Journal of Materials Processing Technology 223 (2015) 193–202

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Cold upset forging joining of ultra-fine-grained aluminium and copper

M. Pawlicki*, T. Drenger, M. Pieszak, J. Borowski

Metal Forming Institute, Jan Pawel II Street no. 14, Poznan 61-139, Poland

ARTICLE INFO

Article history:
Received 11 December 2014
Received in revised form 31 March 2015
Accepted 3 April 2015
Available online 16 April 2015

Keywords:
Joining
Plastic deformation
Copper
Aluminium
Ultra-fine grain

ABSTRACT

This paper describes a study investigating joining copper, which is expensive but has excellent electrical properties, with aluminium, which is cheaper but is characterized by much worse mechanical and electrical properties. Metals with ultra-fine-grained structure were studied to understand the process of cold upset joining of hydrostatically extruded materials with a large deformation. Much greater difficulties were expected, based on the combination of conventional metals. The study verified the possibility of bonding such metals with various surface preparation methods and different parameters of the joint. The bond quality was checked by the static tensile test to study their tensile strength. To present the difference in joining conventional materials and ultra-fine-grained materials, was tested joining annealed copper and aluminium, and the results of this test were compared with tests for hydrostatically extruded material. The permanent joints were tested based on the hardness distribution across the joint and by observation of the fracture specimen's joints and EDS examination, which allowed us to determine that the connection mechanism does not rely on the diffusion of copper atoms to aluminium and vice versa.

1. Introduction

Cold joining of metals by deformation is a technology that has been developed over several decades. Tylecote (1976) described various methods for joining metals, in particular with regard to the historical, even ancient solutions. Tylecote (1968) also researched and described the solid phase welding of metals from the modern point of view. One of the first scientific works on the joining of metals by rolling was led by Vaidyanath et al. (1959). He described the first results on the mechanism of joining in cold pressure welding. The issue of cross-shear roll bonding was researched and described much later by Bay et al. (1994). They, among others, proved that pseudo-cross-shear roll bonding (where the cross-shear effect is obtained by running two equal sized rolls at different speeds) gives the same results.

Literature reviews were being written even in the 1960s in eastern Europe (Niewiadomski and Olszewski, 1961) in which authors described the methods and parameters of cold joining rather thoroughly but did not delve too deeply into the mechanisms and phenomena occurring during the joining of the metals.

Zhang and Bay (1992) presented the influence of plastic deformation on the strength of the joint in a variety of configurations and methods for the preparation of metal surfaces. However, this issue raised the interest in Bay et al. (1985), whose results showed that it is possible to generate a theoretical model for strength in cold pressure welding. Experimental results demonstrated substantial compliance with the results of the theoretical calculations. Clemensen et al. (1986) studied the effects of surface preparation on the bond strength of metal structures. Ciupik (1983) researched the mechanisms of the process of cold deformation metal bonding. Cave and Williams (1973) worked on the mechanism of metal joining. Ciupik (1988) determined that this mechanism is related to the adhesion phenomenon. Cooper and Allwood (2014) researched and then created a new model of bonding strength and also determined that their experiments had established the basic relationships between deformation parameters and weld strength.

There are a myriad of cold joining methods, and descriptions of these methods can be found in publications concerning working plastic: the problem with cold extrusion technology was often discussed in scientific papers. Mstowski and Ciupik (1981) took into account the energetic parameters of the extrusion process of the bimetal (researching this process from the technological point of view). The problem of combining divergent extrusion processes was discussed by Kudo (1978). Semi-free upset forging was also the subject of discussion by Ciupik et al. (1985).

* Corresponding author. Tel.: +48 061 657 05 55x169.
E-mail addresses: marek.pawlicki@inop.poznan.pl (M. Pawlicki), drenger@inop.poznan.pl (T. Drenger), michal.pieszak@inop.poznan.pl (M. Pieszak), borowski@inop.poznan.pl (J. Borowski).

http://dx.doi.org/10.1016/j.jmatprotec.2015.04.004
0924-0136/

Wozniak et al. (2005) described the influence of temperature on the strength of the Al—Cu bond. Wozniak (2009) also presented the evolution of the surface geometrical structure, but evolutionary reconstruction of the geometric structure of the surface and subsurface when approaching the surface bonded to each other was not discussed; he also studied free upset forging and the boundary conditions of the connection.

Abe et al. (2006) discussed the problem of jamming in joining technology—they presented research on aluminium alloy and mild steel joining. High strength steel and aluminium alloy joining was discussed by Abe et al. (2012). The mechanism of superiority of fatigue strength for aluminium alloy sheets joined by mechanical clinching was discussed by Mori et al. (2012), but practical application of clinching had already been presented by Nong et al. (2003).

Even today, many academic papers are devoted to studies of joining by rolling—Piragazi and Akbarzadeh (2008) characterized nanostructured aluminium sheets processed by accumulative roll bonding. The Electron Back Scattered Diffraction (EBSD) method and Transmission Electron Microscopy (TEM) in this paper were utilized for characterization of the subgrain and grain structures of the processed sheets. The microstructure and mechanical properties of commercial purity titanium severely deformed by the ARB process were presented by Terada et al. (2007).

Kodjaspirov et al. (2007) presented the problem with production of ultra-fine-grained sheets from ultra-low-carbon steel by pack rolling. Moreover, Takata et al. (2009) researched ultra-fine-grained copper alloy sheets having both high strength and high electrical conductivity. The combination of these two good properties is a serious problem. Shaarbaf and Toroghinejad (2008) dealt with the problem of gaps in the joint of nano-grained copper strips produced by the accumulative roll bonding process.

Jaamati and Toroghinejad (2010) presented the effects of friction, annealing conditions and hardness on the bond strength of Al/Al strips produced by the cold roll bonding process. Danesh Manesh and Shabani (2009) discussed effective parameters of the bonding strength of roll bonded Al/St/Al multilayer strips. They presented the "Peeling test" as the method of measure for the strength of the joint, whereas Yang et al. (2009) explained the effect of oxide layers on the quality of the connection. All of these authors emphasize the importance of surface preparation in cold joining because only the appropriate processing of the surface can ensure a permanent joint.

Kim et al. (2012) discussed problems and possibilities with wire-brushing; however, etching, washing, and stripping of the surface layer before joining were taken into consideration by Ciupik and Nonckiewicz (1985). Certain papers present the problem of joint durability at high temperatures and determining a threshold temperature of exploitation that does not cause structural changes in joints between two metals.

Eizadjou et al. (2009) indicated that the temperature resistance of a joint is different than in the case of bulk material, and this is linked to increased diffusion between the two different metals and the possibility of intermetallic compound formation. He also showed the disappearance of the gap between the layers during rolling.

The increase in strength that is achieved is due to refinement of the grain structure, in accordance with the well-known Hall–Petch equation. Carlton and Ferreira (2007) discussed this matter with reference to causes of the dynamic development of nanomaterials. Muszka et al. (2006) reported that the experimental results confirm the previous theoretical assumptions and show that the mechanical response of low carbon and micro-alloyed steels strongly depends on thermomechanical history and ferrite grain size; additionally, in the case of quasi-static deformation, the mechanical properties of the material can be fully controlled by processing parameters.

Unfortunately, every additional or more complicated process increases the costs of material production, which is why scientific research is being conducted to enable, e.g., joining of products with a nanometric structure (characterized by certain specific parameters) with conventional materials, i.e., with a typical grain size (a dozen to several dozen μm), which will allow reduced production costs in the future.

The lower thermal structural stability of alloys with a nanometric structure is also known. Lewandowska and Kurzydlowski (2010) presented the synergistic effects of grain refinement and precipitation strengthening with relation to the temperature. Lewandowska and Kurzydlowski (2008) discussed recent developments in the grain refinement of material produced by the hydrostatic extrusion process.

Borowski et al. (2011) discussed properties of semi-products made of aluminium alloys with a nanometric structure as a base for all further research on nanometric metals. Borowski et al. (2010) also presented practical applications of nanocrystalline metals; based on this investigation, material-forming parameters to maintain the nanostructure have been determined.

This paper pertains to studies of permanent cold joining of aluminium and copper with an ultra-fine-grained (UFG) structure. This work fits into problems related to metal joining by plastic deformation on the principle of adhesion of two semi-product surfaces with an UFG structure produced by the hydrostatic extrusion method. Reduced plasticity related to the achievement of a refined structure may be the reason why cold joining of materials is more difficult, and thus, the goal of this paper is to assess joining possibilities and to determine the forming parameters required for obtaining a permanent joint, as well as to evaluate the strength of such a joint. Such joints (aluminium—copper) find applications in industrial plants that manufacture parts for electrical networks as well as electrical and electronic devices.

2. Material and methodology

During the execution of the "Nanomet" project—"New metallic materials with nanometric structures for applications in modern branches of the economy", rod stock Ø≈8 mm and Ø≈10 mm in

Table 1
Chemical composition of initial samples.

Material sample nos.	Material type	Chemical composition [%]									
		Si	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Fe	Al
1.	Aluminium	0.344	0.058	0.030	0.038	0.017	0.017	0.048	0.015	0.557	Other
2.		0.357	0.057	0.017	0.040	0.028	0.028	0.065	0.014	0.597	Other
3.		0.371	0.049	0.036	0.036	0.016	0.016	0.030	0.014	0.542	Other
The average		**0.357**	**0.055**	**0.028**	**0.038**	**0.020**	**0.020**	**0.048**	**0.014**	**0.565**	**Other**
Material sample nos.	**Material type**	**Si**	**Al**	**Sn**	**Sb**	**As**	**Ni**	**Zn**	**Bi**	**Fe**	**Cu**
1.	Copper	0.022	0.004	0.002	0.002	0.001	0.001	0.003	0.002	0.004	Other
2.		0.011	0.021	0.001	0.003	0.004	0.002	0.002	0.001	0.005	Other
3.		0.035	0,014	0,003	0.001	0.002	0.002	0.004	0.001	0.005	Other
The average		**0.023**	**0.013**	**0.002**	**0.002**	**0.002**	**0.002**	**0.003**	**0.001**	**0.005**	**Other**