Investigations on the Wire Bonding Capability on Selective Laser Melted Structures

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Abstract

The paper displays the influencing factors, as well as the possibilities and challenges that come along with the process combination of selective laser melting (SLM) and heavy wire bonding. For the investigations, test samples were created from bronze powder on a SLM-machine. Then, 300 µm aluminum and copper wires were bonded on the SLM generated structures. Wire bonding capability is analyzed on untreated as well as on post-processed surfaces. The influence and effectiveness of various steps of post-processing such as cleaning, sandblasting and grinding are analyzed. Thus, interdependencies between both manufacturing process as well as the post-processing can be revealed. The effect of surface roughness and hardness of the assembly partner are investigated as well. To draw statistically backed conclusions, all tests are performed using DoE (Design of Experiment) studies. The primary characteristics besides the bond parameters that influence the wire bonding capability are focused in this paper. The process stability as well as the interconnection quality are evaluated by optical non-destructive laser microscopic analysis. Destructive pull and shear tests and metallographic cross sections are performed to evaluate the adhesion characteristics. The process stability and the yield obtained are important factors to describe the process and to evaluate the industrialization potential. By a profound understanding of all interdependencies between the two processes, a flexible manufacturing technology for power devices can be established.

Key words

additive manufacturing, electronics packaging, heavy wire bonding, selective laser melting

I. Introduction

Digital manufacturing technologies may change the production landscape significantly by increasing manufacturing flexibility and design freedom as well as by cutting development time, enabling complex shapes and structures, and opening new fields of application. Various additively generated products are available for aerospace and healthcare sectors, but the potential of the additive manufacturing (AM) for electronic applications is yet to be explored. The selective laser melting (SLM) technology is a key driver for AM, as it allows the generation of three-dimensional metal structures from powder based raw materials, such as titanium, bronze, or aluminum. In order to translate these prospects into functional electronic applications, the ability to apply standard as well as advanced packaging technologies on printed SLM surfaces and substrates needs to be investigated [1].

Heavy wire bonding is the dominant top-level interconnect technology in power electronic assemblies [2]. Over 80 % of all top-level-interconnect techniques on power semiconductors are based on aluminum wires [3]. Not only being cost-efficient and robust, but also being a flexible interconnection process, wire bonding bears the chance to be a valuable partner for additive manufacturing technologies in creating advanced layouts and packages. In order to apply SLM into complex and highly integrated power devices, connections between AM-structures and active components, such as bare dies, as well as connections to the peripheral package need to be established. Heavy wire bonding, as a versatile packaging technology, offers the possibility to go along with the additive manufacturing’s flexibility in order to facilitate individual power packages.

II. Additive Substrate Manufacturing

Selective laser melting is an additive and generative manufacturing process in which a 3D object can be directly printed from an appropriately consistent digital CAD model. In SLM processes the object is built layer by layer from a powder bed. This distinguishes the process from established subtractive methods in which the component is formed by removal of non-associated layers of solid or semi-finished products. Herein is also one of the great advantages of additive manufacturing. It realizes a very good material utilization and increases the design freedom. Thus, most complex geometries can be produced in a flexible manner that would otherwise not be possible.

A. Selective Laser Melting

In this paper, a Concept Laser MLab cusing R machine with a laser power of 100 W has been used. The printed test samples were rectangular substrates with a variable edge length of 20-25 x 15-20 x2 mm^3. The structures are produced additively by printing of 15 µm powder layers consecutively. For a uniform distribution of energy, the powder bed is selectively irradiated. A pattern, where islands of 1 x 1 mm^2 are built, was chosen. The 3D CAD-file as well as a printed substrate just out of the machine and an isopropyl cleaned substrate with removed support structures are shown in Figure 1.

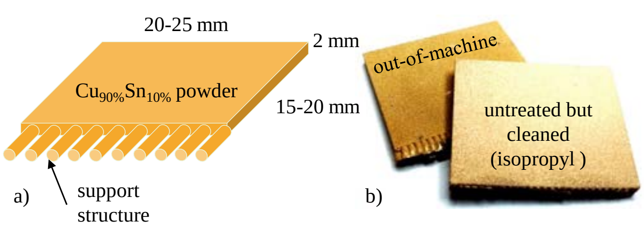

Figure 1 3D CAD file (left) and SLM test substrate (right)

The printing process is executed under inert gas atmosphere using nitrogen. As the use of pure copper powder is still under investigation due to difficulties of high reflection and unstable heating a bronze alloy in powder form was used. The CL 80CU powder consists of 90 % copper and 10 % tin. The specified tensile strength is approximately 500 MPa with a young's modulus of 120 GPa and a Vickers hardness $HV_{0.2}$ of 171±7. The particle size diameter in the powder varies from 9 µm to 50 µm.

B. Post Processing and Substrate Quality

Typically, post processing steps are needed after the fabrication of AM products. A removal of support structures and a dry or chemical cleaning process in order to remove remaining powder particles is the minimum requirement. These specimens are still called untreated substrates during this paper. If a higher surface quality is needed various technologies such as sand blasting, different forms of grinding or polishing, and CNC-milling are available. This can be especially important for functional surfaces of additively manufactured parts such as bond pads. A single method or a combination of different techniques can be used. However, since many of these possibilities are hard to apply on geometrically complex SLM components, specialized techniques such as vibratory or frictional grinding, sandblasting, and electro- or plasma-polishing must be used. The best surface quality results can be expected from a combination of several post processing methods [4].

Since surface roughness and oxidation are known to influence the wire bonding capability, especially on additive manufactured layers, both were evaluated using a Keyence VK-9700 3D laser scanning microscope [5]. Surface roughness was determined as the average distance between the highest peak and lowest valley in each sampling length called R_z according to DIN 4287. Figure 2 a) shows the untreated surface of a SLM substrate. Here, the partly melted top bronze particles are visible resulting in a very high surface roughness of $R_z > 100$ µm. After a ten second sand blast treatment, which is a standard post processing treatment for many AM technologies, these particles are removed resulting in a much smoother surface as shown in Figure 2 b). A consecutive automated grinding process eliminates all traces of contamination resulting in a very smooth surface according to the grain size of the abrasive paper. The result can be seen in Figure 2 c).

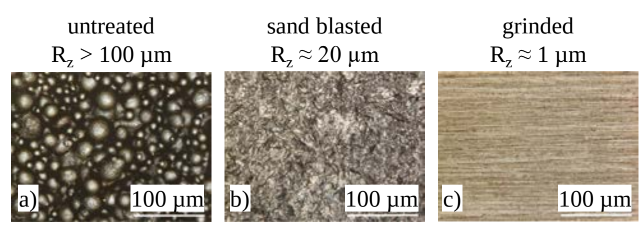

Figure 2 Surface quality of untreated (left), sand blasted (middle), and grinded (right) SLM structures

In contrast to hard and brittle alumina, which is formed in nanometer scale around aluminum wires, that can be removed during the bonding process easily, copper and bronze form manifold types of oxides and patina. These tend to be soft, more ductile and rather slippery. Therefore, they need to be removed during the ultrasonic welding process in order to create an active contact zone [6]. A higher young's modules in combination with a greater hardness hinder plastic deformation and thus the oxide layer removal, additionally.

Copper and bronze do not form uniform oxide layers.

The so-called patina may build up according to environmental conditions. Hence, it does not only contain copper-(I)-oxide or copper-(II)-oxide or a mixture thereof but also other compounds, mainly basic copper salts based on sulfate (SO_4^{2-}) and carbonate (CO_4^{2-}). The patina formation is influenced by humidity, temperature and oxygen as well as the existence of carbon dioxide (CO_2), ammonia (NH_2), sulfur dioxide (SO_2) and hydrogen sulfide (SH_2). After the grinding process oxide layers are removed and all further storing took place under N_2 atmosphere.
The surface hardness of SLM substrates as a function of their surface treatment was evaluated in comparison to a standard direct bonded copper (DBC) substrate. Table 1 shows the test conditions as well as the results.

Table 1 Vickers hardness of SLM and DBC substrates

Vickers hardness	**SLM and DBC substrates**			
	test load	*n*	*mean*	*StdEv*
SLM untreated	HV 10	3	-	-
SLM sand blasted	HV 10	3	187	1.5 %
SLM grinded	HV 0,5 / 0,05	3 / 5	162	4.9 %
DBC Substrate	HV 0,05	3	46	2.6 %

It can be seen that additive manufactured SLM substrates show a significantly, by more than three times, higher Vickers hardness in comparison to DBC substrates. Among the different surface conditions of SLM substrates variations in hardness can also be seen. Due to the extremely rough surface of undertreated SLM substrates no trustworthy value could be determined. However, untreated SLM substrates tend to feature a lower surface hardness than grinded SLM substrates. The sand blasted substrates by contrast show a 15 % higher hardness which might hint at a strain hardening effect on the surface as well as an enclosure of additional particles during the sand blasting process.

The meaning of these substrate specific differences in hardness can be understood more easily if they are put into perspective with the wire bond materials hardness. As the wire bond's hardness is influenced by the joining process as well as by the forming of the bond loop, Figure 3 shows the Vickers hardness $HV_{0.05}$ of bonded aluminum and copper wires as a function of the investigated location.

The copper wire's hardness is about three times higher than the aluminum wire's hardness. As copper shows a more intense strain hardening behavior there is also a greater difference between bond loop and bond stitch hardness on the copper wire than on the aluminum wire. As a result, aluminum wire is typically softer than the DBC substrate, whereas copper wire tends to be harder than the DBC substrate, especially after the forming induced strain hardening. On SLM substrates, in contrast, there is a high discrepancy between wire and substrate hardness. The laser melted bronze substrate is about two times harder than the copper wire and even about six times harder than the aluminum wire.

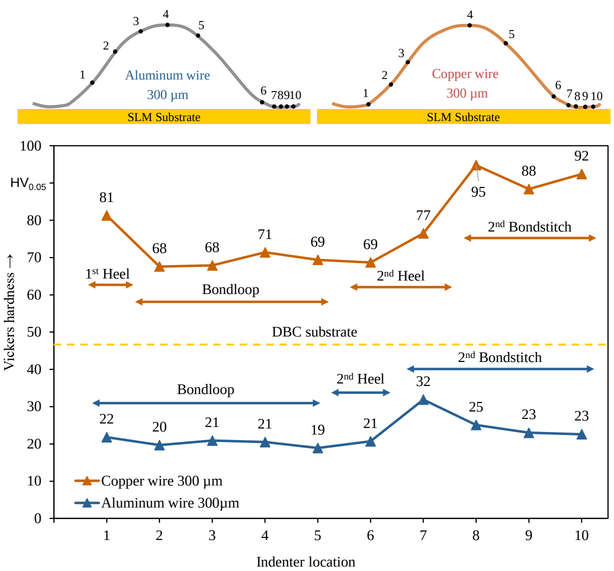

Figure 3 Vickers hardness $HV_{0.05}$ of wire bonds as a function of indenter location

III. Wire Bonding on SLM Substrates

The bonding process was performed using a semi-automatic wire bonder 5650 by F & S Bondtec Semiconductor GmbH. The wire material applied was either a 300 µm aluminum wire Al-H11 or a PowerCu wire with the same diameter provided by Heraeus GmbH & Co. KG. Furthermore, it should be emphasized that the ultrasonic frequency is fixed to 60 kHz. The distance between the first and second bond stitch as well as the aspect ratio are kept constant at 6,000 µm and 0.4 respectively. The bond force ramp is 0.5 for all tests.

Pull and shear tests on a xyztec Condor 150-3 form the basis for mechanical quality assessment. The settings for pull and shear test are based on the DVS standard 2811. Therefore, pull hook's diameter was 1,000 µm, and pull speed was 300 µm/s. For shear testing, a tool with a width of 800 µm was selected. Shear tests were performed 30 µm above ground applying a shear velocity of 300 µm/s as well.

A. Aluminum Wire Bonding

Contrary to expectations bonding of 300 µm aluminum wire is possible even on untreated SLM substrates. However, significantly higher ultrasonic power and bond forces are needed in order to overcome the high surface roughness of $R_z > 100$ µm. Thus a strong bond connection as well as a stable bond process can be established.

Running a Box-Behnke design of experiment (DoE) study with the three bonding parameters bond time T, ultrasonic power US and bond force F, as shown in Table 2, results in inconclusive dependencies of the response variables pull force F_p and shear force F_s. As the coefficient of determination R^2_{adj} of the derived statistical model is too low to draw any meaningful conclusions strong additional influencing factors need to be present.

Table 2 DoE study of aluminum wire on untreated SLM substrate

Al DoE on untreated SLM substrates	**Box-Behnke design**			
	unit	*-1*	*0*	*1*
Al bond time T_{Al}	ms	50	275	500
Al ultrasonic power US_{Al}	digits	200	355	510
Al bond force F_{Al}	cN	700	1250	1800

Looking at a cross section of an aluminum bond stitch on untreated SLM substrate, as pictured in Figure 4, explains why on the one hand significantly higher bonding parameters are needed and why on the other hand extremely high shear forces can be obtained without seeing a direct correlation to the bonding parameters.

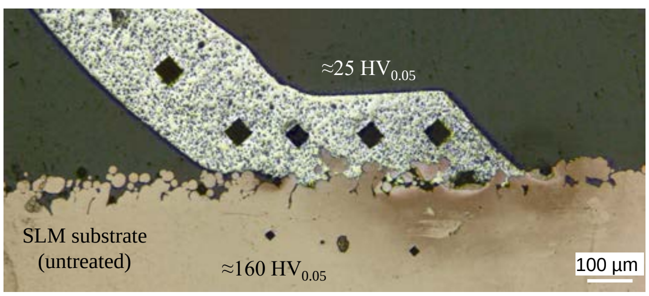

Figure 4 Cross section of aluminum bond stitch on untreated SLM substrate

The one and a half to two times higher bond parameters force the considerably softer aluminum to flow around the peaks of roughness. Thus not only a material fit by the diffusion processes but also a form fit is established. This, however, results in unpredictable bond quality as the result is mainly influenced by the SLM substrate's surface structure which varies significantly along the substrate's surface. During shear testing a mix of wire material and substrate material might have been shared, resulting in high but inconclusive shear results.

B. Copper Wire Bonding

Under the given machinery limits on ultrasonic power and bond force no stable copper wire bonding process could be established on untreated SLM substrates. The same holds true for bonding on sand blasted substrates which do not offer an adequate surface quality. For this reason, and as it is expected to gain a higher level of relevance, copper wire bonding was investigated on grinded SLM substrates. Table 3 shows the parameter levels of the face centered central composite response surface DoE. In total 30 replications for each of the 20 runs were conducted and used for 20 shear and ten pull tests at each factor level.

Table 3 DoE study of copper wire on grinded SLM substrate

Cu DoE on grinded SLM substrates	**Response surface design**					
	unit	-α	-1	0	+1	+α*)
Cu bond time T_{Cu}	ms	200	200	350	500	500
Cu ultrasonic power US_{Cu}	digits	400	400	455	510	510
Cu bond force F_{Cu}	cN	1000	1000	1400	1800	1800

*) machine limit

Using a p-value of 0.05 results in linear dependencies of the pull and shear force on bond time and ultrasonic power. Bond force in contrast, shows linear and squared influences on pull and shear test values. This results in a higher influence of bond force on the much harder SLM substrates than on DBC substrates. Furthermore, it emphasizes the relevance of the substrate on the copper wire bonding process itself. R^2_{adj} is at comparable levels to copper wire bonding DoEs on DBC substrate. Thus, a model based process window for wire bonding on grinded SLM substrates can be derived and compared to the bonding process on DBC substrate. The results are given in Figure 5.

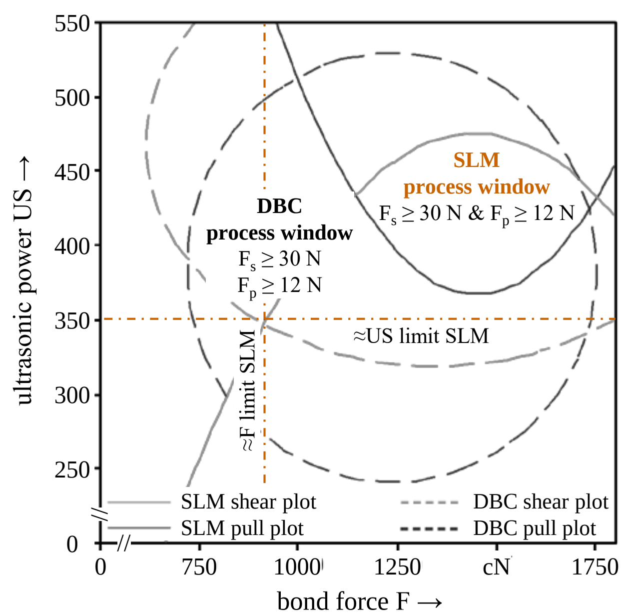

Figure 5 Model based process windows for 300 µm copper wire on DBC and SLM substrates with respect to minimal pull and shear force levels

The maximal shear values are slightly lower than on DBC substrates, whereas pull values are almost identical. The failure modes for pull and shear tests are similar with no lift-offs although the shear nuggets tend to be smaller on the much harder SLM substrates. Standard deviation is comparable below 10 % for both substrate types. Although the process optimum on both substrates is relatively close together, the overall model based process window is significantly smaller on laser melted bronze substrates if identical shear values of $F_s > 30$ N are requested. When adjusting for the lower maximal shear forces on SLM surfaces a similar stable process can be set up. The recommended ultrasonic power on the very smooth SLM surface of $R_z \approx 1$ µm is about 10 % lower than the optimum on mechanically polished DBC with $R_z \leq 6$ µm. The model based bond force optimum on SLM substrate, however, is about 15 % higher than on DBC substrate. This finding coincides with earlier studies on the influence of surface roughness on copper wire boding [7]. The influence of surface roughness is also reflected in the interface formation and can be visualized in a cross section as seen in Figure 6.

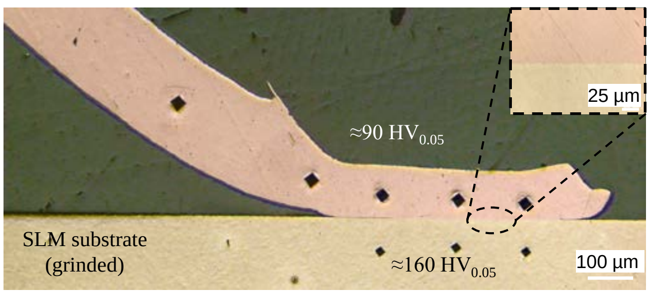

Figure 6 Cross section of copper bond stitch on grinded SLM substrate

The cross section shows a perfectly flat substrate with no deformation from the previous bonding process. The interface is free of vertical cracks that could typically be seen on DBC substrates when applying similar bond parameters [8]. Hence, the resulting interface is similar to the one of aluminum bonds on DBC surfaces. The dominant cause for this parallelism can be seen in the hardness ratio. Both for Al-wire on DBC substrates and for Cu-wire on SLM substrate the substrate's surface hardness is about 2.3 times the wire's initial hardness.

IV. Conclusion and Outlook

Selective laser melted structures offer substantial bonding capability for aluminum as well as copper wire. If process parameters are increased adequately wire bonds can even be placed on untreated and extremely rough SLM surface structures. Nevertheless, a matching post process is recommended in order to create defined surface structures with respect to chemical and mechanical surface characteristics. This allows for reduced bond parameters providing highly stable mechanical joint formations as well as predictable and reliable processes. The significantly harder surface structures of laser melted substrates prevent crack formation during the manufacturing process. Whether this results in an even more stable bond connection needs to be tested in passive as well as active reliability tests.

In order to transfer the full potential of additive manufacturing technologies into electronics production, a complete process chain has to be established, investigated and qualified. All intelligent mechatronic products are a combination of various materials, components and process technologies. Their material and process properties have to be understood on single process level as well as on the system level. Therefore, a profound knowledge of each process as well as the process interdependencies has to be established.

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