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Review

Simulation analysis of thermal state of conducting elements with narrowings made by use of laser micromachining

R. Pawlak, A. Rosowski, M. Tomczyk, M. Walczak*

Technical University of Lodz, Division of Material Engineering and Measurement Systems I-12, Stefanowskiego 18/22, 90-924 Lodz, Poland

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ABSTRACT

Localized laser microtechnologies like microremelting, microalloying or material removal allow manufacturing of submilimeter scale elements with accuracy sufficient for applications in electronics and electrical engineering. In this respect, traditional mechanical cutting of miniature fuse links did not give satisfactory results. Here we present our new, laser-based approach to creation of conductive elements for new generation of fuses. This paper contains our results of manufacturing process and computer model-based simulations of thermal state of obtained fuse links. In particular the proper power densities for laser microcutting of holes in fuse links with Nd:YAG laser (355 nm) and fiber laser (1070 nm) were determined. Simulation analysis combined with experiments allowed estimation of the best values of laser process parameters for producing fuse links with good functional properties. Simulation of the thermal state of fuses (made in optimal conditions) has indicated their disintegration due to predicted short circuit current.

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1. Introduction

In the recent years there were some investigations concerning application of microengineering techniques to production of passive electronic elements, among other miniature fuse links. These fuses are indispensable for protection of expensive high voltage apparatus with small nominal current (e.g. 60 kV, 1 A) or for protection semiconductor devices. Conductive elements that constitute such fuse links could be produced by means of innovative technologies like thin layer deposition or laser manufacturing [1–4]. In particular, different laser microtechnologies, such as microremelting and strongly localised laser microalloying of thin FeNi/Cu wires, as well as microwelding or removal of the silver layer of a two-layered Ag/kanthal wire were used to create special areas of high electrical resistance on conducting elements. Such modified areas can play a role of micro-heaters or miniature fuse-links [1,4,5]. However, application of the above mentioned technologies to extremely precise fuse links constitutes a new challenge and reveals new problems. These fuse links have a form of stripes of foil with thickness about 0.050 mm and width less than 1 mm or wires with diameter less than 0.2 mm. Alternatively, these links could be wires of diameter less than 0.2 mm. Achieving proper functional properties of fuse links requires creation of narrowings on a conducting element. A steep decrease of cross section in narrowings is necessary for shortening of switch-off-time and pre-arcing integral [2]. The search is still on for the best way of

* Corresponding author. Tel.: +48 42 6312527; fax: +48 42 6312525.
E-mail addresses: rypawlak@matel.p.lodz.pl (R. Pawlak), adamros@wpk.p.lodz.pl (A. Rosowski), martom@matel.p.lodz.pl (M. Tomczyk), mwalczak@matel.p.lodz.pl (M. Walczak).

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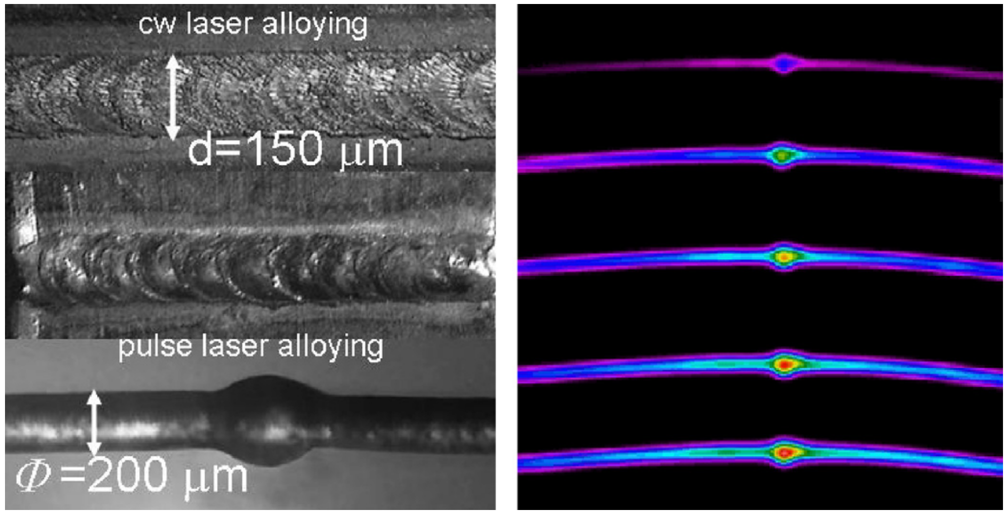

Fig. 1. (a) – A view of HRMA made by cw and pulse laser on Cu foil (thick. 0.18 mm, alloying metal–Ni) and on Cu wire (ϕ = 0.2 mm); (b) – thermographic picture of heating with current of Cu wire, diameter 0.18 mm, with HRMA.

obtaining good switching properties of fuses. Laser cutting with small heat affected zone, laser alloying of a very small area and thermal or ablative removal of conducting layers by the laser radiation are the microtechnologies which could be used for production of described fuse links. However there are still many problems associated with these applications of laser technology, that need to be solved. They concern not only proper selection of the laser beam parameters but also the choice of the most appropriate laser micromachining method (like microalloying, remelting, microcutting, ablative-removal). This work presents a new approach to solving these problems by combining process modelling of treatment and fuse link operation with experimental investigation of laser micromachining. The use of laser micromachining for creation of narrowings and hole sequences in stripes of thin metallic foil offers new possibilities for determination of limiting current and allows construction of fuse links with very small nominal current.

2. Conductive elements with high resistance on fine wires

2.1. High resistivity micro-areas on thin wires and thin foils

The idea of producing high resistivity micro-areas (HRMA) on thin wires and thin foils drove the first approach to achieve high resistance gradient along conductive elements. HRMA had been created by a special type of laser alloying of thin wires and foils, restricted to very small spatial areas comprising the whole cross-section of the element (of a volume of an order of 0.01–1 mm^3). The alloyed micro-area can manifest the electrical resistivity several dozen times greater than the resistivity of the base metal [2,4]. Among others, Cu–Ni, Al–Ni and Ag–Al areas on thin wires and metallic foils were produced (the corresponding base metals are Cu, Al and Ag, respectively).

In the case of a resistive micro-area the aim is not only to obtain fusion but also to produce a homogeneous alloy area. In the process of producing resistive micro-areas with a pulsed Nd:YAG laser the goal was to obtain the structural homogeneity of an alloyed area. The treatment was repeated with altered parameters of a laser beam. In the experiments with continuous laser beam the Nd:YAG laser (Haas Laser Technologies) with P_{max} = 5 kW was used. To obtain a uniform and homogeneous area along the whole path in alloying with cw laser the temperature of surface was measured continuously during the scanning of the beam. The signal from the pyrometer was used to control the process and the power of the beam was regulated in such a way as to ensure that the temperature of the alloyed area was constant. The beam power, depending on the foil thickness and the wire diameter (an alloying element), diminished from its initial value P_p = 100–400 W to P_k = 60–350 W. The scan speed was selected optimally from the range of 50–500 mm/min. The protective gas (N_2) was applied to avoid oxidation. Fig. 1a shows HRMA, made by pulse laser on Cu foil and Cu wire, and Fig. 1b – a thermographic picture of heating of Cu wire with current (diameter 0.18 mm) with HRMA – after 4, 8, 12, 22, 28 s following the switching of current (6 A) and last – in the steady state.

2.2. Alloying and melting of extra-thin wires

The first investigations of conductive elements with HRMA as new type of miniature fuse links has confirmed their good, but not excellent functional properties [3]. It turned out that not only high change of resistivity and heating properties should be taken into account but also the ability to melt and vaporize a conductive element in the spot determined by existing of HRMA. To meet this requirement new types of HRMAs were worked out with the goal of a further increase of resistivity accompanied by a simultaneous decrease of volume of HRMA. Two types of double-layer wires of very small diameter, consisting of the core with high electrical resistivity and the surface layer with high electrical conductivity were considered (Fig. 2). Laser micro-melting-alloying has been suggested for the purpose of producing HRMA. To this end the Cu-

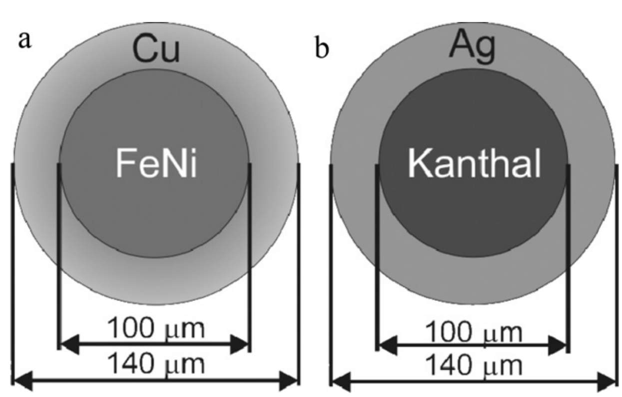

Fig. 2. Two-layered wires used for producing of new types of fuse links by laser alloying or melting.