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Experimental research of optimization methodology for local, resistive - heating of thin molybdenum plates

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ABSTRACT

Because of the unique mechanical and chemical behavior of molybdenum and its alloys, they become one of the most advanced materials for high-temperature heating elements, the most exposed areas of furnace, the aircraft industry and the components of the crystallization apparatus at sapphire single crystal growth. This paper presents unique design an experimental system, which shall be in future optimized through simulation model, for comprehensive analysis of important parameters of resistance heating of pure molybdenum sheet with the thickness of 0,5 mm. The specific details of the shape, size and spatial distribution of the heating electrodes based on copper and graphite are investigated. Technical solutions for generation of contact pressures as well as the mechanism for moving the sheet through the zone of thermal exposure is described in detail. Details of the control of power components of the experimental system are shown schematically in the paper. Numerical simulation of resistance heating are provided in Comsol SW, which gives optimal support for experimental analysis at different conditions of electric current and voltage exposure for resistive contacts made of copper, graphite, and combination of those two materials. Further optimization is done in the way of shape and location modification of the contact electrodes, modification of the specific contact pressure-lowering contact resistance, and modification of time of stress exposure and also the distribution of temperature fields in the exposed zones of molybdenum samples. Presented are also experimental thermal characteristics of the heated volumes of molybdenum metal after the end of the heating-response to thermal exposure using a thermal image technology.

1. Introduction

Sapphire single crystals are widely used especially in laser devices. Sapphire is in the fact an ideal material for production of so-called structures of silicon on sapphire single crystals high temperature epitaxy technology. Production of single crystal sapphire is possible by several vertical technologies such as single crystal growth by the methods like Czochralski, Verneuill or Stepanov. Method of horizontally directed crystallization growth of plate sapphire crystal elaborated in Russia at the end of 60 years by Bagdasarov. Horizontal method for the growth of the single crystal has the enormous advantage compared to the vertical progression that has a precisely pre-given orientation of the optical axis of the crystal to the surface of the growing crystal [1–3]. These process are carried out under high vacuum and temperature up to 2150 °C. As mentioned above, the horizontal method of crystallization of the single sapphire crystal provides product-crystal of the highest optical quality, so this method is the most promising even though a large number of engineering-design challenges is present. One of which is a crucible-vessel, where crystallization takes place. The container is exposed to the temperature gradient of up to 100 °C./mm at the maximum temperature of 2150 °C. in the longitudinal direction of the container, where in one part is the melt and in the adjacent part is the corundum as already growth product, i.e. single sapphire crystal. Currently, container-vessels-crystallization „boats“are made of molybdenum sheet having a thickness of 0,5 mm, made by powder metallurgy technology, i.e. by plastic deformation and sintering procedure. Specifically, the molybdenum sheet Grade M1 corresponding to the American standard ASTM B386 or GB 3877, where the chemical composition are approximately the same. The shape and dimensions currently identified molybdenum containers for single sapphire

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crystallization meet the requirements for hand-manual production and of course automatic production in the complex mechatronic deformation systems with local resistance heating of thin molybdenum sheets. Very important is the fact that deformation ability of the presented types of molybdenum sheets are minimal, in additional there is a great affinity of Mo to oxygen. This affinity has a very strong progressive initiating effect on the corrosion happening, which dominantly occur in the surface layers of molybdenum sheets [4–9].

From the presented reasons the orientation for model and experimental analysis is very important when problems related to local resistance heating of thin molybdenum sheet are considered. It deals about dynamic measurement of all electrical parameters and control elements for optimum heat deformation in the process of real container production. It is necessary to avoid any damage of the micro-structural properties of these plates.

Due to above mentioned facts; the important thing about molybdenum heating is related to very precise temperature distribution within given area of the sheet. Molybdenum sheets are well known due to their flexible properties when are heated for certain temperature. They can be formed into shapes that can be limiting for other steel materials, while application purpose is also for special industrial processes. In this study we are trying to investigate possibilities of local heating of molybdenum sheets, which shall be used for further formation of sapphire crystallization forms. For that purpose it is necessary to heat certain area to given temperature, while other area will have much different temperature. Thus controllable heating for small surfaces is required. For these purposes it is important to investigate performance of various heating components of the local resistance heating system. Direct resistance heating is a technology that is used in numerous industrial processes. One of its goals is local softening of both magnetic and nonmagnetic electrically conductive materials and workpieces for subsequent hot forming or stamping. A number of examples can be mentioned [10–13] which give an application of this technology to fast continuous procedures. The process of heating is generally characterized by a considerable consumption of electrical energy. This is particularly the case for molybdenum sheets, when the material must be heated above its hot forming temperature, which is usually about 950–1050 °C. In order to reduce the amount of energy, the process should be optimized appropriately. Nowadays the cheapest way of doing that, is in the form of computer modeling [14–16]. The mathematical simulations for direct resistance heating of molybdenum thin sheets describing the time evolution of the distribution of the current and temperature fields in the heated molybdenum work piece are given in detail in this paper. The problem, moreover, is nonlinear due to the temperature dependence of the physical parameters/electrical and thermal conductivities and specific heat/of the system, some of them vary nonlinearly, within a relatively wide range of values. For this reason the problem must be solved numerically and the results confronted with experimental measurements. In proposed paper several configuration of heating device are given, while detailed focus is given for shape and material properties of heating electrodes.

2. Possible solutions for local heating

Heating is proportional to the electrical resistance of the molybdenum sheets. High resistance, corresponding low thermal conductivity, produces large amount of heat on the material. Although the resistance heating method has been known for a long time, it has been recently used for sheet metal applications. Maki et al. [1] used the resistance heating method to heat an A 357 billet. Homogeneous temperature distribution, voltage and pressing force parameters were evaluated. It is pointed out that contact surfaces are important to achieve homogeneous heating. Maki et al. [2] also used the resistance heating method for the thermo-mechanical treatment of AA 6061.This quick treatment decreases the grain size by approximately one-half but mechanical properties were not improved considerably. Mori et al. [3] showed that the resistance heating method is suitable to eliminate springback for high strength steel. It was proposed that this method is suitable for industrial applications and remarked that surface oxidation is less than a conventional heating method due to a short heating time. Fan et. Al [4]. used the electrical resistance heating method in incremental forming operations for poor formability materials of AZ 31 and TiAl2Mn1,5 sheets. Formability of these materials was improved. Yanagimoto and Izumi [5] developed an electrical resistance heating system and produced successful geometries with Ti 64 alloy. This system has advantageous characteristics such as easy temperature control, negligible effect of heating dissipation during heating and rapid forming capability. Ozturk et al. [6] investigated the effect of temperature on formability and springback compensation for a CP 2 Titanium sheet. It was found that formability was increased and springback was substantially decreased with increase in the temperature. Mori et al. [7] used the resistance heating method for a spline forming process of an ultra-high strength steel. The uniformity of the temperature was improved by inserting copper foils between the electrodes and the side wall and by decreasing contact area.

The prototype of proposed resistance heating system is based on the study of proper heating electrode configuration from the material and geometrical properties point of view. For these purposes a precise finite-element thermal model in COMSOL was developed, while proper material determination presents the most important task. The accuracy and credibility of designed thermal simulation model was therefore optimized based on comparisons with experimental measurements. It can be found, that close proximity between simulation and measurements can be found, and thus rapid prototyping of the heating elements and their performance might be well optimized just with the use of simulation model. At the end of the paper a new knowledge about possibilities of resistance heating molybdenum thin plates is given together with future proposals for research in this application field.

3. Proposal for system requirements and experimental set-up

According to the previous description and regarding requirements for the thin molybdenum plates forming, it is necessary to characterize main system requirements of the experimental prototype. Listed below is the summary of the proposal for physical prototype, which was deduced according to the knowledge from extensive search [17].

- High productivity of the system
- Possibility to heat materials with various thickness
- Possibility of translation move
- Originality of the concept of local heating system (safe operation, reliability, long – term operation, sustainability against high temperatures)
- Possibility of parametrical settings of various physical variables (voltage, current, contact pressure, electrode materials, electrode modularity etc …)

Respecting previously listed system requirements, the design of the physical experimental prototype set-up was created (Fig. 1). At this point it must be mentioned, that proposal is relevant just for the mechanical part of whole system. The main parts can be divided into following sections: