Examination of steel surfaces treated by different lasers

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Abstract. The aim of this paper is to discuss the effect of laser surface treatment with different lasers on the wettability between DC01 steel and SAC305 lead-free solder paste. The field of laser technology is in a constant state of further development. The possible applications of lasers, such as in industrial manufacturing processes and tools for material processing through welding, cutting or engraving, are plentiful. A specific laser treatment can modify the surface energy of steel and affect the wetting properties. In this work, the surfaces of steel plates were treated by Nd:YAG and CO₂ laser with different laser powers. After the laser surface treatment wetting experiments were performed between the steel plates and lead-free solder paste. The effect of laser treatment on steel surface microstructure was analyzed by optical microscopy. The wettability of solder pastes were measured with different opening time. The experimental results showed that in case of Nd:YAG laser, the wetting contact angles do not change up to 700 W laser power. Moreover, increasing CO₂ laser power results increase of the wetting angles.

1. Introduction

Soldering is the most popular joint technique in microelectronic and optoelectronic industries which technologies are widely used in the vehicle industry [1, 2]. Soldering is the process of joining two metals by the use of a solder alloy, and it is one of the oldest known joining techniques. In the soldering process, the molten solder wets the metal and reacts with a small amount of the base metal by forming intermetallic compounds. Therefore, the wetting property between solders and substrates is crucial to the reliability of the soldering joints [3-5].

During 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. Previous works found that the laser surface treatments of copper lead to wettability changes [6]. Lawrence et al. [7] found that the wettability of carbon steel, alumina/silica-based oxide could be improved by high power diode laser irradiation. The surface roughness and properties of the carbon steels treated with high power diode laser irradiation changed the surface roughness became higher and partly oxidized. The changes of the wettability was attributed to three aspects: surface oxygen content; surface roughness; surface microstructure. They also found that the phase change and the increase in crystal size could lead to the changes of surface energy.

This work experimentally determines the wetting property changes between SAC solder and laser treated DC01 steel and microstructure changes in DC01 steel following the Nd:YAG or the CO₂ laser treatment.
2. Materials and methods

The investigations were carried out on DC01 steel plates. Table 1. shows the chemical composition of the used steel. The components were measured by GDA Alpha spectroscope. This type of steel is widely used for cold forming and other applications. The plates were sectioned into 15 x 15 mm squares. Before the laser treatments the steel plates were grinded and polished to remove the oxide layer and reach similar surface properties in every sample and washed with 96 % ethanol (C$_2$H$_6$O). The used solder paste was M705-GRN360-KV. It is a SAC305 solder paste with 96.5 w% Sn 3.0 w% Ag 0.5 w% Sn content.

| Fe  | C  | Mn | Si  | P  | S  | Cr | Ni | Cu | Al | Ti | Nb 2 | Co | Zr |
|-----|----|----|-----|----|----|----|----|----|----|----|-----|----|----|
| 99.5217 | 0.0543 | 0.2630 | 0.0013 | 0.0105 | 0.0250 | 0.0257 | 0.0063 | 0.0247 | 0.0257 | 0.0003 | 0.0143 | 0.0027 | 0.024 |

Two types of lasers were used in this study a CO$_2$ and a Nd:YAG laser. The used CO$_2$ laser is an Oerlikon precision laser (LE2000T000AA) with emission of 10600 nm wavelength laser beam (Figure 1.). The laser used in continuous wave mode, its power density distribution is TEM$_{00}$. The movement of the X−Y table are controlled by CNC-program. CNC control unit accuracy is 0.005 mm. During the treatment the laser spot size was 0.4 mm, the beam offset was 0.3 mm and the speed of the table was 2000 mm/min. Argon gas was used with the flow-rate of 10 l/min. The treatments were made with 50 W, 100 W, 150 W and 200 W laser power.

![Figure 1. Oerlikon precision CO$_2$ laser.](image-url)

The other laser used in the study was Rofin DY 027, Nd:YAG laser with emission of 1064 nm wavelength laser beam (Figure 2.). The laser beam (TEM$_{00}$) was focused directly onto a 0.4 mm diameter spot on the surface of steel plate. During the laser surface treating process, the laser beam was traversed across the steel samples by means of a laser scanner at speed of 500 mm/s. The laser scanning speed must be controlled properly to ensure that a 40 x 40 mm square (4 samples) area can be treated by laser. Different laser powers from 100 W to 1000 W, were used in this process. The laser
was used in continuous wave. Argon gas was used as shielding gas to protect the samples from oxidation during laser irradiation with the flow-rate of 12.5 l/min.

![Figure 2. Rofin DY 027, Nd:YAG pulsed laser and working space with the samples.](image)

The wetting experiments were performed in a wetting angle measuring system (Figure 3.) which can measure the wettability using sessile drop method [8], taking the methodological issues summarized by Sobczak [9] into account.

![Figure 3. Wetting angle measuring equipment.](image)

The measurements can be performed in air or inert atmosphere. The heat required for the measurements provided by a resistance-heated tube furnace which can ensure the measuring temperature up to 1473 K. In this paper the measuring temperature was not high, the melting temperature of investigated solder are below 523 K.

At the beginning of the wetting angle measurements the samples were positioned into the furnace at ambient conditions. The measurements were performed in air atmosphere. 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 ±0.75°.
In order to analyze the influence of the laser treatment on microstructure, the specimens, before and after laser treatment, were sectioned with a cutting machine using a diamond-rimmed cutting blade. The sectioned specimens were mounted with methyl-methacrylate casting resin then, subsequently, ground with SiC grinding paper and polished with diamond suspension down to 1 µm. The steel surface were examined on the cross sectioned samples by optical microscope.

3. Results and discussions
The solder paste is a mixture, which contains solder alloy powder and flux. The storage time and storage conditions have effect on the usability of the solder. The flux contains some volatile components and if these components evaporate the paste becomes worse and for example not suitable for stencil printing.

3.1. Effect of solder paste age
To get some information about the effect of holding time on the wettability between the SAC305 solder [10] and DC01 steel three different pastes were examined. The three paste conditions are fresh solder paste, old solder paste (older than the double shelf life time) and old solder paste diluted with another flux (to balance the drying of the paste). The wettability measurements were made on polished and untreated DC01 substrates. Figure 4. shows the results of 9 different measurements with each solder paste.

![Figure 4. Measured contact angles of 3 different SAC305 solder paste and DC01 steel.](image)

The results show that the fresh solder paste and the old solder paste do not show differences between the wettability. The contact angles are higher, when the old solder paste used which diluted with another flux. Based on the results we can say that in our measurement system the age of the measured solder paste are not affect the wettability, if it is fresher than the double shelf life of the paste.
3.2. Effect of laser treatment with CO\textsubscript{2} laser

The surface treatment experiments have been performed with CO\textsubscript{2} laser. The parameters of the treatments were described above. The treatments were made with 50 W, 100 W, 150 W and 200 W laser power. When the laser power was 200 W the edges of the samples were discolored, burned. It could be the effect of that the grinding and polishing was not the best near to the edges of the samples and the laser absorption was bigger in this points. But this has no effect on the whole treated sample because the wetting measurements were performed in the center of the square shaped steel samples. All of the samples have Ra 0.05 μm surface roughness after the laser treatment. Figure 7. presents a visual inspection on the wettability characteristics of Sn Ag Cu solder on the DC01 steel substrate after CO\textsubscript{2} laser surface irradiation.

![Graph showing contact angles](image)

Figure 5. Measured contact angles of CO\textsubscript{2} laser treated DC01 steel and SAC305 solder paste.

The graph shows that the contact angles slightly increase when the laser power increase. Compared to the measurements when the samples were treated with Nd:YAG laser the difference shows a more gradual changing wetting angles. The surface layer microstructures of the optical metallographic samples of the CO\textsubscript{2} laser treated steel plates are shown in Figure 8. As may be seen by comparing Figure 8(a, b, c, d, e) the laser treatment did not cause noticeable change on the steel surface layer. The microstructures are look like a cold rolled steel structure.
3.3. Effect of laser treatment with Nd:YAG laser

In this study there is a target that the laser treatment does not leave an optically visible trace on the surface. Taking this objective into account, the Nd:YAG laser treatment with the parameters described above has the upper limit at 1000 W. In this power level, a little discoloration begin. Figure 5. presents a visual inspection on the wettability characteristics of Sn-Ag-Cu solder on the DC01 steel substrate after Nd:YAG laser surface irradiation. In case of the wettability measurements there were 3 measurements and on Figure 5. the average of the 3 measurements and the differences are shown for each laser power level.

Figure 6. Optical microphotographs of the surface layer microstructures of DC01 steel: a) without laser treatment, after laser irradiation with b) 50 W, c) 100 W, d) 150 W, e) 200 W laser power (CO₂).
Figure 7. Measured contact angles of Nd:YAG laser treated DC01 steel and SAC305 solder paste [11].

The graph shows that the contact angles do not change definite when the steel plates treated with up to 700 W laser power. If the laser power was 1000 W the contact angles increased. On the surface of the treated samples there is no optically determinable change up to 700 W. Surface roughness measurements verify this statement. There is no difference between the surface roughness of the treated surfaces up to 700 W laser power.

Figure 8. Optical microphotographs of the surface layer microstructures of DC01 steel: a) without laser treatment, b) after laser irradiation with 600 W laser power, c) after laser irradiation with 1000 W laser power (Nd:YAG) [11].
The measured average roughness of the samples up to 700 W laser power was Ra 0.05 μm. In case of the 1000 W laser power treatment the surface of the polished steel was optically visibly changed. The measured surface roughness of this sample was Ra 0.11 μm.

The surface layer microstructures of the optical metallographic samples of the Nd:YAG laser treated steel plates are shown in Figure 6. As may be seen by comparing Figure 6(a, b, c) the laser treatment cause noticeable change on the steel surface layer when the laser power was 1000 W. The observations indicate that when the laser power was 600 W, the heat absorbed by the steel could not lead to change of the microstructure. The microstructures are look like a cold rolled steel structure. The microstructure near to the surface layer was changed, when the laser power was 1000 W. The modified thickness was ~90 μm.

4. Conclusion
In summary, the effect of Nd:YAG and CO₂ laser irradiation on the wettability and the microstructure of DC01 steel plate was investigated in this paper. It was found that with Nd:YAG laser using a laser power of 0 W to 700 W the wettability between the steel and the solder paste do not change, namely there were no significant changes in the measured contact angles. When the laser power was 1000 W the contact angle became higher. The microstructure was influenced by the laser treatment when the laser power was 1000 W. When the samples were treated with CO₂ laser, the wetting angles of the molten solder slightly increase when the laser power increase. The microstructures do not show difference even for the used highest CO₂ laser power level.

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