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Fiber-reinforced composite microdrilling with high-power Sirius XeCl excimer laser for aerospace applications

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Abstract

Over the last several years hybrid laminar flow control has gained a lot of interest for drag reduction by boundary layer suction, using small holes at the leading edges of aircraft wings and tail elements. A lot of effort has been spent on drilling of small holes into different materials with diameters around 100 µm. This paper focuses on practical aspects of bringing laser micro-drilling technology from the laboratory level closer to the real-life applications in carbon fibre reinforced composite materials. The fabrication of large suction inserts was performed with an XeCl Sirius excimer laser with a power of 1 kW at a pulse repetition rate up to 1 kHz. The percussion drilling approach require the adjustment of several parameters, such as number of pulses, pulse energy and repetition rate and resulted in the fabrication of round holes with diameter of 100 µm in carbon fibre reinforced thermoplastic with a thickness of 900 µm.

Keywords: laser drilling; composite materials; excimer laser; carbon fibre reinforce polymer,pulse energy modulation.

1. Introduction

Composite materials gained much interest during last decades and are slowly replacing metals as structural elements in modern aircrafts. Composite materials are lightweight which allows a decrease of CO_2 emission of aircrafts. Recently, two main civil aircraft manufactures released new models A350 and B787 containing more than 50 % of composites in the structure (Yao et al. 2018). Clearly, this trend will continue in the following years and it is of great importance to develop manufacturing processes and techniques for composite materials. Carbon fibre reinforced polymers (CFRP) play an important role as structural elements of a fuselage, a wing and a tail of the aircraft, but also can be used as fan blades and other parts of an engine. Among several types of carbon fibre composites thermoplastics are more attractive for aerospace industry as long as they were proved to be sustainable and reusable (Yao et al. 2018). Accordingly, current research in this field is mostly focused on this type of CFRP.

Microdrilling of such a large number of holes (order of magnitude 1 million holes per square meter) in CFRP is a challenging task because of high requirements to the hole quality and a reputability on a large

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scale. Microdrilling of holes is reducing fuel consumption by several percent using the Hybrid Laminar Flow Control (HLFC) technique (Krishnan, Bertram, and Seibel 2017). Millions of holes are perforated in various locations on the wings and tail frontier of the aircraft to maintain laminar flow along the surface reducing drag forces. The idea has been developing for several decades already and currently is actively being tested in research programmes. Another important application for perforated CFRP is acoustic intake liners, which are used for reduction of jet engine noise emission. The inner surface of the jet engine is covered with sandwich composite comprising of CFRP layer on top of honeycomb plastic grid. For these applications size of the holes in a CFRP composite should be around 100 to 200 µm and normally has area of several square meters.

Lasers are powerful tools for materials machining and allow a precise drilling of aerospace materials (Gautam and Pandey 2018; El-Hofy and El-Hofy 2018; Yeo et al. 1994; Dhar, Saini, and Purohit 2006; Schulz 2013). Laser pulse duration and wavelength have a great influence on material removal rate and hole quality. Nowadays IR lasers with variable pulse duration have gained big part of market due to high efficiency and excellent beam quality. They are widely used for drilling of aerospace materials but still have some limitations (Messaoudia et al. 2015; Marimuthu, Antar, and Dunleavey 2018; Adel Salama et al. 2016; Stephen et al. 2014; El-Hofy and El-Hofy 2018). In particular, drilling with short pulsed IR lasers results in rather large heat affected zone (HAZ). Whereas, ultrashort pulsed laser are capable of producing clean holes, the removal rate of 100 nm/pulse is currently a limiting factor for their industrial usage. In case of CFRP a polymer matrix has a much lower IR absorption, which ultimately decreases hole quality since higher thermal conductivity of fibres results in anisotropic heat flow around the hole. Thus, it is beneficial to use UV nanosecond pulsed laser for CFRP microdrilling in order to achieve excellent hole quality.

Developed in 1970’s excimer lasers found applications in photolithography, medicine and material processing (Basting and Marowsky 2005). XeCl excimer lasers possess high average power and were used for laser drilling for many years (Schoonderbeek et al. 2003, 2004). They provide excellent hole quality together with low HAZ. Although the excimer laser technology is outdated for materials drilling, it is still an instrument of choice for CFRP where the drilling quality is of great importance.

In this study several laser parameters and techniques will be considered and tested for CFRP perforations using high-power XeCl excimer laser. The hole taper angle and HAZ will be studied using optical micrsoscopy. Also pulse energy modulation will be applied in order to actively control hole taper angle and HAZ.

2. Experimental and Methods

2.1. Laser drilling system

Short UV laser pulses are generated with Sirius excimer laser. The laser was developed in 2005 at the Netherlands Centrum for Laser Research (NCLR) in order to industrialize a well-known high-power excimer laser technology (Timmermans et al. 2000; Hofstra, Timmermans, and Van Heel 2000). It is XeCl excimer laser with a gas mixture 0.7 mbar HCl, 8 mbar Xe and 5 bar Ne. The maximum pulse energy 1 J at 1 kHz repetition rate provides up to 1 kW output power at 308 nm wavelength with 200 ns pulse duration. It was used in the past for different applications including material micromachining (Timmermans et al. 2000). Fig. 1 (a) shows a schematic layout of the Sirius laser. Three stage electrical discharge is used for the pumping of the gas mixture in order to achieve a stable glow discharge and to extend the life time of electrodes and the gas itself. At the first step, the gas mixture within the laser resonator is exposed to X-ray preionization in order to seed more Xe ions for larger number of formed XeCl molecules. A spiker-sustainer circuit is used for stable discharge to the active medium providing longer laser pulse duration. The spiker pulse has higher peak voltage (up to 38 kV) and shorter duration for homogeneous breakdown of the laser gas. The main pulse can be several times longer allowing up to 350 ns laser pulse duration (Timmermans et al. 2000). An advanced flow control system provides laminar flow of the gas mixture between electrodes at a maximum speed of 70 m/s for homogeneous discharge.

The resonator of the Sirius laser contains two mirrors located outside of the gas vessel at a distance of 1.2 m from each other. The rear dielectric concave mirror has a high reflectivity and radius of curvature 5 m. The output coupler is a graded reflectivity mirror with 60 % reflection in the center and 4mm radius of reflective area. Such unstable resonator provides almost diffraction limited beam quality and divergence around 50 µrad (Kovalenko 1994). A laser beam shape is analyzed with a beam profiler SP620U (Spiricon). The beam diameter at the 10 m remote workstation is 23 mm with close to the doughnut shape intensity profile.

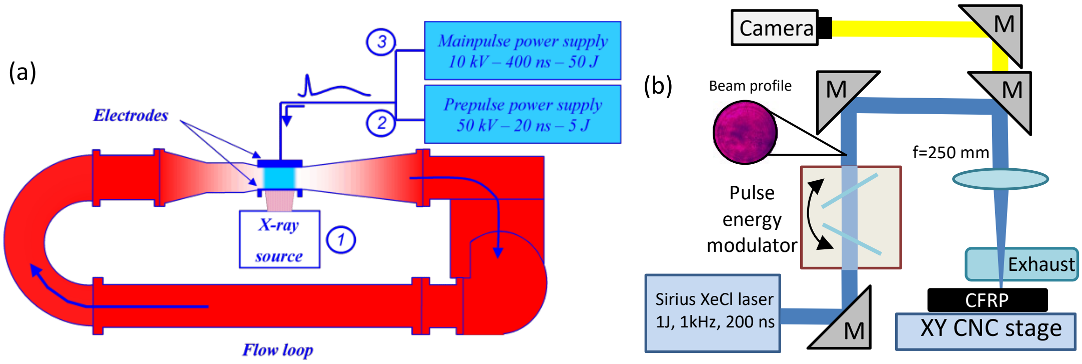

Fig. 1. (a) Sirius XeCl excimer 3-stage laser discharge scheme and gas flow loop, (b) Optical setup for CFRP microdrilling

The optical setup for laser microdrilling is shown in Fig. 1(b). The laser beam delivery system involves nine dielectric folding mirrors each with 99% reflectivity. Laser pulse energy is controlled with motorized attenuator, which consists of reflective attenuator and compensator substrates with adjustable angle. Motorized control of the attenuator allows full range pulse energy variation for 100 ms, which can be used for Pulse Energy Modulation (Low, Li, and Byrd 2000). Following positive lens with focal distance f=250 mm focuses laser beam below the sample surface. The long focal distance is necessary for satisfactory hole tapering and with current beam quality the hole diameter is limited to 200 µm. A custom made CNC setup is used for specimen scanning comprising of XY linear stages IDL225-1000 and IDL165-300 (Newport) with 1.0x0.3 m^2 machining area. A camera acA1300-22gc (Basler) with 50 mm lens is used for in-line specimen positioning with the linear stages. Laser drilling of composite materials especially, containing those carbon fibers can bring hazard pollution to the laboratory environment (Walter et al. 2017). One should take into account a retention of the debris and carbon particles from the drilling area by introducing an exhaust system. In addition, particle counter 985 (Fluke) is used in order to track particle size distribution in the air around the workstation.

An optical microscope VHX-2000 (Keyence) with zoom lens VH-Z20R (x20-200) was used for HAZ size assessment, hole depth measurements and overall hole quality evaluation.

2.2. Material

The plates used in this study were manufactured from Cetex five harness satin weave carbon fabric reinforced polyphenylene sulfide (CF/PPS) composite semipreg material, supplied by TenCate Advanced Composites. Three layers were stacked according to 0°/90°/0° fiber orientations, where [0°] and [90°] correspond to the warp and weft directions, respectively, and subjected to 320°C and 10 bar for 15 min, resulting in laminates with a nominal thickness of 0.9 mm. This CFRP material consists of about equal volume of carbon fibers and resin, but the carbon fibers have a more than 20 times higher sublimation temperature than the damage temperature of the resin (Table 1). In addition, the fibers have much higher heat conductivity and much higher latent heat of sublimation than the resin, which is important for the laser processing of the CFRP. To be able to perforate the CFRP, the temperature of the material has to be increased to the sublimation temperature of the carbon fiber and on top of that the sublimation energy has to be supplied in order to enforce the phase-change from solid to gas to remove the carbon. The more time that is required for the laser to supply this energy, the more heat can dissipate to the environment due to the good heat conductivity of the fibers. This will result in extended damage around the hole, because the damage temperature of the resin is much lower than the sublimation temperature of the carbon fibers.

Table 1. Thermo-optical properties of CF/PPS

Parameter	Resin	Carbon fibre
Density, kg/m^3	1250	1850
Heat conductivity, (W/(m K))	0.2	Parallel = 50 / perpendicular = 5
Sublimation temperature, K	800	3900
Latent heat, kJ/kg	1000	43000
Structure damage temperature, K	450	3000

3. Results and Discussions

3.1. CFRP laser drilling

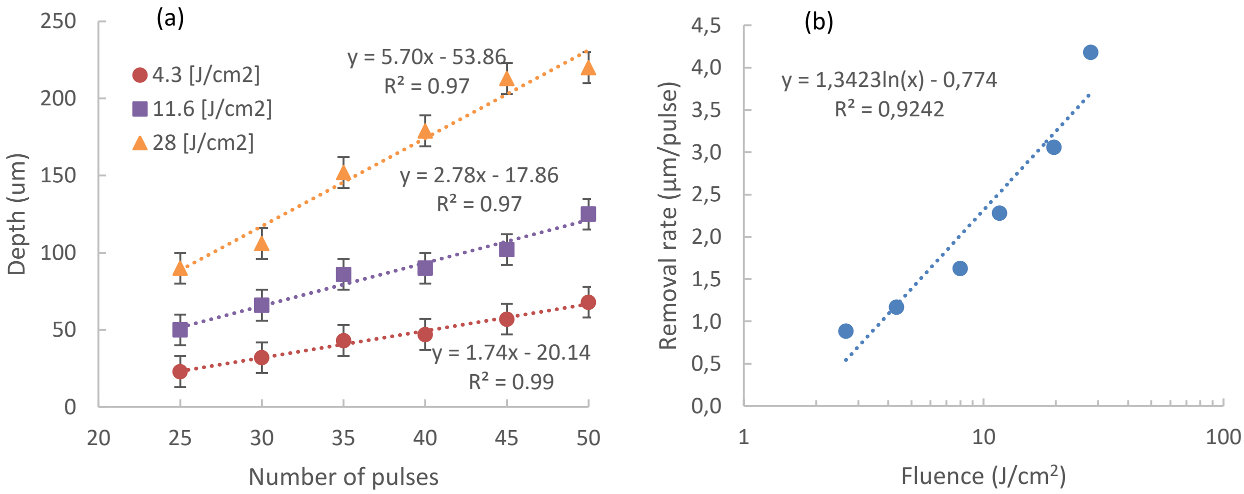

Fig. 2. (a) Effect of number of pulses on the ablation depth of CFRP sample for different fluence, (b) Removal rate dependance on flaser fluence

The effect of fluence and number of pulses was studied in order to estimate the removal rate for CFRP sample for the holes with diameter 100 µm. Fig. 2. (a) shows the dependence of drilling depth on number of pulses for 2-30 J/cm^2 fluence range. A linear response is observed for three fluence level in agreement with expectations. The removal rate can be calculated as average depth over number of pulses for a given fluence. Fig. 2 (b) shows experimental values of removal depth for different fluence. The removal rate varies from 0.9 µm/pulse for 2.7 J/cm^2 to 4.2 µm/pulse for 28.0 J/cm^2. This value is in agreement with removal rate of CFRP measured for different lasers (A. Salama et al. 2016; Wolynski et al. 2011; Modelling 1998). Using logarithmic approximation one can estimate ablation threshold as F_{th}=2 J/cm^2 for the CFRP sample in study. The absorption of the composite material comprises the absorption of the carbon fibres and the epoxy. The absorption coefficient is derived from the measured removal rate and the laser fluence using

$$\boldsymbol{d} = \frac{\mathbf{1}}{\boldsymbol{\alpha}} \ln\left(\frac{\boldsymbol{F}}{\boldsymbol{F_{th}}}\right) \tag{1}$$

where α the absorption coefficient (cm^{-1}), *d* the removal rate (µm/pulse) and *F* the laser fluence (J/cm^2). According to calculated values the absorption of CFRP is around 6400 cm^{-1}. This value is one order less than

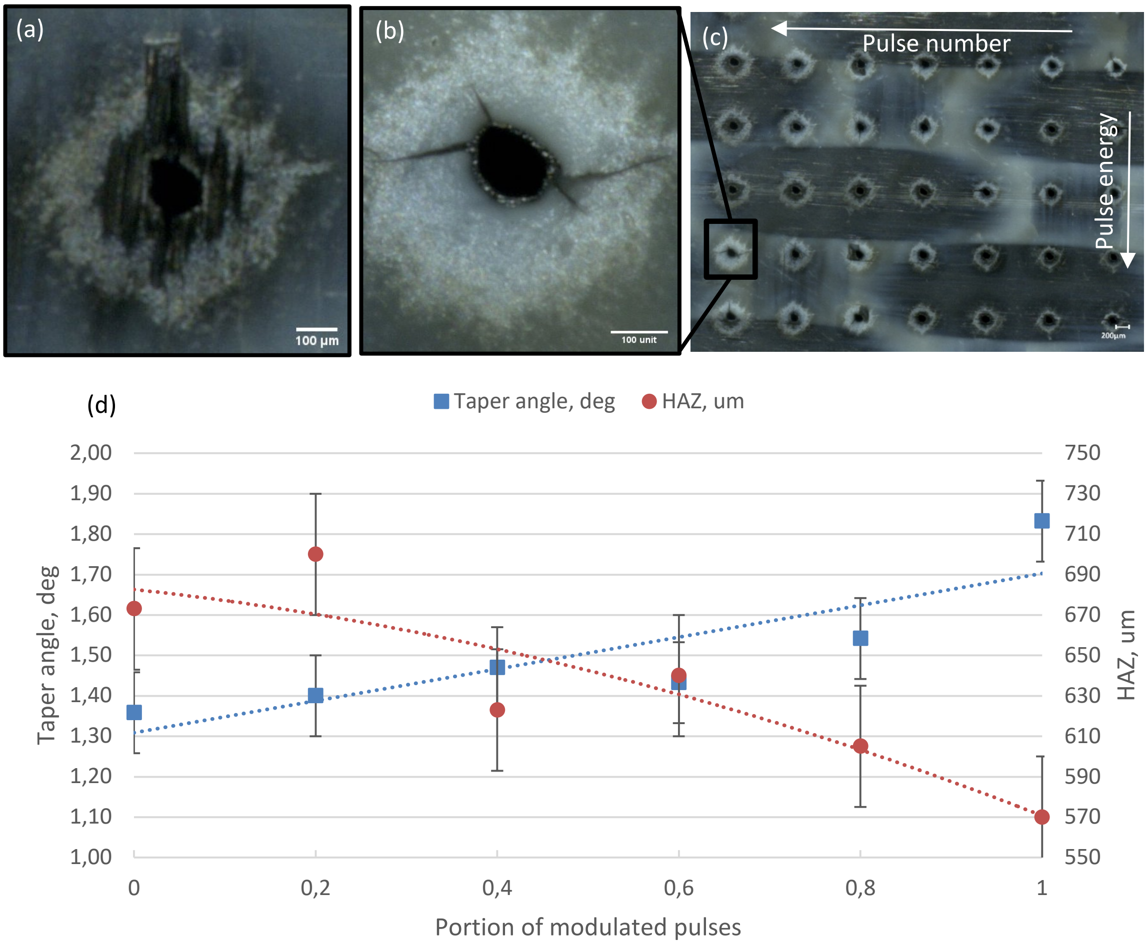

Fig. 3. (a) Image of hole without pulse energy modulation and with (b) with pulse energy modulation, (c) CFRP with multiple holes drilled with variable fluence (10-100 J/cm^2) and pulse number (200-300) and linear increase of pulse energy,(d) dependence of taper angle and HAZ on pulse energy modulation

the published one for graphite, which is caused by 50-60% volume fraction of carbon fibres in the composite (Kwiecinska, Murchison, and Scott 1977).

The processing speed of a laser can be estimated by dividing the amount of laser energy that the laser can provide in a given time by the amount of energy that is required to produce a hole. The minimum laser energy to perforate a hole is the energy required to heat the material to the sublimation temperature and the energy required for the sublimation. To heat up the resin to the sublimation temperature requires 700 J/cm^3 and the sublimation itself requires another 1300 J/cm^3, so the total removal energy of the resin is 2000 J/cm^3. The fibre removal energy is about 84000 J/cm^3 of which 4000 J/cm^3 is required to increase the temperature to the sublimation temperature and 80000 J/cm^3 is required for the solid-gas phase transition (Negarestani et al. 2010; Wolynski et al. 2011). Most of the laser energy is used for the phase transition and not for the temperature increase. For CFRP composites the total fibre removal energy depends on the fraction of carbon fibres and resin and can be compared with the thermal loading produced during laser drilling using

$$\gamma = F_{th}\alpha \quad (2)$$

It can be determined as γ=12800 J/cm^3 and it is of the same magnitude with the fibre removal energy.

3.2. Pulse energy modulation

Fig. 3 (a) shows a surface of CFRP specimen after laser hole drilling with average diameter 100 µm. At relatively high fluence 100 J/cm^2 the top layer of the specimen easily gets damaged already after few laser pulses. The damage is composed of a crack formation across the hole with partial delamination of the top layer of the composite around the hole. It can be caused by a sudden increase of local temperature in the hole surrounding, and occurs preferentially in the direction of the fibres in the top layer. However, it should be noted that different types of damage propagation were observed in carbon fibre thermoset made with residual stress in the matrix due to hand-layup. Apparently, in this case the intrinsic residual stress was much higher than the one caused by difference in heat transfer for different fibre orientation. So the damage was always in one direction regardless specimen orientation, direction of scanning and the laser beam profile.

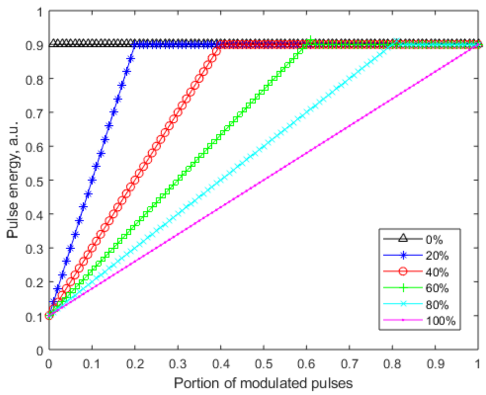

Fig. 4. Pulse energy modulation for different portion of pulses in the laser burst

An active control of pulse energy during hole drilling can considerably reduce the damaged area around the holes. Several years ago a sequential pulse delivery pattern control (SPDPC) method was suggested with pulse energy being linearly increased during the hole perforation (Low, Li, and Byrd 2000). In this paper we use a similar approach and call it pulse energy modulation. In this case the drilling is started with 50-60% lower intensity, so the generated temperature gradient is weaker and causes less damage. However, the rate of drilling per hole is reduced because larger number of pulses is required to remove same volume of material. In this current study, a linear pulse energy increase was applied for different parts of pulse burst. So if 200 pulses were required to make a through hole, then for 10% burst modulation the energy of first 20 pulses was linearly increased as it shown in Fig. 4. On the other hand, 100% burst means linear pulse energy increase through the whole burst. Of course, the damage area also can be reduced with lower pulse energy and larger number of pulses. However, that can cause an increase of HAZ due to lower peak power and the increase of a taper (Dubey and Yadava 2008).

Fig. 4 (d) shows a dependence of taper angle depending on portion of modulated pulses. The taper angle can be calculated using

$$\boldsymbol{\theta = atan\left(\frac{d_1 - d_2}{2t}\right)\frac{180}{\pi}} \quad (3)$$

where d_1 and d_2 are the entrance and exit diameter of the hole, t the thickness. One can observe the decline of the taper angle with the larger portion of modulated pulses. This decline is related with decrease of total energy deposited to the drilling area as the pulse energy is gradually increasing. However, at the expense of a removal rate the HAZ size is smaller for larger pulse energy modulation. Indeed, the crack formation is happening only in the beginning of laser burst, when the incidence angle is close to 90^{o}. High pulse energy unavoidably results in the instant local rapid temperature increase and following crack and delamination formation. However, the surface is less damaged and HAZ is smaller for the pulse energy in the beginning of the burst improving hole quality. Whereas the incidence angle gets larger for the central part of the laser pulse for the rest of the burst and it is no longer affecting the surface quality. Overall surface quality improvement can be observed in Fig. 4 (b) and (c). One can see minor crack formation around the hole and a HAZ size decrease. Thus, to achieve the best hole quality the burst profile can be tailored on demand particularly for thick specimens (<1 mm). In this case it is reasonable to gradually increase pulse energy in the beginning of the burst, then pass the bulk at maximum removal rate and finally decrease pulse energy to prevent delamination on the other side of the composite. However, such a scenario does not consider heat accumulation at high repetition rate, when the multivisiting drilling approach should be used in order to address high thermal loading.

4. Conclusions

In this paper the perforation of microholes in CFRP composite materials using XeCl excimer laser was studied. Several important parameters for laser machining were evaluated such as damage threshold, removal rate and HAZ. Also, it was shown that the hole quality can be improved using active control of pulse energy in burst. It allows one to reduce HAZ size by about 20% and to prevent crack and delamination formation at the surrounding of the hole. A comparison with other types of lasers provides a clear vision that the Sirius XeCl excimer laser is a competitive laser source for large scale microdrilling for aerospace application. However, additional studies should be carried out in order to increase the speed of perforation and also to address the problem of heat accumulation at high speed laser drilling.

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