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The Application of Kinetic Friction Energy for Ceramics Metallisation

Abstract: The paper presents the problem of ceramics metallisation using the friction method based on the mechanism of joint formation, where the energy of kinetic friction is directly transformed into heat and supplied in specified amounts directly to the joint formed between the layer and the substrate. The paper also presents friction-utilising ceramic metallisation process developed by the authors as well as shows the results of microstructural examination of metallised layers obtained.

Keywords: metallisation of ceramics, ceramic-metal joints

Introduction

Advanced ceramics used in industry often find applications in ceramic-metal joints and surface processing [4,5,8,20,21,23]. Such solutions make it possible to combine different properties of ceramics and metals into a specific product feature. Ceramic-metal joints are made using either of the two methods presented below. The first method is based on direct joining of solid elements, yet as a result, the configuration of the pairs of elements joined is very limited [6,7,9,10,12,13,15,16,18,19,20]. A more commonly used method utilises metallisation, the purpose of which is to form a thin metallic coating on a ceramic surface, which next can be relatively easily joined with metals, e.g. by means of brazing. Traditional methods of ceramics metallisation are characterised by high quality, yet also by high cost and technological complexity, time-consumption, necessity of using high temperature (the whole volume of ceramics to be metallised is exposed to heating) and shielding atmosphere of vacuum or hydrogen. The most commonly used methods include powder metallisation, active brazing and applying coatings by means of PVD, CVD and IPD methods [16,24,27]. In another solution, a ceramic layer is activated for joining with metals by means of metal ion implantation [4,13,19,23].

Difficulties in joining ceramics with metals result from the extreme properties of joint components enumerated below [22]:

- lack of wettability of ceramics with metals; practically, the lack of interaction (ceramics is based on ionic, covalent and mixed bonds, whereas metals are based on metallic bonds),
- lack of mutual solubility,
- poor diffusivity of metal ions in ceramics,
- differences in crystallographic lattices,
- significantly varying melting points,
- significant differences in hardness, brittleness, thermal conductivity and thermal expansion.

Making ceramic-metal joints requires the use of advanced joining techniques based mainly

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on diffusion, usually accompanied by high process temperature and requiring relatively long time as well as costly and chemically active filler metals.

The most general condition for the creation of a directional diffusion stream is the gradient of chemical potential (Gibbs molar free enthalpy), including the following factors:

- matrix chemical composition and structure,
- matrix matter type and properties,
- matrix ion-diffusive ion diameter ratio,
- corpuscular radiation,
- temperature level,
- temperature gradient,
- type and value of external mechanical load,
- strain degree.

In the context of the friction metallisation proposed in the article, the last three of the factors mentioned above gain special importance as, during friction welding, they reach relatively high values and can compensate a relatively short process time. All joining processes require an energy input in the form of joining process activation energy. In the joining practice, the activation has usually a thermal character; it provides surface atoms with energy necessary for overcoming the activation barrier and making a joint. These phenomena were used in the process described, supplying the required activation energy to the system in a mechanical way, by converting kinetic friction energy into thermal energy directly in the area of a joint to be formed. Reference publication contain information about other cases of mechanical influence on a joint being formed [11].

Friction Metallisation

In order to create a thin metal coating on the ceramic surface it was necessary to apply a process based on the friction effect of a titanium cylinder face on that of an Al_2O_3 ceramic cylinder. In comparison with other joining methods, the method of friction-based coating application has many advantages such as the formation of a joint in the solid state, high process efficiency, high repeatability of joint formation conditions, possibility of joining materials having significantly varying properties (often requiring joining in the solid state). Scientific publications have also reported cases of using the method for applying metallic coatings on metallic substrates [14].

The friction force moment is a reliable indicator of welding process course [3,17,25,26] and depends on several factors, i.e. unitary pressure, rate of rotation, properties of workpieces and the geometry of friction surface. The cycle starts with dry friction and leads to a rapid increase in the value of friction moment. This is when the first tack welds are formed (subjected to shear stresses). Next, the particles of the more plastic material are torn out and undergo plastic deformation followed by the disappearance of the ceramic surface roughness. The plastic deformation is accompanied by an increase in temperature stimulating adhesive phenomena. Adhesion, frictional wear and internal friction cause the motion of mass in the friction area. The value of moment increases until friction influences the whole interface area. On the surfaces to be joined, local tack welds are formed. Next, these local tack welds undergo shearing in the plane parallel to the friction surface. In the case of the frictional deposition of the Ti coating on the ceramic base, the shear plane is located in the surface layer of the titanium cylinder face. In general, in dissimilar joints with significant differences in the yield point Re, the torn-out material particles are transferred to the harder material surface [1, 2]. The sliding period is characterised by the stable friction moment course. At the same time, on the friction surface a high plasticity layer is formed. As a result, the friction changes from internal into external. In classical welding, whose purpose is the joining of elements, this change is disadvantageous as it leads to the generation of quasi-stationary sliding friction, during which less heat is emitted on the friction surfaces. However, during ceramics metallisation this phenomenon is advantageous and desirable (Fig. 1) as it separates a metal coating connected with ceramics from the metallic cylinder. It was observed that the extension of friction time, dependent on the rotation rate value and the value of pressure on the friction area, leads to the formation of a plastic metal coating on the ceramics surface.

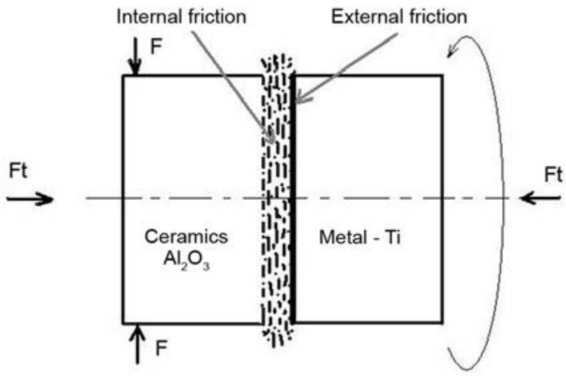

Fig. 1. Simplified scheme of metallic coating formation when friction changes from internal into external

With the passage of time the coating starts to flow out in the direction of radius. In order to obtain the metallisation coating the process should be stopped at this stage and the ceramic element should be separated from the metal one. The metal coating deposits on the ceramic surface. The described tests related to ceramics metallisation were performed on a friction welding device manufactured by Harms und Wende. The ceramic cylinder was installed in a rotating head, whereas the titanium cylinder was fixed in a stationary clamp. After performing many attempts it was possible to determine the best process parameters enabling the obtainment of a uniform titanium coating on the whole ceramic face area. In the case under discussion, the so-called technological parameter window is narrowed to the point in the Cartesian space where three axes represent the rotation rate, pressure and friction time. Table 1 presents the process parameters used for obtaining the best results of the frictional metallisation of the Al_2O_3 ceramics surface layer with titanium.

Table 1. Parameters of the frictional metallisation of Al_2O_3 substrate with titanium

Parameter	Value
Rotation rate	2550 (rev./min.)
Pressure on friction surface	13.4 (MPa)
Friction time	14 (s)
Ceramic test piece diameter	9.5 (mm)
Titanium test piece diameter	9.5 (mm)
Length of test pieces	20 (mm)

Selected Properties of Metallisation Coating and of its Joint with a Ceramic Substrate

Figure 2 presents the surface of the Ti frictional coating on the Al_2O_3 ceramics substrate. The surface is characterised by a regular stereometric structure and visible directivity resulting from the mutually directional friction of components during metallisation. The coating thickness is restricted within the 3÷7 μm range. In the photograph it is possible to observe the presence of the surface layer structure components in the form of plasticised titanium crystals, which indicates the exertion of significant pressure on the friction surface as well as the presence of high temperature.

Figure 3 presents the fracture of the Ti coating-Al_2O_3 substrate system. The obtainment of the test piece fracture aimed to receive a surface for further tests proved a demanding task confirming very good adhesion of the frictional metallisation coating to the substrate.

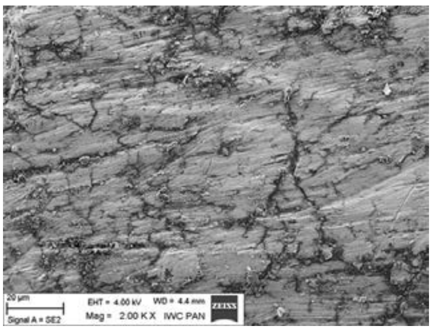

Fig. 2. Surface of the Ti coating friction-welded to the Al_2O_3 substrate

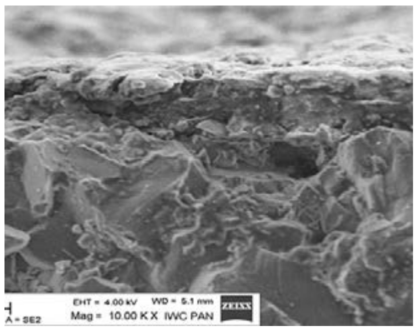

Fig. 3. Surface of Ti coating-Al_2O_3 substrate system fracture with a visible joint area

The coating material is very well joined with the substrate and fills the substrate unevenness well. The fracture tests did not reveal the coating material spalling in the joint area. Figure 4 presents the surface distribution of oxygen, aluminium and titanium on the cross-section of the ceramic base–titanium coating system. The results indicate the presence of the titanium coating having a thickness of several micrometres. Figure 5 presents the diffraction pattern of the titanium coating and the Al_2O_3 ceramic cylinder face friction-metallised with titanium. The phase analysis results indicate that titanium did not undergo oxidation during coating welding. Only the titanium crystals and aluminium oxides from the substrate were observed. Nothing indicates either that welding led to the formation of a clearly visible intermediate diffusive layer.

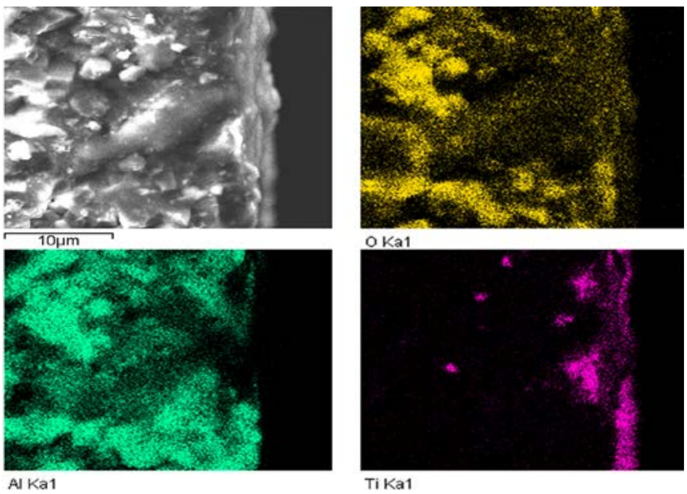

Fig. 4. Surface distributions of oxygen, aluminium and titanium in the cross-section of the Al_2O_3 substrate- titanium metallisation coating system

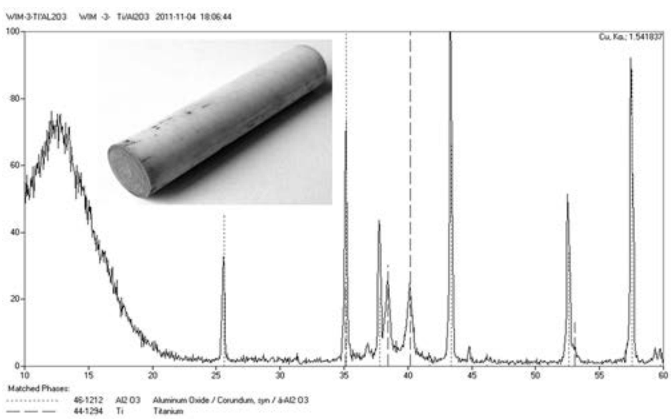

Fig. 5. Diffraction pattern of the surface layer of the Ti coating friction-welded to the ceramic substrate

Figure 6 presents the microstructure of the joint of the titanium coating with the ceramic substrate and the linear distribution of the chemical elements (Ti, Al, O) in the joint cross-section. The Al_2O_3 substrate – Ti coating interphase boundary was examined using a scanning electron microscope (SEM) in the cross-section perpendicular to the interphase boundary surface. The figure presents the microstructure of the joint formed and the linear distribution of chemical element concentration. The Al and Ti concentration profiles are characterised by the smooth course of changes, yet there are not any indications of the joint with a so-called intermediate layer, i.e. a joint of diffusive character.

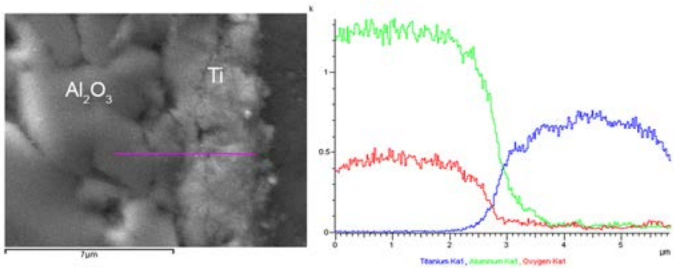

Fig. 6. Microstructure of titanium coating friction welded to Al_2O_3 ceramic substrate with the linear distribution of chemical elements (Ti, Al, O)

Summary and Concluding Remarks

The tests performed have revealed that energy supplied to the system mechanically is a very efficient ceramics metallisation process factor. Such a method makes it possible to supply the system with required energy portion supplied to a precisely specified place where a new interphase boundary is to be formed (ceramic-metal joint).

Supplying energy in a mechanical manner provides an additional advantageous effect, i.e. the mechanical removal of various impurities and adsorbed substances from the surface layer of metallised ceramics. The phenomenon leads to an increase in the free surface energy, which should be considered as a specific indication of physical activation lowering the joining energy barrier.

The unique properties of ceramics and resultant difficulties in joining with metals pose a serious technological challenge. In spite of numerous methods and techniques developed for joining ceramics with metals, the obtainment of industrial scale-produced ceramic-metal joints characterised by high operational properties will continue to be the subject of intense research. Presently it is possible to observe the development of many new concepts aimed to produce ceramic-metal joints, yet due to significant differences in component properties, all the joining methods available today prove excessively problematic to be applied in mass production.

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