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## Picosecond laser microvia drilling of ABF material using MHz burst mode

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## PAPER

## Picosecond laser microvia drilling of ABF material using MHz burst mode

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Daniel Franz<sup>1</sup> , Tom Häfner<sup>2</sup>, Kay Bischoff<sup>1</sup>, Jonas Helm<sup>1</sup>, Tim Kunz<sup>2</sup>, Stefan Rung<sup>2</sup>, Cemal Esen<sup>3</sup> and Ralf Hellmann<sup>1</sup><sup>1</sup> Applied Laser and Photonics Group, University of Applied Sciences Aschaffenburg, Würzburger Straße 45, 63743 Aschaffenburg, Germany<sup>2</sup> Schmoll Maschinen GmbH, Odenwaldstraße 67, 63322 Rödermark, Germany<sup>3</sup> Applied Laser Technologies, Ruhr University Bochum, Universitätsstraße 150, 44801 Bochum, GermanyE-mail: [Daniel.Franz@th-ab.de](mailto:Daniel.Franz@th-ab.de)**Keywords:** ultrashort pulsed (USP) laser, laser drilling, Ajinomoto build-up film (ABF), printed circuit board (PCB), ablation threshold, metallography, heat accumulation**Abstract**

We report on a comprehensive study of laser percussion microvia drilling of Ajinomoto build-up film (ABF) material using an ultrashort pulsed laser in MHz burst mode. After laser processing, microvia drilling quality is being evaluated by the fabricated diameter and taper using laser scanning microscopy and metallography. The influences of the incubation effect, heat accumulation and shielding effects as a result of pulse to pulse interactions are being discussed on the ablation threshold, penetration depth and laser microvia drilling quality. We find that an increasing heat accumulation in MHz burst mode processing is responsible for the void formation and delamination of the insulating ABF layer. Therefore, the parameter clearance is introduced to evaluate these effects on the microvia sidewalls. For a comparable clearance, applying 2 intra-burst pulses achieves an average reduced taper of down to 19.5% compared to single pulse mode. At the same time, a reduced laser drilling time of 16.7% per microvia highlights the enormous potential of the MHz burst mode for laser drilling of ABF material in printed circuit board fabrication.

**1. Introduction**

The trend towards miniaturized high-performance electronic components driven by increasing demands on their functionality requires a high-density electronic packaging and interconnection technology. Hence, laser drilling has been intensively studied for various materials used in interconnect devices, such as, e.g., ceramics or different printed circuit board (PCB) materials [1–6]. In particular, ultrashort pulsed (USP) laser percussion drilling has been established for the fabrication of blind vias, so-called microvias, to inner conductive layers in multi-composite PCB material [5–8] with small diameters of  $< 10 \mu\text{m}$  [9, 10]. To ensure reliable electrical interconnections with a high thermal durability, the capture pad should be spatially exposed as much as possible, typically in a range of 70%–90% with respect to the upper microvia diameter [11]. In addition to the most common printed circuit board substrate FR-4, an epoxy resin filled with spherical glass particles called Ajinomoto build-up film (ABF) material is gaining interest as an insulating layer [7, 11–14].

An USP laser enables material ablation with small focal diameter and negligible thermal stress due to its short laser pulse duration in the picosecond and femtosecond range [8, 15]. Characteristic nonlinear absorption mechanisms are the result of very high pulse peak intensities of above  $10^{13}$ – $10^{14} \text{ W/cm}^2$  [16, 17], allowing an absorption of even transparent materials such as polymers and glasses [18, 19]. The tremendous interest and potential of USP lasers has led to an ongoing development and therefore high average powers of 1kW and more are nowadays available for laser micromachining [20–23]. Consequently, the arising laser pulse energies of up to some 100  $\mu\text{J}$  lead to a laser fluence that is significantly above the well-known optimum for maximizing the ablation efficiency and rate [24]. For scaling the laser pulse energies closer to the optimum ablation efficiency,

so-called laser burst mode can be used to split a laser pulse into at least two and typically up to a few hundred intra-burst pulses with a temporal intra-burst interval in the nanosecond regime [24–31].

However, within the timescale of a few nanoseconds between successive intra-burst laser pulses, several pulse to pulse interactions occur and their significant influences on processing efficiency and quality in laser micromachining have to be considered [6, 32–38]. Even with ultrashort laser pulses, a fraction of the laser pulse energy remains in the substrate as heat during the ablation process [26, 36]. Heat accumulates over time if the time interval between successive laser pulses is insufficient to dissipate the induced heat into the surrounding material, which in turn is limited by the material-specific thermal conductivity [37, 39]. Furthermore, interaction of laser pulses with laser-induced plasma and ejected particles has to be taken into account, since individual intra-burst pulses can be absorbed, scattered or reflected [32, 40]. These shielding effects are perceptible in laser micromachining of metals using MHz burst mode, observing a remarkably decrease of the ablation efficiency for an even number of intra-burst laser pulses [26, 34, 41]. In addition, a change of the absorbance of ultrashort pulsed laser processed surfaces is reported for metals and dielectrics [33, 42, 43] for laser bursts in the MHz range. For example, the absorbance of copper is 49% after processing in single pulse mode and increases to 60% when using MHz burst mode with a number of intra-burst pulses of  $N_{BP} = 3$  at a wavelength of  $\lambda = 532$  nm [42].

Several studies and simulations of laser drilling of metals [28, 41, 44], dielectrics [45] and glasses [46, 47] have reported improved ablation efficiency, ablation rate, ablation volume, penetration depth and drilling quality as a consequence of using laser bursts in the MHz regime. The results are mainly attributed to heat accumulation and are discussed in terms of laser-induced shielding effects by plasma or ejected particles and incubation effects as a result of pulse to pulse interactions of successive intra-burst laser pulses. In contrast to these studies on laser drilling of single component materials with USP lasers in MHz burst mode, the effects of pulse to pulse interactions in laser drilling of multi-composite materials such as ABF material for PCB fabrication have not yet been investigated. Hence, the aim of this study is to fundamentally understand the impact of pulse to pulse interactions in laser percussion drilling of ABF substrate with MHz bursts on the ablation threshold, penetration depth as well as drilling quality of microvias. Therefore, bore craters are generated into ABF material under various MHz burst configurations and evaluated by laser scanning microscopy and metallography.

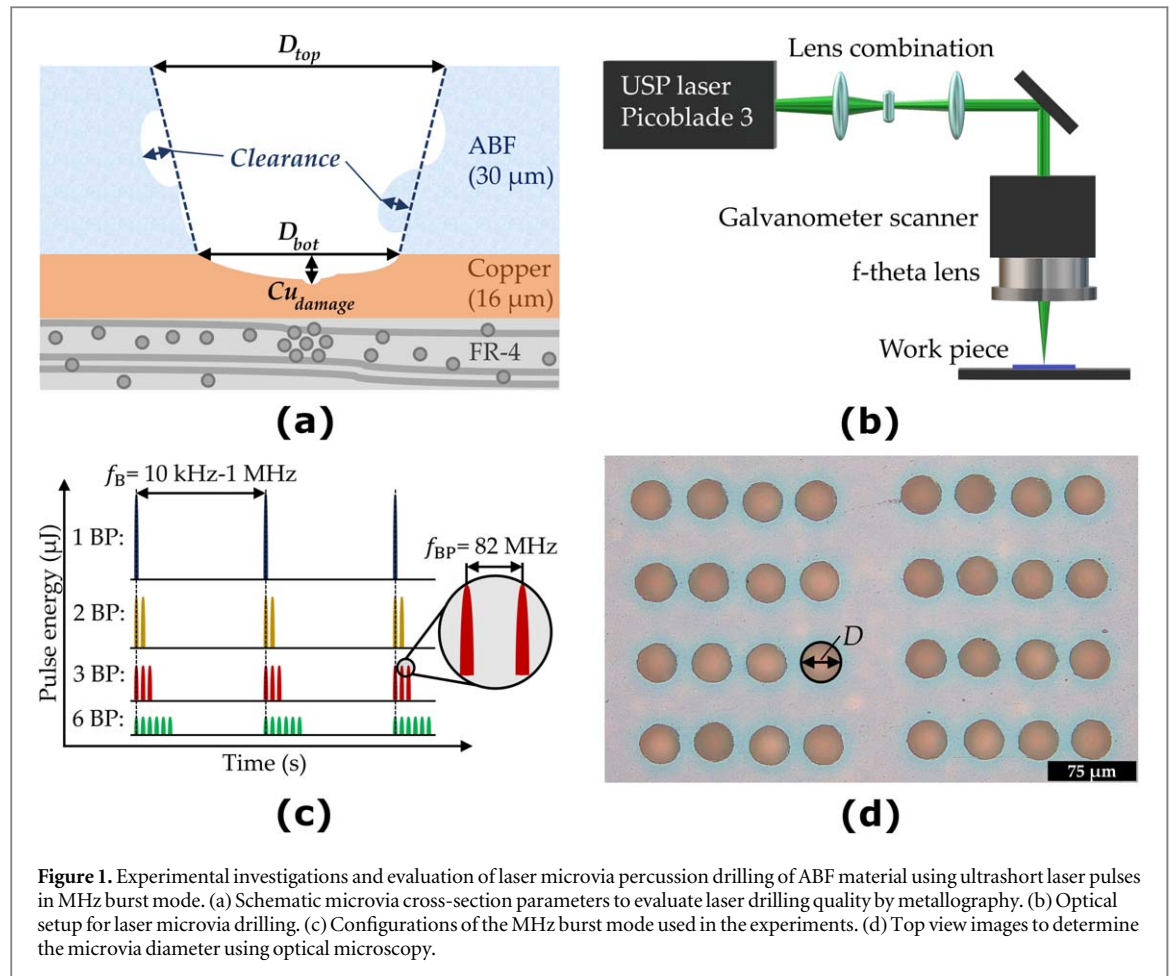
## 2. Experimental setup and sample preparation

Experimental investigations of laser microvia percussion drilling in ABF material are performed using a high-power USP laser (Lumentum, Picoblade 3) with a laser pulse duration of  $\tau = 10$  ps, a wavelength of  $\lambda = 532$  nm and a beam quality of  $M^2 < 1.3$  in MHz burst mode. In all experiments, GX-T61 ABF PCB material with a layer thickness of  $30 \mu\text{m}$  and a  $16 \mu\text{m}$  thick inner copper layer is examined, cf figure 1 (a). An overview of the thermal and dielectric properties of the studied ABF substrate is provided by Hichri *et al* [14] and Nair *et al* [48]. The simplified optical setup for sample processing is depicted in figure 1 (b), wherein a combination of biconvex and plano-concave lenses is used to adapt the raw beam diameter to  $d_0 = 3\text{mm}$  ( $1/e^2$ ). For deflection and subsequent focusing of the laser radiation, a combination of a 2D galvanometer scanner (Newson, RTA-AR-800-3G) and a telecentric f-theta lens (LINOS F-Theta-Ronar 515–540 nm, fused silica) with a focal length of  $f = 100$  mm is applied. The laser focus diameter of  $d_f = 29 \mu\text{m}$  ( $1/e^2$ ) is calculated by substituting the experimental used data in equation (1) [6].

$$d_f = \frac{4 \cdot f \cdot \lambda \cdot M^2}{d_0 \cdot \pi} \quad (1)$$

The study evaluates the ablation behavior of ABF material and copper as well as the laser microvia drilling quality using a number of intra-burst pulses of  $N_{BP} = 1–6$  and an intra-burst pulse repetition rate of  $f_{BP} = 82$  MHz (consequently a time interval between successive pulses of  $\Delta t_{BP} = 12$  ns), cf figure 1 (c). For each bore crater, both the total energy input and the intra-burst pulse energy distribution was maintained constant. Therefore, the pulse energy in MHz burst mode has been set accordingly by adjusting the gain factor of each intra-burst pulse. For example, to compare the results with a single pulse mode (1 intra-burst pulse) at a laser pulse energy of  $E_{BP} = 30 \mu\text{J}$ , the laser pulse energy is reduced to  $E_{BP} = 10 \mu\text{J}$  using 3 intra-burst pulses. First, the damage threshold method based on Liu [49] is used to determine the ablation thresholds of GX-T61 ABF material and pure copper material with a sample thickness of  $500 \mu\text{m}$  at a laser burst repetition rate of  $f_B = 10$  kHz and 1 MHz with laser fluences of up to  $7.6 \text{ J cm}^{-2}$  and a number of laser bursts of  $N_B = 15$ . To evaluate of the ablation threshold of the PCB materials, first the laser fluence  $F_{BP}$  is calculated according to

$$F = \frac{E_{BP}}{A} = \frac{E_{BP}}{w_0^2 \cdot \pi} \quad (2)$$



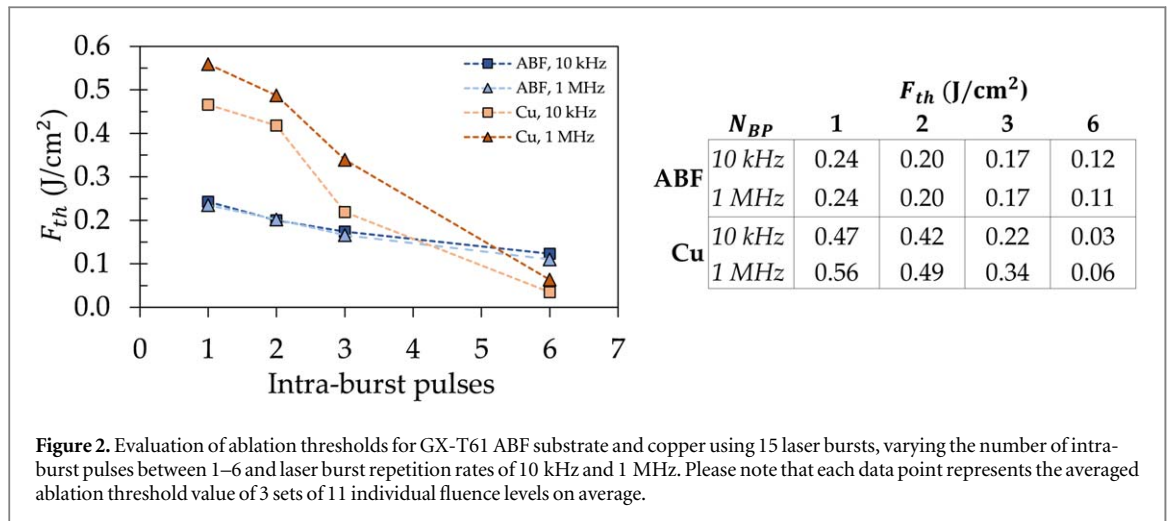
**Figure 1.** Experimental investigations and evaluation of laser microvia percussion drilling of ABF material using ultrashort laser pulses in MHz burst mode. (a) Schematic microvia cross-section parameters to evaluate laser drilling quality by metallography. (b) Optical setup for laser microvia drilling. (c) Configurations of the MHz burst mode used in the experiments. (d) Top view images to determine the microvia diameter using optical microscopy.

where  $E_{BP}$  is the laser pulse energy and  $w_0$  the radius of the beam waist ( $1/e^2$ ) [6]. The logarithmic representation of the squared drilling radii generated as a function of the laser fluence is then used to determine the material-specific ablation threshold  $F_{th}$ .

After studying the ablation thresholds, the microvia formation is evaluated in terms of ablation volume, diameter and depth in increments of 2 laser bursts using a 3D laser scanning microscope (Keyence VK-X200) at a laser burst repetition rate of 200 kHz.

Furthermore, the percussion drilling quality of microvias in ABF substrate is evaluated using different MHz burst configurations in terms of fabricated microvia diameter and taper. The taper is defined by the ratio of the upper ( $D_{top}$ ) and the lower ( $D_{bot}$ ) microvia diameters [5, 6] and is determined by optical microscopy (Leica DM6000 M), cf figure 1(a). For metallographic preparation, drilling grids were generated into target material applying laser pulse energies of  $E_{BP} = 2.5\text{--}30 \mu\text{J}$ , a number of intra-burst pulses of  $N_{BP} = 1\text{--}6$  and a number of laser bursts between  $N_B = 30\text{--}36$  at a laser burst repetition rate of  $f_B = 1 \text{ MHz}$ . After laser processing, top view images were first taken using optical microscopy to determine the diameter  $D$  of the microvias, cf figure 1(d). Afterwards, drilling grids were embedded by a 2-component synthetic material based on modified polyester resin (Demotec 15 plus). Finally, the hardened material was removed with a grinding machine (Latzke LS3V) to examine the microvia drilling quality in cross sections. As voids and delamination occur within the ABF layer after laser drilling, the parameter clearance is introduced for its evaluation. The clearance is in turn defined by the maximum deviation with respect to a line between the lower and upper microvia diameter for each sidewalls, cf figure 1(a). To obtain high-resolution images of the microvias, the polished samples were first treated with acetone and then sputtered with a thin conductive gold layer. Images were then captured using a scanning electron microscope (SEM) (Tescan MAIA3) with an acceleration voltage of 5 kV.

A detailed overview of the laser parameters used in the experimental investigations of laser microvia percussion drilling in MHz burst mode for analyzing of the ablation threshold, penetration depth, microvia diameter and taper is provided in table 1.



**Table 1.** Overview of laser parameters used to analyze the quality and process efficiency of laser microvia percussion drilling in MHz burst mode.

Constant laser parameters	
Wavelength $\lambda$ (nm)	532
Laser pulse duration $\tau$ (ps)	10
Beam quality $M^2$	< 1.3
Intra-burst repetition rate $f_{BP}$ (MHz)	82
Variation of laser parameters	
Laser pulse repetition rate $f_B$ (MHz)	0.01–1
Laser fluence $F_{BP}$ (J/cm <sup>2</sup> )	< 7.6
Number of laser bursts $N_B$	2–36
Number of intra-burst pulses $N_{BP}$ (MHz)	1–6

### 3. Results and discussion

#### 3.1. Ablation behavior in MHz burst mode

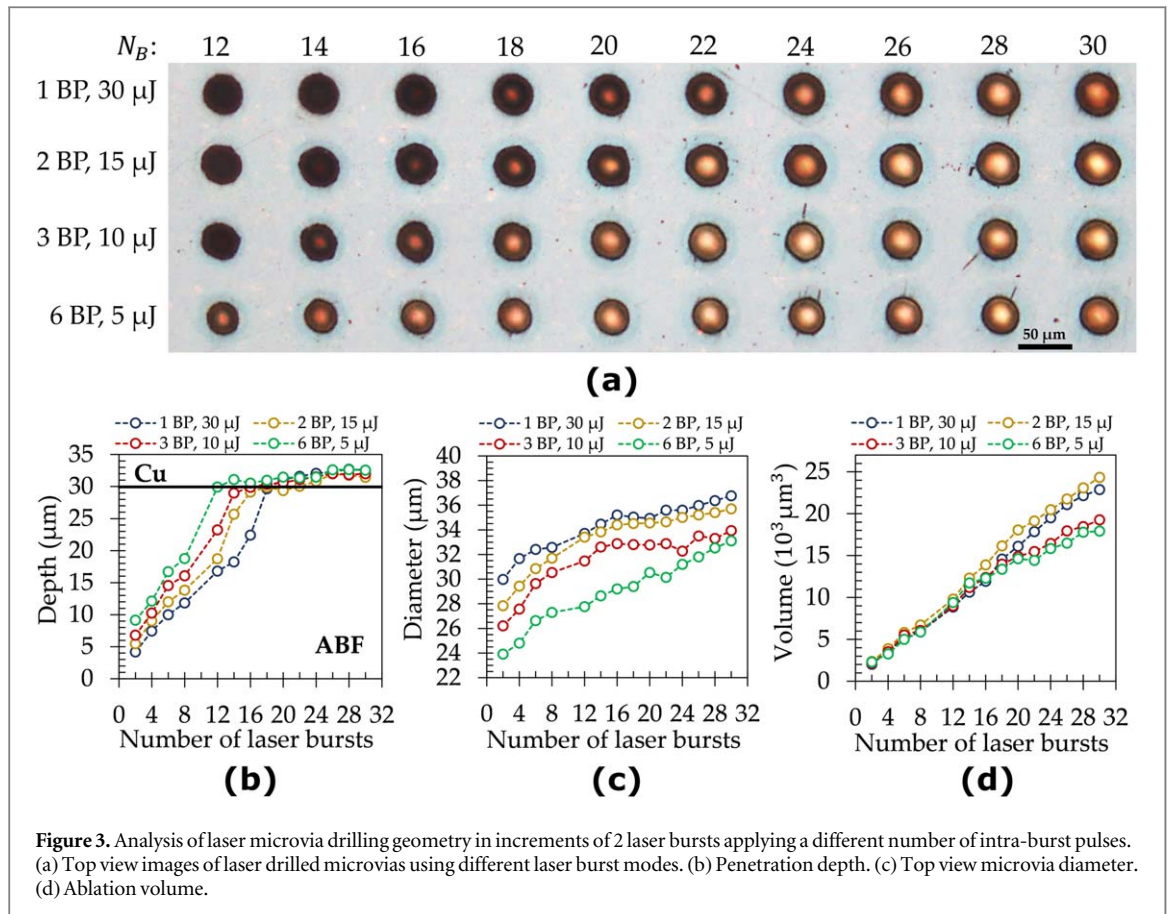
##### 3.1.1. Ablation threshold

In order to evaluate the potential of picosecond laser pulses in MHz burst mode for percussion drilling of microvias into PCB material, firstly, a fundamental characterization of the ablation behavior of process involved materials is mandatory. Hence, the ablation thresholds of GX-T61 ABF material (dielectric layer) and pure copper (conductive inner layer) are determined.

An overview of the achieved ablation thresholds  $F_{ths}$  for copper and ABF depending on the number of intra-burst pulses is shown in figure 2. It is evident that the ablation thresholds are consistently decreasing with an increasing number of intra-burst pulses for both ABF material and copper, whereby the drop of the graphs are significantly greater for copper. This results in a lower ablation threshold for copper compared to ABF material using 6 intra-burst laser pulses for both laser burst repetition rates, although the ablation threshold for copper is up to 2.3 times higher in single pulse mode. At laser burst repetition rates of  $f_B = 10$  kHz and 1 MHz, the ablation threshold of ABF in single pulse mode of  $F_{th} = 0.24$  J cm<sup>-2</sup> is more than halved by using MHz burst mode. For copper, a substantially drop of up to 90.4% is obtained for applying 6 intra-burst pulses compared to the single pulse threshold of  $F_{th} = 0.51$  J cm<sup>-2</sup>.

The decrease of the ablation thresholds for both materials with an increasing number of intra-burst pulses is attributed to the incubation effect [29, 50, 51]. This phenomena is ascribed to the accumulation of laser-induced chemical and structural changes as well as plastic deformation of the substrate as a result of thermal stress fields [52, 53]. In addition, an enhanced absorbance of the laser processed surface using MHz burst mode as a result of its higher roughness can support the ablation process. This was demonstrated by Jaeggi *et al* [33] and Neuenschwander *et al* [42] for copper and silicon with an increasing number of intra-burst pulses.

In contrast to the dielectric, copper exhibits a dependency of the ablation threshold of the laser burst repetition rate. The ablation threshold is consistently about 0.08 J cm<sup>-2</sup> lower for  $f_B = 1$  MHz compared to



**Figure 3.** Analysis of laser microvia drilling geometry in increments of 2 laser bursts applying a different number of intra-burst pulses. (a) Top view images of laser drilled microvias using different laser burst modes. (b) Penetration depth. (c) Top view microvia diameter. (d) Ablation volume.

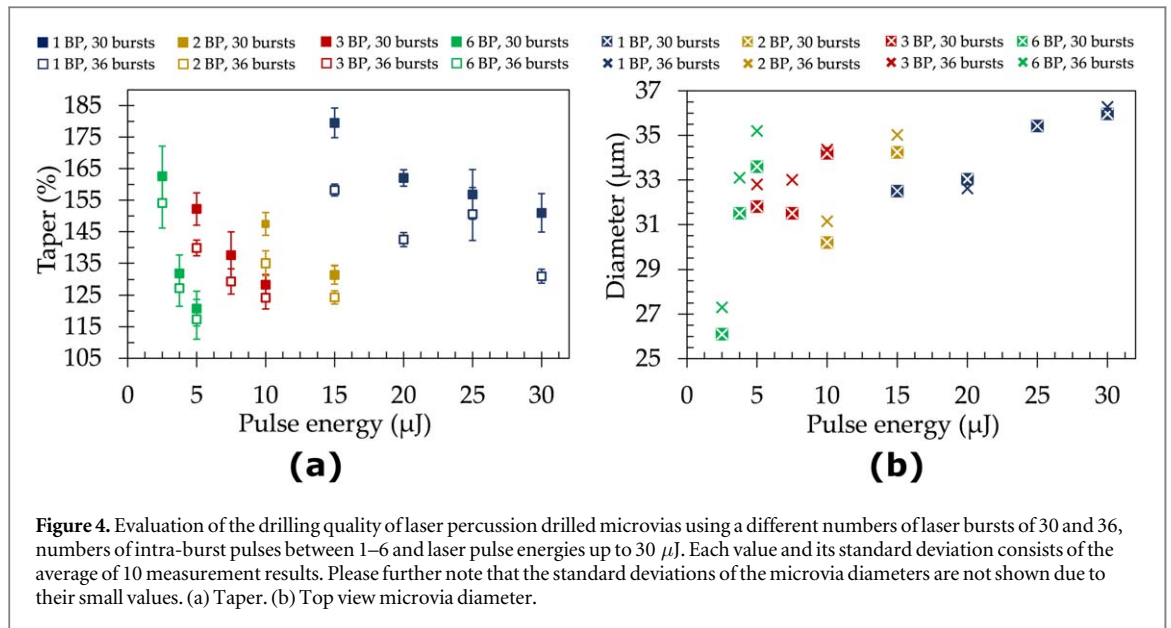
$f_B = 10$  kHz. This is associated to the different thermal properties and especially heat dissipation of both materials. Whereas copper provides a high thermal conductivity between 377–385 W/mK [54, 55] and is thus capable to dissipate the occurring heat at higher laser burst repetition rates into the surrounding material, the multi-component ABF substrates are assigned to have low values between 0.5–2.5W/mK [56]. Therefore, we assume that strong heat accumulation already occurs at a laser pulse repetition rate of  $f_B = 10$  kHz for processing ABF material. For this reason, no significant difference in ablation threshold is observed compared to a higher laser burst repetition rate of  $f_B = 1$  MHz.

### 3.1.2. Penetration depth, diameter and ablation volume

The ablation volume, penetration depth and diameter were determined using laser scanning microscopy in increments of two laser bursts. The averaged results are shown in figure 3 for a sample size of 3, a number of intra-burst pulses of  $N_{BP} = 1$ –6 and a laser burst repetition rate of  $f_B = 200$  kHz.

An overview of top view images of percussion drilled microvias into ABF material in increments of 2 laser bursts in dependence of the number of intra-burst pulses is provided in figure 3(a). It is clearly visible that for applying the same total energy, the inner copper layer is reached with fewer laser bursts for MHz burst mode in comparison to single pulse mode. The evaluation of the penetration depth as a function of the number of applied laser bursts and intra-burst pulses is depicted in figure 3(b) and reveals that the 30 μm thick ABF insulating layer is drilled through by using 18 laser bursts for single pulse mode. In contrast, applying a number of intra-burst pulses of  $N_{BP} = 2, 3$  and 6 intra-burst pulses, only 16, 14 and 12 laser bursts, respectively, are required to reach the inner copper layer. From this point of view, throughput in PCB fabrication can be improved by reducing the laser microvia drilling time of 16.7%–33.3%. It is also worth noting that after reaching the conductive layer in MHz burst mode, the penetration depth in copper is not affected and comparable to that in single pulse mode.

The increasing penetration depth in ABF during laser percussion drilling using MHz burst mode is assigned to accumulate residual heat within a microvia, which in turn alters the absorption properties of the ABF material, allowing a deeper penetration. This assumption is also reported by Metzner *et al* [57], obtaining up to 20 times higher penetration depth for laser structuring of silicon and cemented tungsten carbide applying an intra-burst pulse repetition frequency of 80MHz and a number of intra-burst pulses of up to eight. In contrast to previous mentioned studies on laser burst processing of metals [26, 34, 41], shielding effects by laser-induced plasma and ejected particles are not identified for an even number of intra-burst pulses. Since these effects are in turn both material and fluence dependent [26], we assume based on our observations that shielding effects have



a negligible impact on laser microvia percussion drilling of ABF material at higher intra-burst pulse repetition rates and that incubation effect and heat accumulation play a dominant role. Therefore, shielding effects are not considered in the following evaluations.

Furthermore, consistently smaller microvia diameters are determined for a number of intra-burst laser pulses with  $N_{BP} = 3$  and 6, cf figure 3(a) and (c). After laser processing using 30 laser bursts, a reduction in hole size of approximately 10% is observed compared to a diameter in single pulse mode of  $D = 37 \mu\text{m}$ , which is a result of the significantly lower fluence of each intra-laser burst pulse. In contrast to this, 2 intra-burst laser pulses obtain a similar diameter range, although the laser energy density is halved. In turn, this contradictory result confirms the assumption that occurring shielding effects are negligible and for this case, the reported beneficial ablation behavior using MHz bursts counteracts the lower laser fluence. In addition, this is evident by consideration of the ablation volume in figure 3(d), whereby the highest averaged volume of  $V = 24,332 \mu\text{m}^3$  is ablated for using 2 intra-burst pulses. However, to completely determine the influence of the MHz burst on the microvia drilling geometry, a metallographic preparation of the microvias is essential, which is discussed in the following.

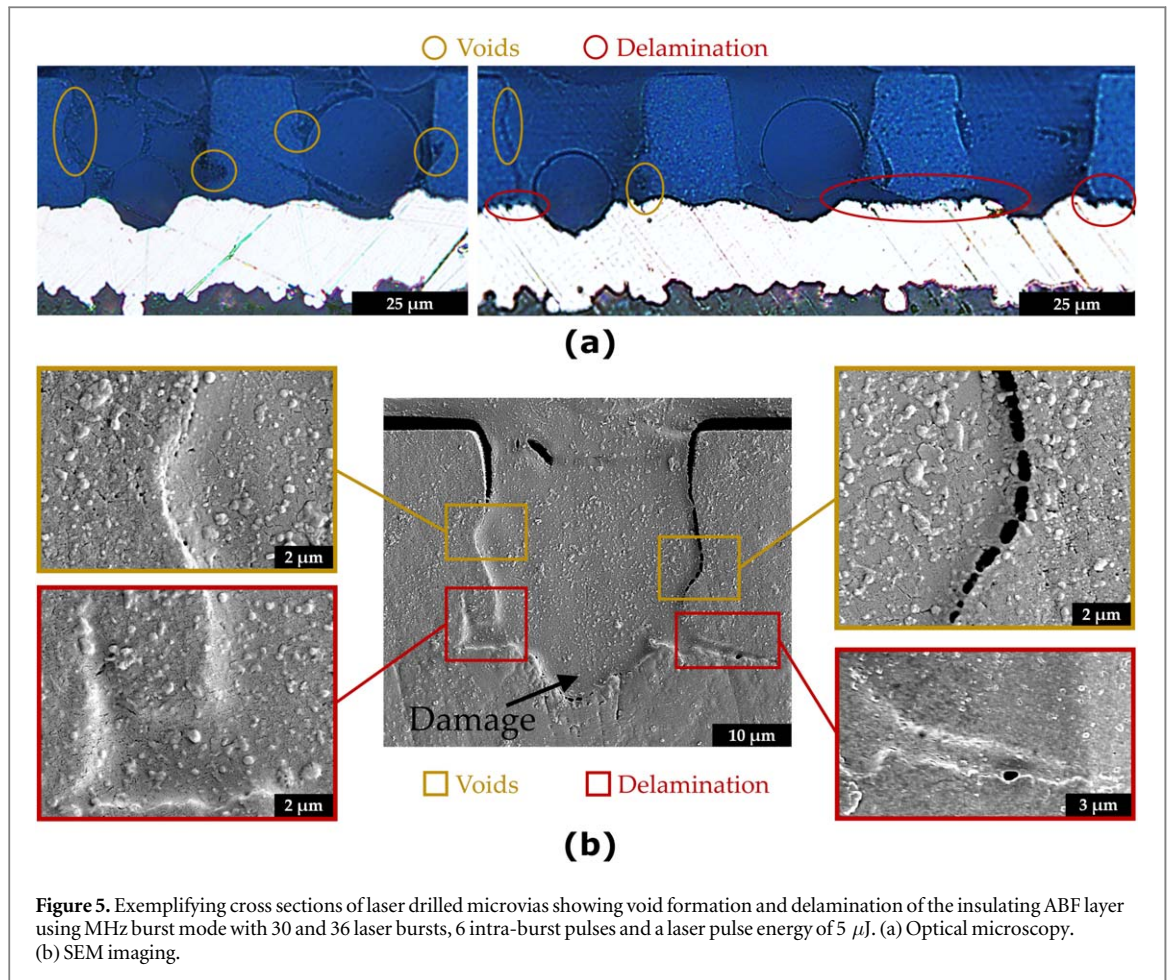
### 3.2. Evaluation of the microvia drilling quality

#### 3.2.1. Taper, diameter and damage of inner copper layer

The taper and diameter of drilled microvias are illustrated in figure 4 for a number of intra-burst pulses of  $N_{BP} = 1-6$ , laser bursts of  $N_B = 30$  and  $N_B = 36$  and laser pulse energies between  $E_{BP} = 2.5-30 \mu\text{J}$  at a laser burst repetition rate of  $f_B = 1 \text{ MHz}$ .

As an overall result, significantly smaller taper ratios are observed for a higher number of laser bursts with a negligible increase in microvia diameter, cf figures 4(a) and (b), respectively. Thus, in combination with the analysis of microvias in increments of 2 laser bursts for MHz burst mode from figure 3, it can be concluded that after reaching the inner copper layer, additional laser bursts mostly contribute to the reduction of the taper. In addition, the resulting taper ratios show a trend towards steeper microvia walls with increasing number of intra-burst pulses. Therefore, the smallest averaged taper of  $117.4 \pm 6.3\%$  is achieved with 6 intra-burst pulses with a pulse energy of  $5 \mu\text{J}$  and 36 laser bursts. For the same total energy input, the taper is thus 13.7% smaller than in the single-pulse mode. The slope of the graphs decreases more rapidly with the laser pulse energy in MHz burst mode than in single pulse mode and again the decrease is more pronounced for a higher number of intra-burst pulses. A similar trend is identified when evaluating the microvia diameters. The smaller diameters for the MHz burst mode result from of a decreasing laser fluence with an increasing number of intra-burst pulses. The smallest hole sizes are  $26.1 \pm 0.2 \mu\text{m}$  for 6 intra-burst pulses and 30 laser bursts.

We mainly ascribe the widening of the microvia at the bottom area to an increasing heat accumulation during laser drilling using MHz burst mode. If an intra-burst pulse is absorbed by the insulating ABF substrate, a certain amount of the absorbed laser fluence below the ablation threshold is converted to heat in the material [58]. In turn, due to the low thermal conductivity of ABF substrate of  $<2.5 \text{ W/mK}$  [56], the induced heat can not dissipate into the surrounding material within the time scale of successive intra-burst pulses of  $\Delta t_{BP} = 12 \text{ ns}$ . Therefore, in laser microvia percussion drilling, heat accumulates as the number of laser bursts and intra-burst



laser pulses increases, producing a smaller taper value. As reported by Metzner *et al* [57, 58], the temperature may even exceed the evaporation temperature of the substrate using high laser burst repetition rates of several MHz and thus leading to an additional removal mechanism which contributes to the total ablated material.

In addition, it is worth mentioning that for all MHz burst configurations no measurable damage in the inner copper layer is attained, except for applying a number of intra-burst pulses of  $N_{BP} = 6$  and 36 laser bursts. Here, an average damage of the inner copper layer of  $4 \pm 1.3 \mu\text{m}$  is observed, as illustrated by selected optical microscope images and SEM images of microvia cross sections in figures 5 and 7. This, in turn, confirms the favorable ablation behavior for both copper and ABF from the previously reported studies for a higher number of intra-burst pulses.

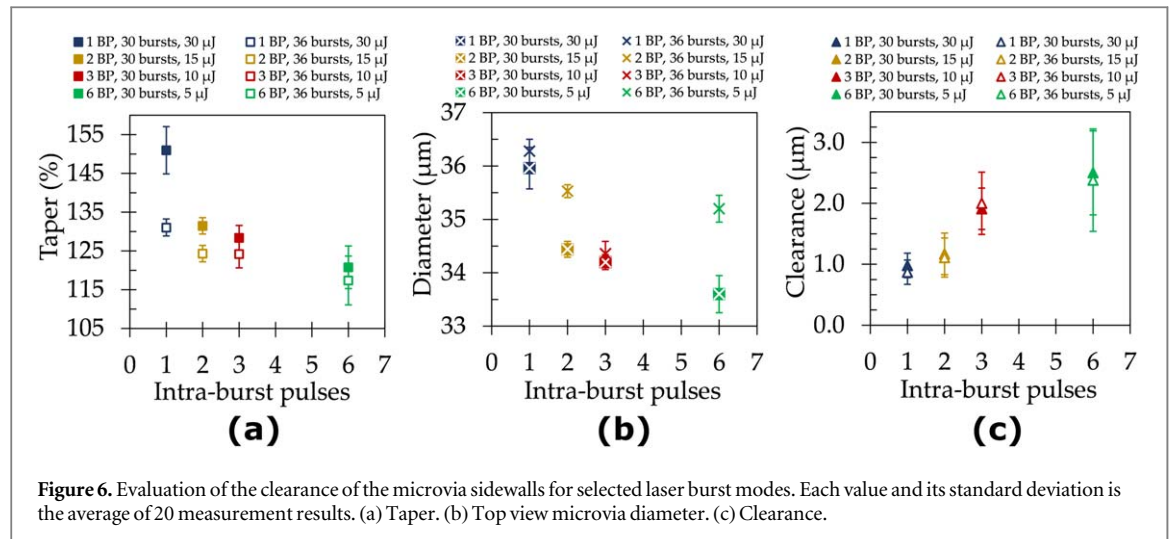
Furthermore, molten and re-solidified copper is evident at the inner copper layer towards the sidewalls of the microvias in the cross sections. On the one hand, this is again attributed to increasing heat accumulation at the bottom of the hole during percussion drilling process using MHz burst mode. On the other hand, occurring melt formation may lead to a modification of the ablation characteristics during laser bursts with a temporal separation of a few nanoseconds, which is comparable to that of a nanosecond laser pulse, as reported by Domke *et al* [25].

### 3.2.2. Clearance of microvia walls

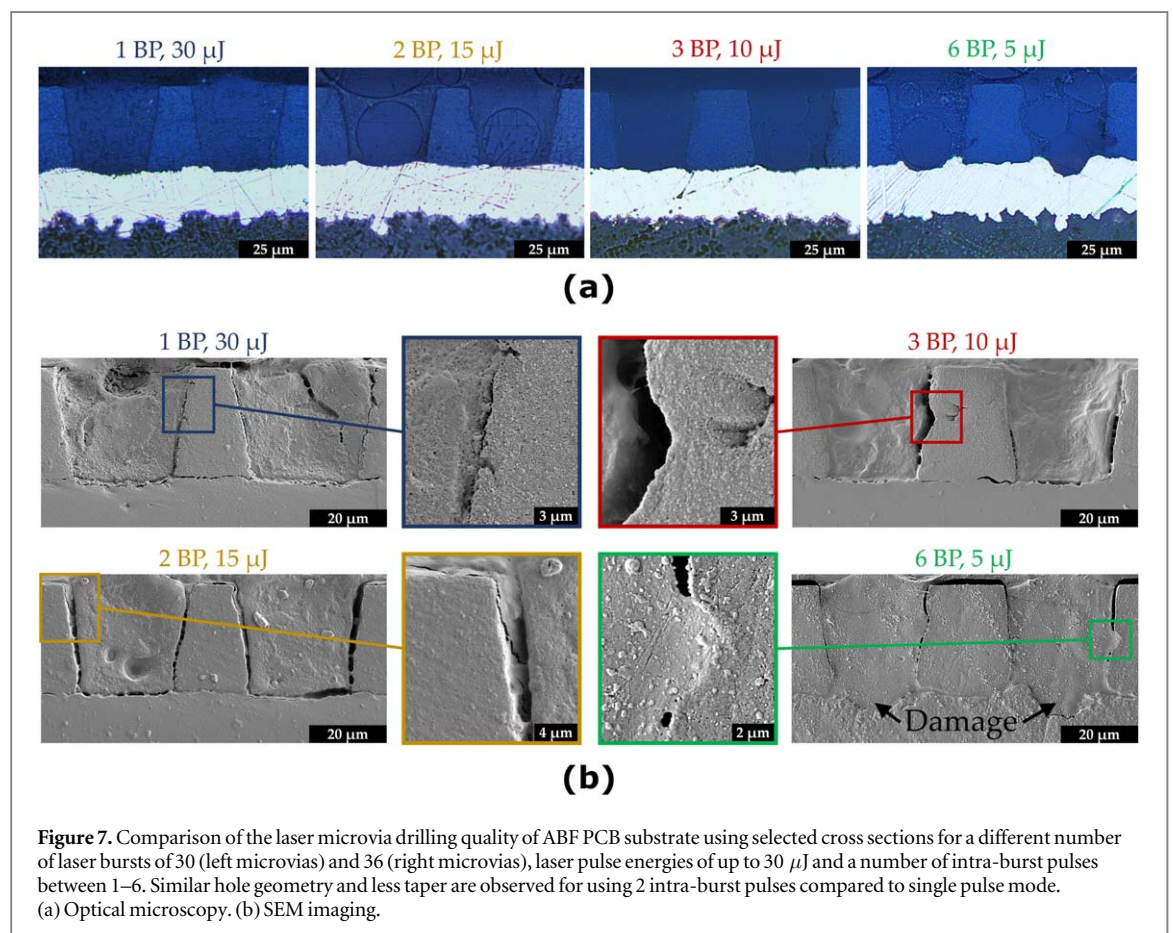
Although the laser drilling quality is improved by accumulated heat using MHz burst mode, negative side effects occur. Voids are created and even delamination of the insulating ABF layer is observed for 6 intra-burst laser pulses. For illustration, selected cross sections of laser drilled microvias with 30 and 36 laser bursts and a number of intra-burst pulses of 6 are shown in figure 5 using optical microscopy and SEM imaging. Since the formation of voids can lead to a significant reduction of the electrical connection lifetime after electroplating by more than 90% [59], a characterization of the voids is indispensable. Hence, the previously introduced parameter clearance is used to evaluate the size of these modifications, cf figure 1(a). This parameter is also retained to quantitatively describe the effect of accumulated heat when using MHz bursts.

The results of the clearance are shown in figure 6(c) for single pulse mode with a laser pulse energy of  $E_{BP} = 30 \mu\text{J}$  and its comparative MHz burst modes with the same total energy input. For an overall comparison of the microvia drilling quality, the taper and microvia diameters for these laser burst parameters are extracted





**Figure 6.** Evaluation of the clearance of the microvia sidewalls for selected laser burst modes. Each value and its standard deviation is the average of 20 measurement results. (a) Taper. (b) Top view microvia diameter. (c) Clearance.



**Figure 7.** Comparison of the laser microvia drilling quality of ABF PCB substrate using selected cross sections for a different number of laser bursts of 30 (left microvias) and 36 (right microvias), laser pulse energies of up to 30  $\mu\text{J}$  and a number of intra-burst pulses between 1–6. Similar hole geometry and less taper are observed for using 2 intra-burst pulses compared to single pulse mode. (a) Optical microscopy. (b) SEM imaging.

from figure 4 and additionally depicted in figure 6(a) and (b). Obviously, the clearance is independent of the selected number of laser bursts of  $N_{BP} = 30$ –36, but increases continuously with the number of intra-burst pulses, reaching highest averaged values of  $2.44 \pm 0.76 \mu\text{m}$  for 6 intra-burst pulses. Compared to the single pulse mode with small clearance values of  $0.93 \pm 0.2 \mu\text{m}$ , the values are doubled with  $1.96 \pm 0.43 \mu\text{m}$  for 3 intra-burst pulses and in a comparable range with  $1.16 \pm 0.3 \mu\text{m}$  for 2 intra-burst pulses. From this point of view, the evaluation of the clearance represents well the evolution of the voids with an increasing number of intra-burst pulses. This is also in good agreement with selected optical microscope images and SEM images of microvia cross sections shown in figure 7.

Furthermore, the clearance parameter suggests that residual heat accumulates rapidly with the number of applied intra-burst pulses. We assume that the generated heat within a microvia exceed the boiling point of the ABF substrate and thus lead in some areas to melting and evaporation of the insulating layer. As already

mentioned, such a second removal process as a result of increasing heat accumulation is also suggested by Metzner *et al* [57, 58] for MHz bursts. For applying 2 intra-burst pulses, these effects lead to an improvement of the laser drilling quality by widening the microvias at the bottom area. However, using a greater number of intra-burst pulses, accumulated heat within a microvia is too extensive and thus the generation of voids and even delamination of the insulation ABF layer occur.

Comparing the evaluation of the clearance with the achieved taper and microvia diameters of figure 6(a) and (b), respectively, we find an improvement in drilling quality in terms of reduced taper of down to 19.5% using MHz burst mode with 2 intra-burst pulses and 30 laser bursts compared to single pulse mode. In addition, this burst configuration allows an optimization of throughput in PCB fabrication compared to single pulse mode, since a comparable microvia drilling quality is accomplished with 6 fewer laser bursts. Consequently, a reduction of laser drilling time for an individual microvia of 16.7% is demonstrated.

## 4. Conclusion

We have reported on the influence of the MHz burst mode on laser microvia percussion drilling of ABF substrate for PCB fabrication using an ultrashort pulsed laser with a wavelength of 532 nm. In the study, the impact of pulse to pulse interactions are being discussed on the ablation threshold, ablation volume and the penetration depth as well as the laser drilling quality, which in turn is defined by the taper and the microvia diameter. It has been shown that shielding effects of laser-generated plasma and ejected particles have a negligible impact on both ablation behavior and microvia drilling quality. In contrast, increasing heat accumulation significantly influences the microvia geometry during percussion drilling process with MHz bursts. On the one hand, it has been proven that the fabricated taper is reduced to a value of 117.4% due to accumulated heat in MHz burst mode. On the other hand, for a higher number of intra-burst pulses, the heat accumulation has a negative impact on the drilling quality, as voids and even delamination are observed in the insulating ABF layer. As a particular result, the use of 2 intra-burst laser pulses is beneficial to the microvia drilling quality, as the taper is reduced by down to 19.5% without the generation of voids. In addition, the drilling time per microvia with comparable characteristics can be reduced by up to 16.7% with 2 intra-burst pulses, which in turn allows an enhancing of the throughput in PCB fabrication.

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## Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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