

Wetting properties of Nd:YAG laser treated copper by SAC solders

József Hlinka and Miklós Berczeli

Department of Automobiles and Vehicles Manufacturing, Budapest University of Technology and Economics,
Budapest, Hungary

Gábor Buza

Department of Laser Technology, Bay Zoltán Nonprofit Ltd. for Applied Research, Budapest, Hungary, and
Zoltán Weltsch

Department of Materials Technology, Pallasz Athéné University, Kecskemét, Hungary

Abstract

Purpose – This paper aims to discuss the effect of surface treatment on the wettability between copper and a lead-free solder paste. The industrial applications of laser technologies are increasing constantly. A specific laser treatment can modify the surface energy of copper and affect the wetting properties.

Design/methodology/approach – The surfaces of copper plates were treated using an Nd:YAG laser with varying laser powers. After laser surface treatment, wetting experiments were performed between the copper plates and SAC305 lead-free solder paste. The effect of laser treatment on copper surface was analysed using optical microscopy and scanning electron microscopy (SEM).

Findings – The experimental results showed that the wetting contact angles changed with the variation in laser power. Furthermore, it means that the surface energy of copper plates was changed by the laser treatment. The results demonstrated that the contact angles also changed when a different soldering paste was used.

Originality/value – Previous laser surface treatment can be a possible way to optimize the wettability between solders and substrates and to increase the quality of the soldered joints.

Keywords Microstructure, Sn-Ag-Cu, Solder, Wetting, Laser treatment

Paper type Research paper

1. Introduction

Soldering is the most popular joint technique in microelectronic and optoelectronic industries, the technologies of which are widely used in the vehicle industry (Baumli, 2015a, 2015b; Judd and Brindley, 1999; Lau, 1997; Tu, 2007; Kaptay, 2016).

Because of worldwide environmental concerns, public sentiments and market strategies, as well as governmental regulations on the use of toxic Pb in electronic products, the conventional Sn-Pb solders are under strict scrutiny. Therefore, many Sn-rich alloy systems have been developed as alternative candidate Pb-free solders, which have attracted much research and trial applications in recent years (Abtew and Selvaduray, 2000; Lau *et al.*, 2016). With a combination of process attributes (modest melting point and reasonable solderability), comparable electrical performances and good mechanical properties, the Sn-Ag-Cu system is one of the potential choices (Zhong *et al.*, 2006; Liang *et al.*, 2007).

Although great effort has been made for more than 10 years to get Pb out of the electronic industry, until now, there are still some tough barriers needed to override for a widespread and uniform industrial acceptance of favourable solder alloys

and matched materials plus processes (Garner *et al.*, 2000; Casey and Pecht, 2002). Pb-free alloys are used exercising tremendous caution nowadays (compared to the well-established Sn-Pb soldering system) because of the lack of legislation, the high cost and insufficient backup data on the usage of such alloys (Zhong *et al.*, 2006; Du *et al.*, 2015). Therefore a lot of investigations deal with lead-free soldering and properties of soldered joints made using lead-free solders (Chen *et al.*, 2015; Du *et al.*, 2015). The Sn-Ag-Cu system is one of the potential choices recommended by some organizations (Zhong *et al.*, 2006; Koscielski and Sitek, 2014).

Soldering may be defined as the joining of metals by utilizing another metal, whose melting point equals or ranges below 450°C approximately and is lower than that of the metals to be joined (Groover, 1996).

In the soldering process, the molten solder wets the substrates, and the interfacial reaction occurs at the solder-substrate interface, thus forming the soldering joints. Therefore, the wetting property of solders and substrates is crucial to the reliability of the soldering joints (Chen *et al.*, 2000; Yost *et al.*, 1993; Nobari *et al.*, 2016; Fima *et al.*, 2012).

The current issue and full text archive of this journal is available on Emerald Insight at: www.emeraldinsight.com/0954-0911.htm



Soldering & Surface Mount Technology
29/2 (2017) 69–74
© Emerald Publishing Limited [ISSN 0954-0911]
[DOI 10.1108/SSMT-01-2016-0003]

This research work was performed as part of the EFOP-3.6.1-16-2016-00014 project. The project is supported by the European Union, and co-financed by the European Social Fund, which is gratefully acknowledged.

Received 24 January 2016
Revised 11 May 2016
27 July 2016
Accepted 28 July 2016

Soldering requires a solder, substrate and flux system that are compatible with a specified soldering atmosphere and temperature profile.

In the past years, a number of researches have clarified the effects of the laser irradiation on different material surfaces, such as metals, semiconductors, polymers and multilayer materials. However, very little work has been focused on improving the material's wettability by modifying surface properties of materials using laser (Zhao *et al.*, 2006).

Lawrence *et al.* (1999a, 1999b), Lawrence and Li (1999a, 1999b), Hao and Lawrence (2004a, 2004b) found that the wettability of carbon steel and alumina/silica-based oxide could be improved by high-power diode laser irradiation and the change in wettability was attributed to three aspects: surface oxygen content; surface roughness and surface microstructure. They also found that phase change and increase in crystal size could lead to changes in surface energy.

This work experimentally determines the changes in the wetting property of copper following Nd:YAG laser treatment. The changes in surface energy were investigated using contact angle measurements of solders on copper.

2. Materials and methods

The measurements were taken applying Senju M705-GRN360-KV lead-free SAC305 solder paste, a common commercial soldering paste, with properties of a solder alloy powder, consisting of Sn (96.5 wt %), Ag (3 wt %) and Cu (0.5 wt %), and a low activity flux system.

The wetting angle of the solder was examined on Cu ETP R240 (CW004A) copper plates as substrates. This type of copper is widely used for electrical and electronic applications. Before the measurements the copper plates were ground and polished to remove the oxide layer and to reach similar surface properties in every sample and washed with 96 per cent ethanol (C_2H_6O).

The laser used in the study was Rofin DY 027-type, Nd:YAG pulsed laser with emission of 1,064 nm wavelength. The laser beam was focused directly onto a 0.4 mm diameter spot on the surface of the copper plate. During the laser surface treatment, the laser beam was traversed across the copper samples by means of a laser scanner at a speed of 500 mm/min. The laser scanning speed must be controlled properly to ensure that a 40 x 40-mm² area can be treated by laser. Different laser powers, from 100 W to 2000 W, were used in this process. The laser was used in a continuous-wave mode. Argon gas was used as the shielding gas to protect the samples from oxidation during laser irradiation with a flow-rate of 12.5 l/min.

The wetting experiments were performed by measuring the wettability using the sessile drop method (Abtey and Selvaduray, 2000), taking into account the methodological issues summarized by Sobczak *et al.* (2005).

The measurements can be performed in air or inert atmosphere. The heat required for the measurements was provided by a heat-resistant tube furnace which can ensure measuring temperatures of up to 1,473 K. In this paper, the measuring temperature was not high, and the melting temperature of the investigated solder is below 523 K.

In the initial part of the wetting angle measurements, the samples were positioned into the furnace under ambient

conditions. When the measurements were performed in an inert atmosphere, the pressure was then reduced in the chamber and the vacuum was replaced by 99.999 per cent Ar or Ni gas at 10⁵ Pa. The vacuuming and the inert gas filling processes were repeated three times. When the measurements were performed in air, these vacuuming and inert gas refilling steps were not required. Thereafter, the temperature was raised up to the measuring temperature. The contact angle values of the drop were measured directly from its images. The total uncertainty of the measured values was $\pm 0.75^\circ$.

After the wetting angle measurements, the furnace was switched off and left to cool to ambient temperatures. After that, the furnace was dismantled and the sample was removed. It was then mounted onto a resin, and one-half of it was polished. This half cross section of the alloy was used for further investigations (optical microscopy, scanning electron microscopy (SEM), etc.).

To analyse the influence of the laser treatment on microstructure, the specimens, before and after laser treatment, were sectioned using a cutting machine with a diamond-rimmed cutting blade. The sectioned specimens were mounted with epoxy and then, subsequently, polished using a cloth and a 0.1- μ m diamond suspension paste. The cross-sectioned samples on the copper surface were examined using an optical microscope and SEM.

SEM investigations were carried out using a Philips XL-30 FEG SEM machine.

3. Results and discussions

3.1 Surface microstructure after laser irradiation

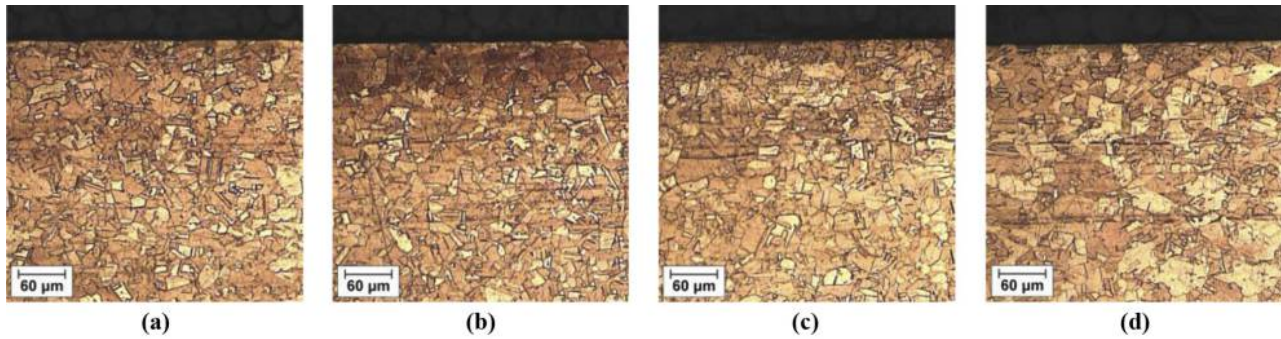
Figure 1 shows the surface layer microstructures of the optical metallographic samples before and after laser irradiation with varying laser power. It may be seen by comparing Figure 1(a)-(d) that the laser treatment did not cause noticeable changes on the copper surface layer. The observations indicate that when the laser power was 2,500 W, the heat absorbed by copper did not create molten pools, which are typically formed in case of laser surface treatments.

The absorptivity of different metals depends on the wavelength of the radiation. The used Nd:YAG laser has a wavelength of 1,064 nm. The absorptivity of copper at this wavelength is 2–3 per cent (Beyer and Wissenbach, 1998). The surface roughness measurements of the laser treated surfaces shows similar results. The roughness parameters affect wettability, which is why it is important that the laser treatment does not change the roughness parameters of the surfaces.

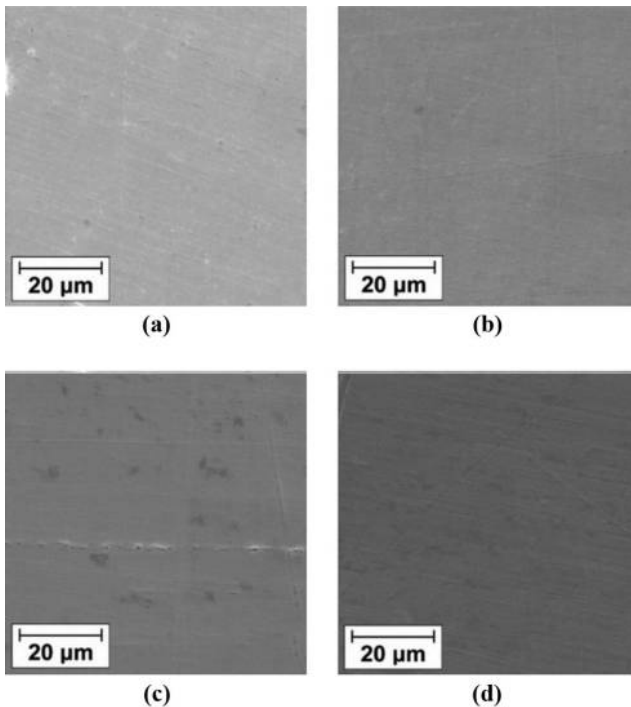
3.2 SEM observations of treated surfaces

An SEM was used for analysis of the laser-treated surfaces. Figure 2 shows the top surfaces of untreated and laser-treated (300 W, 600 W, 2,500 W) samples. The surface of Cu substrates is almost flat; however, after laser treatment, random ridges and grooves were observed.

Using laser irradiation, a fraction of the laser beam energy is absorbed by the material, thus promoting material melting, surface morphological modifications and the formation of a thermal oxide layer. The comparison among the SEM pictures reported in Figure 2 demonstrates the effect of the parameters of laser. The SEM observations demonstrated that the

Figure 1 Optical microphotographs of the surface layer microstructures after laser irradiation using varying laser power

Notes: (a) Untreated; (b) 300 W; (c) 600 W; (d) 2,500 W

Figure 2 SEM image of the Cu surface after laser irradiation using varying laser power

Notes: (a) Untreated; (b) 300 W; (c) 600 W; (d) 2,500 W

range of laser beam power used in this study did not affect the level of surface modification.

To understand how the variation in surface morphology affects wettability, the contact angle is analysed next.

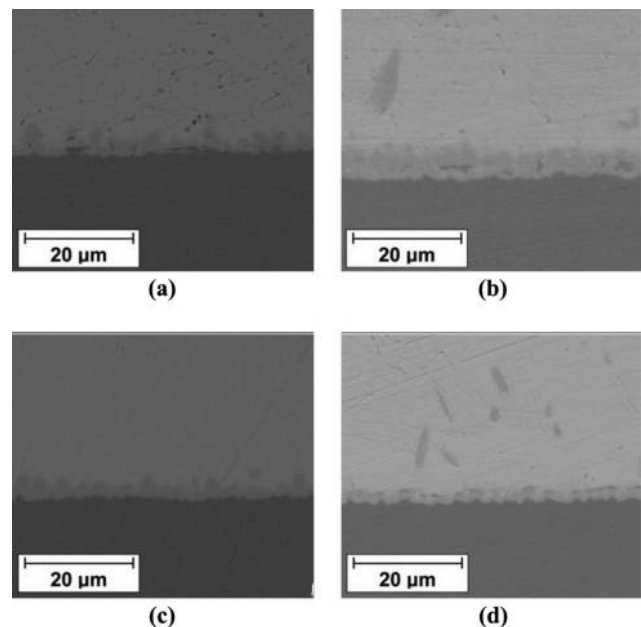
3.3 Contact angle measurements

According to the Young–Dupre equation, the contact angle is determined by the surface tensions between the solid–vapour, solid–liquid, and liquid–vapour interfaces. For the liquid–vapour interface, surface energy is not affected by the surface condition of the solid. In the wetting procedure of solder on copper, a layer of intermetallic compound (IMC) is formed at the solder–copper interface. Consequently, the surface tension of liquid and solid at the equilibrium stage is

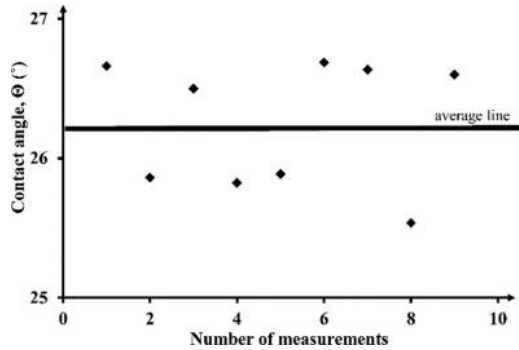
the surface tension of the solder and the IMC formed at the interface (Figure 3). Because the surface tension of solder and IMC is the same, before and after the laser surface treatment, the contact angle is only determined by surface tension at the vapour–solid interface. In Figure 3(c), the thickness of the IMC layer is more (5 μm) than that in Figure 3(a), (b) and (d) (3 μm). It is mean that the 300 W laser power results in surface properties which prefer the IMC layer growing.

Figure 4 shows nine different measurements of the natural copper surface without laser treatment. The measured results are shown in Table I. The maximum deviation of the measured contact angles from the average is $\pm 0.6^\circ$.

Figure 5 shows the micrograph of Sn–Ag–Cu solder from the untreated surface to the 2,500-W laser-treated surface. The micrograph shows the wettability characteristics of Sn–Ag–Cu solder on the copper plate after laser surface irradiation. The contact angle is observed to decrease from

Figure 3 SEM image of the IMC layer of the measured samples using varying laser power

Notes: (a) Untreated; (b) 300 W; (c) 600 W; (d) 2,500 W

Figure 4 Measured contact angles of polished, untreated Cu and SAC305 solder paste**Table I** Measured contact angles of polished, untreated Cu and SAC305 solder paste

No. of measurements	Contact angle, Θ (°)
1	26.7
2	25.9
3	26.5
4	25.9
5	25.9
6	26.8
7	26.6
8	25.5
9	26.6
Average	26.2

26.5 to 19.2, which indicates that the surface energy increased after the 2,500-W Nd:YAG laser irradiation. The results in Table II indicate the variation in wetting angles corresponding to variation in laser power. The average contact angles at any laser power are calculated from three different measurements.

When the laser power was 100–400 W, the contact angles of Sn–Ag–Cu solder on copper increased compared with that on the untreated one. When the laser power was 400–2,500 W, the contact angles decreased. This results are in rapport with Figure 2, where the IMC layer thickness is the biggest at a laser power of 300 W. This mean there is a connection

Table II Measured contact angles of laser-treated Cu and SAC305 solder paste

Laser power, P (W)	Average of contact angles, Θ (°)
Untreated	26.2
100	26.5
200	27.5
300	29.1
400	29.2
430	26.1
600	24.9
700	24.1
800	23.7
1,000	22.9
1,200	22.6
1,250	22.1
1,500	21.4
1,750	21.1
2,500	19.2

between the laser power, IMC layer thickness and contact angle.

Measured contact angles are shown in Figure 6. The pictures show the silhouette of the solder drop and the copper substrate. The horizontal green line indicates the surface of the copper substrate, and the two other green lines are the fit to the contact point and are tangential to the drop's silhouette.

Wettability measurements were performed using another SAC305 solder paste to get some information about the effect of the solder paste used in this study. The measurements were performed on copper substrates which were untreated and treated with 300 W, 700 W and 1,200 W laser power. The line on Figure 7 shows the average contact angle of the SAC305 solder paste on untreated copper substrate. The results show similar changes in contact angles as a function of laser power. The results can confirm that the contact angle changes are caused by the effect of the laser surface treatment.

The copper substrates were heat treated at 350°C in hydrogen for 30 min to change the copper properties and change the surface layers created by the laser treatment. The dashed line

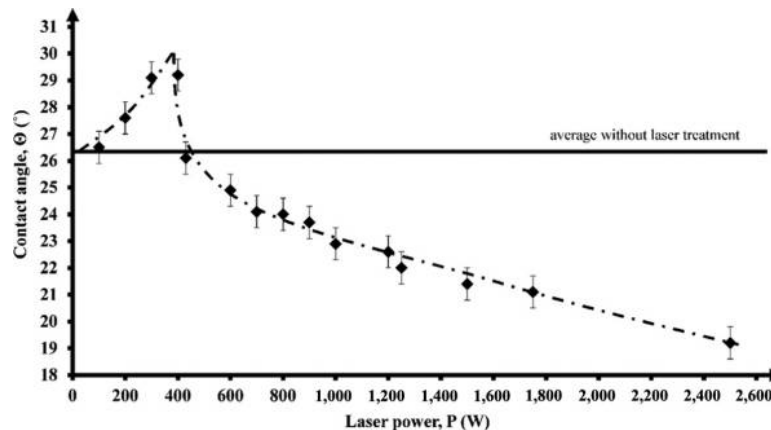
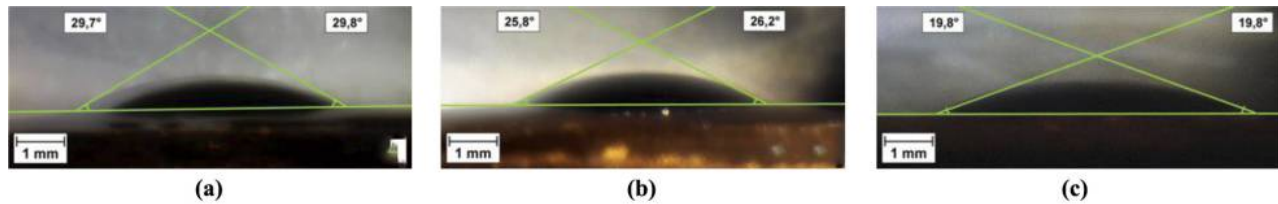
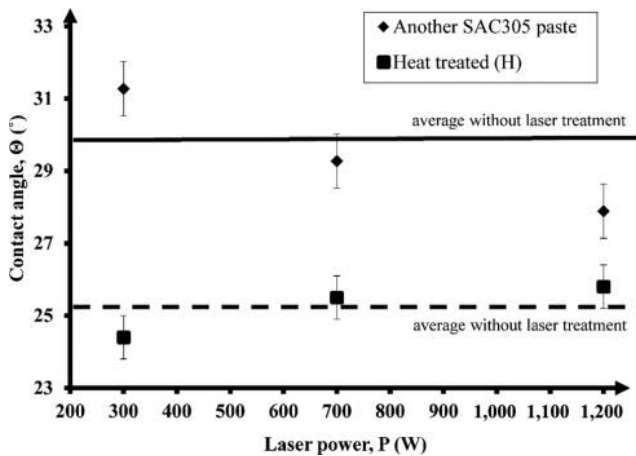
Figure 5 Measured contact angles of laser-treated Cu and SAC305 solder paste

Figure 6 Contact angles of Cu and SAC305 solder paste using varying laser power

Notes: (a) Untreated; (b) 400 W; (c) 2,500 W

Figure 7 Measured contact angles of laser-treated and heat-treated (H) Cu and SAC305 solder paste and measured contact angles of laser-treated Cu and another SAC305 solder paste

on Figure 7 shows the average contact angle of SAC305 solder paste on untreated copper substrate which was previously heat treated in hydrogen. The results show that the heat treatment in hydrogen changed the results compared to the contact angles of only laser-treated substrates. The average contact angles do not differ between the untreated samples and the laser-treated samples. The results can confirm that the heat treatment in hydrogen after the laser surface treatment changes the properties of the copper substrate and eliminates the effect of the laser treatment on wettability (Table III).

4. Conclusions

In summary, the effect of the pulsed Nd:YAG laser irradiation on the surface energy of the copper plate was investigated in

Table III Measured contact angles of laser-treated and heat-treated (H) Cu and SAC305 solder paste and measured contact angles of laser-treated Cu and another SAC305 solder paste

Laser power, P (W)	Measurements of laser-treated and heat-treated (H) Cu Average of contact angles, θ (°)	Measurements of another SAC305 solder paste Average of contact angles, θ (°)
Untreated	25.2	29.9
300	24.4	31.3
700	25.5	29.2
1,200	25.8	27.9

this paper. SEM measurements showed that the laser beam power range used in this study did not affect the level of surface modification. When the laser power was 2,500 W, the measured contact angle was minimum (19.2°). Using a laser power of 0–400 W, there was a range of process parameters which deteriorated the wettability of the solid surface. Surface treatment using a laser power of over 400 W decreased the contact angle; thus, the laser power affects the wettability of the solid surface. The changes may be related to the thickness of IMC layer. The same wettability changes can be measured using a different solder paste. The effect of the laser treatment on wettability can be eliminated by heat treating the laser-treated copper substrates in hydrogen. This can confirm that heat treatment in hydrogen after the laser surface treatment can change the wetting properties of the copper substrate and restore it to its original state.

References

- Abtew, M. and Selvaduray, G. (2000), "Lead-free solders in microelectronics", *Materials and Science Engineering Reports*, Vol. 27 Nos 5/6, pp. 95–141.
- Baumli, P. (2015a), "Solder materials with micro and nanoparticles: a review", *Materials Science and Engineering: A Publication of The University of Miskolc*, Vol. 40 No. 1, pp. 42–49.
- Baumli, P. (2015b), "Alacsony olvadáspontú ólommentes forrasztanyagok", *Anyagok Világa (Materials Word)*, Vol. 1, pp. 24–34.
- Beyer, E. and Wissenbach, K. (1998), *Oberflächenbehandlung mit Laserstrahlung*, Springer-Verlag, Berlin.
- Casey, P. and Pecht, M. (2002), *Proceedings of the Fourth International Symposium of EMP, Taiwan*, pp. 15–24.
- Chen, J., Yin, Y., Ye, J. and Wu, Y. (2015), "Investigation on fatigue behavior of single SnAgCu/SnPb solder joint by rapid thermal cycling", *Soldering & Surface Mount Technology*, Vol. 27 No. 2, pp. 76–83.
- Chen, Y.Y., Duh, J.G. and Chiou, B.S. (2000), "The effect of substrate surface roughness on the wettability of Sn–Bi solders", *Journal of materials science: materials in electronics*, Vol. 11, pp. 279–283.
- Du, Y., Li, C., Huang, B., Tang, M. and Du, C. (2015), "Research and prospect of binary high-temperature Pb-free solders", *Soldering & Surface Mount Technology*, Vol. 27 No. 1, pp. 7–12.
- Fima, P., Gancarz, T., Pstrus, J., Bukat, K. and Sitek, J. (2012), "Thermophysical properties and wetting behavior on Cu of selected SAC alloys", *Soldering & Surface Mount Technology*, Vol. 24 No. 2, pp. 71–76.

- Garner, C.M., Gupta, V., Bissessur, V., Kumar, A. and Aspandiar, R. (2000), *Proceedings of the Third EPTC, Singapore*, pp. 6–9.
- Groover, M.P. (1996), *Fundamentals of Modern Manufacturing*, Prentice-Hall, Saddle River, NJ.
- Hao, L. and Lawrence, J. (2004a), “On the role of microstructure form and dimension in surface energy changes in a magnesia partially stabilized zirconia bioceramic following CO₂ laser irradiation”, *Journal of Physics D: Applied Physics*, Vol. 37, pp. 86–92.
- Hao, L. and Lawrence, J. (2004b), “CO₂ laser induced microstructure features in magnesia partially stabilised zirconia bioceramic and effects thereof on the wettability characteristics”, *Materials Science and Engineering*, Vol. 364 Nos 1/2, pp. 171–181.
- Judd, M. and Brindley, K. (1999), *Soldering in Electronics Assembly*, Newnes, Oxford.
- Kaptay, G. (2016), “Modeling equilibrium grain boundary segregation, grain boundary energy and grain boundary segregation transition by the extended Butler equation”, *Journal of Material Science*, Vol. 51 No. 4, pp. 1738–1755.
- Koscielski, M. and Sitek, J. (2014), “Influence of the fluxes properties on quality and the microstructure of lead-free solder joints executed by selective soldering”, *Soldering & Surface Mount Technology*, Vol. 26 No. 1, pp. 2–7.
- Lau, J.H. (1997), *Solder Joint Reliability of BGA, CSP, Flip Chip, and Fine Pitch SMT Assemblies*, McGraw-Hill, New York, NY.
- Lau, C.S., Khor, C.Y., Soares, D., Teixeira, J.C. and Abdullah, M.Z. (2016), “Thermo-mechanical challenges of reflowed lead-free solder joints in surface mount components: a review”, *Soldering & Surface Mount Technology*, Vol. 28 No. 2, pp. 41–62.
- Lawrence, J. and Li, L. (1999a), “Carbon steel wettability characteristics enhancement for improved enamelling using a 1.2 kW high power diode laser”, *Optics and Lasers in Engineering*, Vol. 32 No. 1, pp. 353–365.
- Lawrence, J. and Li, L. (1999b), “Wettability characteristics of a modified mild steel with CO₂, Nd:YAG, excimer and high power diode lasers”, *Journal of Physics D: Applied Physics*, Vol. 32 No. 18, pp. 2311–2318.
- Lawrence, J., Li, L. and Spencer, J.T. (1999a), “The effects of high-power diode laser radiation on the wettability, adhesion and bonding characteristics of an alumina/silica-based oxide and vitreous enamel”, *Surface and Coatings Technology*, Vol. 115 Nos 2/3, pp. 273–281.
- Lawrence, J., Li, L. and Spencer, J.T. (1999b), “High power diode laser modification of the wettability characteristics of an Al₂O₃/SiO₂ based oxide compound for improved enamelling”, *Materials Science and Technology*, Vol. A266 Nos 1/2, pp. 167–174.
- Liang, J., Dariavach, N., Callahan, P. and Shangguan, D. (2007), “Effects of thermal history on the intermetallic growth and mechanical strength of Pb-free and Sn-Pb BGA solder balls”, *Soldering & Surface Mount Technology*, Vol. 19 No. 1, pp. 4–14.
- Nobari, A.H., Maalekian, M., Seelig, K. and Pekguleryuz, M. (2016), “Effect of Sb on wetting behavior of near eutectic Sn-Cu solder micro-alloyed with Ni and Ge”, *Soldering & Surface Mount Technology*, Vol. 28 No. 2, pp. 93–100.
- Sobczak, N., Singh, M. and Asthana, R. (2005), “High-temperature wettability measurements in metal/ceramic systems – some methodological issues”, *Current Opinion in Solid State and Materials Science*, Vol. 9, pp. 241–253.
- Tu, K.N. (2007), *Solder Joint Technology: Materials, Properties, and Reliability*, Springer, New York, NY.
- Yost, F.G., Hosking, F.M. and Frear, D.R. (1993), *The Mechanics of Solder Alloy Wetting and Spreading*, Van Nostrand Reinhold, New York, NY.
- Zhao, Z., Wang, C., Li, M., Wang, L. and Kong, L. (2006), “The effects of pulsed Nd:YAG laser irradiation on surface energy of copper”, *Applied Surface Science*, Vol. 252 No. 12, pp. 4257–4263.
- Zhong, W.H., Chan, Y.C., Alam, M.O., Wu, B.Y. and Guan, J.F. (2006), “Effect of multiple reflow processes on the reliability of ball grid array (BGA) solder joints”, *Journal of Alloys and Compounds*, Vol. 414 Nos 1/2, pp. 123–130.

Corresponding author

Zoltán Weltsch can be contacted at: weltsch.zoltan@gamf.kefo.hu