Journal of Materials Processing Technology 237 (2016) 155–162

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Fibre laser welding of high-alloyed Al–Zn–Mg–Cu alloys

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ARTICLE INFO

Article history:
Received 9 March 2016
Received in revised form 2 June 2016
Accepted 3 June 2016
Available online 4 June 2016

Keywords:
Fibre laser welding
Al–Zn–Mg–Cu alloy
Weldability
Thermophysical property
Beam diameter

ABSTRACT

The theoretical fundamentals of laser weldability of metals are surveyed and relevant thermophysical parameters are identified – such as vapour pressure, keyhole pressure, beam irradiance, surface tension and viscosity. The derived approach for improving the laser weldability implies the use of a Yb fibre laser with an initial large beam diameter, a top-hat beam profile and a high laser power, which enables the formation of a large and stable keyhole during deep penetration welding. For validating the effectiveness of the developed approach, it is applied to various high-alloyed and hard-to-weld Al–Zn–Mg–Cu alloys. Defect-free welds are obtained even for AA7034 – the alloy with the highest (Zn + Mg + Cu) content commercially available. As reference, the same alloys are welded by using a conventional Nd:YAG laser with a small beam diameter, a Gaussian beam profile and medium laser power. The laser weldability deteriorates with increasing (Zn + Mg + Cu) content in terms of porosity and excess of penetration. The obtained results highlight the importance of the laser system used on the laser weldability of Al–Zn–Mg–Cu alloys.

1. Introduction

Al–Zn–Mg–Cu alloys exhibit severe weldability problems especially for fusion welding processes such as laser beam welding, as for example explicated by Olabode et al. (2015). In the work of Zhang et al. (2015) first results for the fibre laser welding of Al–Zn–Mg–Cu alloys are presented. Nevertheless, the obtained welds still possess some porosity. Moreover, the reasons for the slight improvement of weldability were not explicated. Up to now only by solid state joining – such as friction stir welding – completely defect-free welds for Al–Zn alloys were obtained. This was for example demonstrated by Rajakumar et al. (2011) for AA7075 and by Sharma et al. (2013) for AA7039. However, friction stir welding is characterized by a lower flexibility in comparison to the small-scale, contact-less and often much faster laser beam welding. The current lack of appropriate approaches for solving the weldability problems of Al–Zn–Mg–Cu alloys using laser beam welding prevents the exploitation of their great potential for light-weight application.

The present study deals with the theoretical fundamentals of laser weldability in order to understand the reasons for the weldability problems of Al–Zn–Mg–Cu alloys. By identifying relevant influencing factors it was possible to develop an appropriate approach for improving their laser weldability.

2. Improving the laser weldability of Al–Zn–Mg–Cu alloys

2.1. Theoretical fundamentals of laser weldability

In the work of Mondolfo (1976) it was stated, that the amount of Zn, Mg and Cu of Al–Zn–Mg–Cu alloys have a large influence on their weldability. With increasing (Zn + Mg + Cu) content the weldability deteriorates. This is the reason why high-alloyed Al–Zn alloys are generally assumed to be hard to weld or even not weldable.

For improving the laser weldability of these hard-to-weld Al–Zn–Mg–Cu alloys it is firstly essential to gain understanding about the theoretical fundamentals of laser weldability. Thus, the most important influencing factors can be identified. With the help of this knowledge it is possible to develop an approach, which considers these factors and finally may lead to improved laser weldability.

According to the work of Leong and Geyer (1998), the laser weldability is primarily influenced by the thermophysical properties of the metals intended to be laser beam welded. Since alloys are predominantly used instead of pure metals, their chemical composition has to be considered. In this regard, the keyhole stability during deep penetration laser beam welding, which is affected by the resulting thermophysical properties of the alloy as well as by the laser system used for welding, is of great importance.

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http://dx.doi.org/10.1016/j.jmatprotec.2016.06.002
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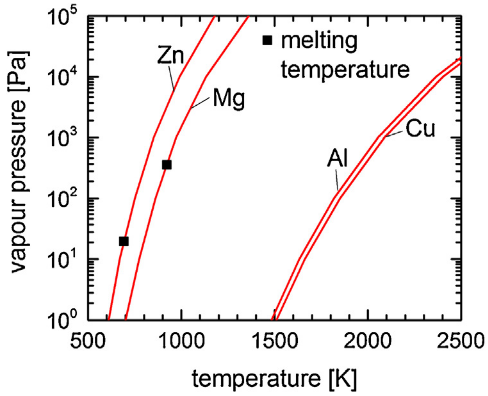

Fig. 1. Vapour pressure of Al and the main alloying elements of Al–Zn–Mg–Cu alloys (according to Haynes, 2012).

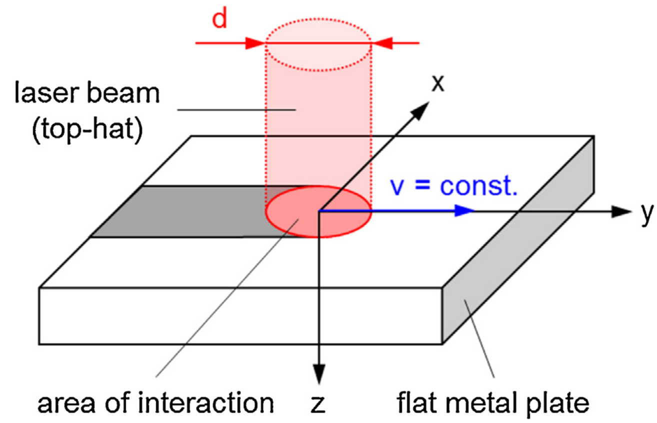

Fig. 3. Surface melting model used for the calculation of the threshold beam irradiance.

The main requirement for achieving a stable keyhole is the balance between vapour pressure, which is necessary for keeping the keyhole open, and keyhole pressure, which tries to close the keyhole. The vapour pressure arises due to the vaporisation of material during laser welding. The main alloying elements of the Al–Zn–Mg–Cu alloys – namely Zn and Mg – vaporise easily and have a high vapour pressure in comparison to Al, as it can be seen in Fig. 1. However, an irregular vaporisation generally emerges due to the local depletion of these volatile elements during laser welding of high-alloyed Al alloys. This can result in a temporary vapour pressure drop and the collapsing of the keyhole. The keyhole pressure is composed of capillary pressure, dynamic pressure, hydrostatic pressure and the ambient pressure, as stated by Beyer (1995). According to Fig. 2, the lowest keyhole pressure is achieved in case of large keyhole diameters d and low welding speeds v, provided that the material and its properties – such as sheet thickness t_s, surface tension γ and density ρ – cannot be changed. Assuming that the laser beam has an ideal irradiance distribution with a constant irradiance at the entire beam area, the keyhole diameter equates the laser beam diameter.

Another beneficial effect of an enlarged keyhole is the improved degassing behaviour. Vapour originating in the keyhole during deep penetration welding can easily be exhausted instead of leading to keyhole instabilities and the formation of porosity.

Firstly Rapp et al. (1994) has emphasised the importance of the beam irradiance on the laser weldability using the equations of Hügel (1992). Later Leong et al. (1997) took up the approach and developed a new equation for the threshold beam irradiance derived from the heat equation. In this context, the threshold beam irradiance defines the minimum beam irradiance required for melting a material at the surface where the laser beam impinges (Fig. 3). According to Leong et al. (1997), it is given by $I_{th} = k(T_m - T_0)/(AdJ_{max})$, where k is the thermal conductivity, T_m and T_0 are the melting and ambient temperature, A is the absorption of the surface and d is the laser beam diameter at the surface. The degree of interaction of laser beam and material is defined by $J_{max} = f\left(\alpha/vd\right)$, which is a function of the thermal diffusivity α, the constant welding speed v and the laser beam diameter d, as explicated by Leong et al. (1997). According to Fig. 4, the lowest threshold beam irradiance is achieved for large beam diameters, low welding speeds and a high absorption, provided that the material and its properties cannot be changed. However, if high beam irradiances are applied to metals with a low surface tension and viscosity the keyhole instabilities will aggravate, as stated by Leong and Geyer (1998). Al–Zn–Mg–Cu alloys exhibit a low surface tension and viscosity mainly due to their high Mg and Zn content, as demonstrated in the work of Hatch (1984).

2.2. Approach for improving the laser weldability

From these considerations it can be concluded, that a large beam diameter has a beneficial effect on the laser weldability of a material. There are two possibilities for increasing the diameter of a laser beam: the use of an appropriate laser optical system or the defocussing of the laser beam. However, too extensive defocussing generally leads to an unfavourable irradiance distribution and to a general reduction of the beam irradiance below the threshold value. Only the latter can be partly compensated by the increase of the laser power. For this reason, a laser with an initially large beam diameter should be preferred. In order to enable a further increase

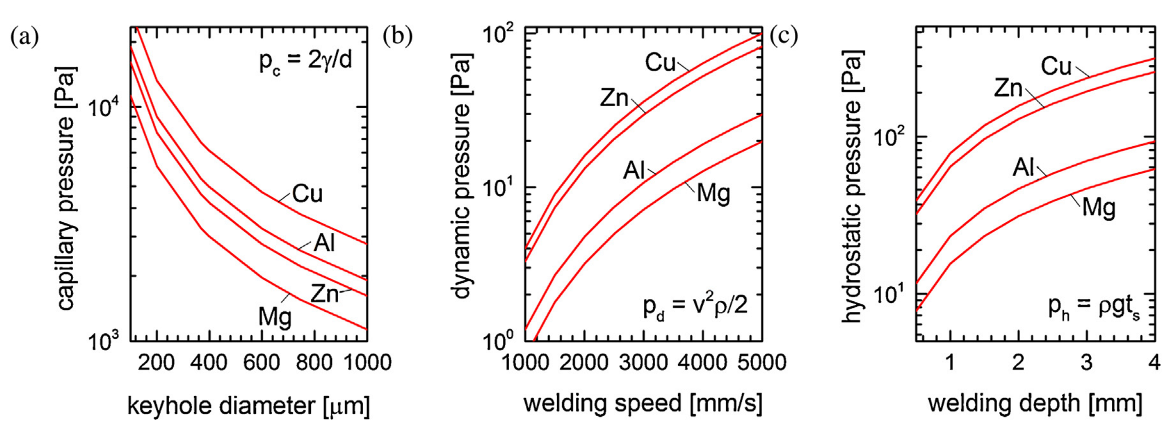

Fig. 2. Main constituents of the keyhole pressure: capillary pressure (a), dynamic pressure (b) and hydrostatic pressure (c) (calculated according to Beyer, 1995).