably increases strength of the alloy after HPT and after additional aging. The Cu-0.3%Cr-0.5%Zr alloy has both high strength and electrical conductivity of 63% IACS [6]. The Cu-Cr-Zr alloys fetch highest strength of 720 MPa with electrical conductivity of
70% of IACS when solutionised samples are ECAPed and aged with enhanced wear resistance [7]. When the warm extruded billets of Cu-Cr-Zr alloys are processed through HPT and subsequent aging yields an electrical conductivity of 75% IACS with a tensile strength of 825 MPa. The aging temperature played crucial role in improving the electrical conductivity [8-9].

A dispersion-strengthened Cu alloy with 1 wt% TiC, having a size of 0.5–1 μm, prepared by in-situ reaction casting, has a tensile strength of 250 MPa and a conductivity of 76% IACS. With increasing the number of ECAP passes, the hardness and strength (566 MPa) of Cu-1 wt% TiC composite increased obviously, but the conductivity and elongation decreased gradually. The post-ECAP annealing at 573 K significantly changed the optical microstructure exhibits a high tensile strength of 550 MPa and a good conductivity of 82.2% IACS. The novel combined process endows the alloy the appropriate performance to serve current high-frequency electrification railway systems [10].

A number of papers investigating the kinetics of strain-induced processes in copper low-alloyed alloys report complex phase processes occurring during SPD, and dispersed particles dissolve in low-alloyed alloys, which provides an additional reserve for precipitation hardening at the aging stage. Thus, during aging, the contribution of precipitation hardening increases. [11-13]. It has been experimentally demonstrated that SPD Processing has a high potential for achieving improved electrical conductivity with high strength in copper alloys by one of the authors [14,15].

3. Summary
In summary, from the results obtained by the various researchers, it can be concluded that the regime of the SPD processing governs the size and volume fraction of precipitates and segregations, thereby affecting the grain size and dynamic aging, influencing the mechanical and physical properties in copper alloys. Thus, the precise control of alloying additions and parameters characterizing SPD, such as combining the operations of heat treatment, ECAP and drawing, can result in the formation of a high set of physical and mechanical properties in copper and its alloys.

References
[1] Meng A, Nie J, Wei K, Kang H, Liu Z and Zhao Y 2019 Vacuum 167 329
[2] Kommel L, Hussainova I and Volobueva O 2007 Materials and Design 28 2121
[3] Goto M, Han S Z, Yakushiji T, Kim S S and Lim C Y 2008 International Journal of Fatigue 30 1333
[4] Lipin’ska M, Olejnik L and Lewandowska M 2018 J. Mater. Sci. 53 3862
[5] Ding R, ChengGuo and Guo S 2013 Mater. Sci. Eng. A 587 320
[6] Shangina D V, Bochvar N R, Morozova A I, Belyakov A N, Kaibyshev R O and Dobatkin S 2017 Materials Letters 199 46
[7] Purcek G, Yanar H, Saray O, Karaman I and Maier H J 2014 Wear 311 149
[8] Purcek G, Yanar H, Shangina D V, Demirtas M, Bochvar N R and Dobatkin S V 2018 Journal of Alloys and Compounds 742 325
[9] Shangina D V, Bochvar N R, Gorshenkov M V, Yanar H, Purcek G and Dobatkin S V 2016 Mater. Sci. Eng. A 650 63
[10] Ni S, Jiang J, Chen J, Song D and Ma A 2016 Progress in Natural Science: Materials International 26 643
[11] Raab G I, Raab A G and Shibakov V G 2015 Metalurgija 54 423
[12] Faizov I A, Mulyukov R R, Aksenov D A, Faizova S N, Zemlyakova N V, Cardoso K R and Yu Zeng 2018 Letters on Materials 8 110
[13] Faizov I A, Raab G I, Faizova S N, Zaripov N G and Aksenov D A 2016 Letters on Materials 6 132
[14] Murashkin M Yu, Sabirov I, Sauvage X and Valiev R Z 2016 J. Mater. Sci. 51 33
[15] Sabirov I, Enikeev N A, Murashkin M Y and Valiev R Z 2015 Bulk Nanostructured Materials with Multifunctional Properties (New York: Springer International Publishing)