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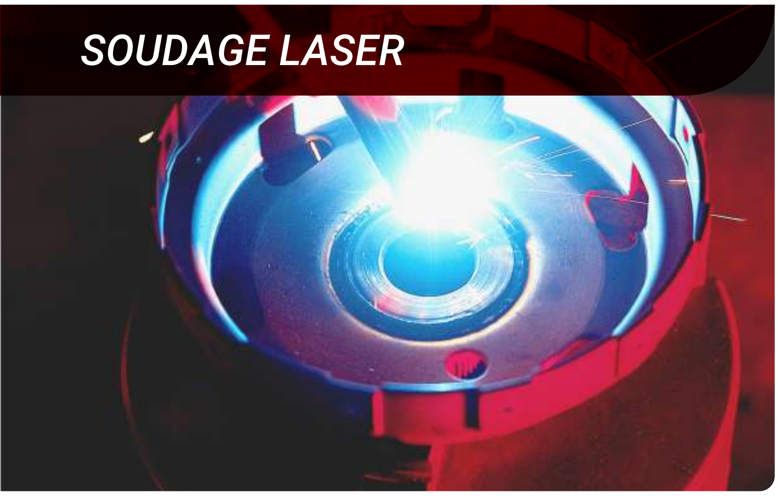
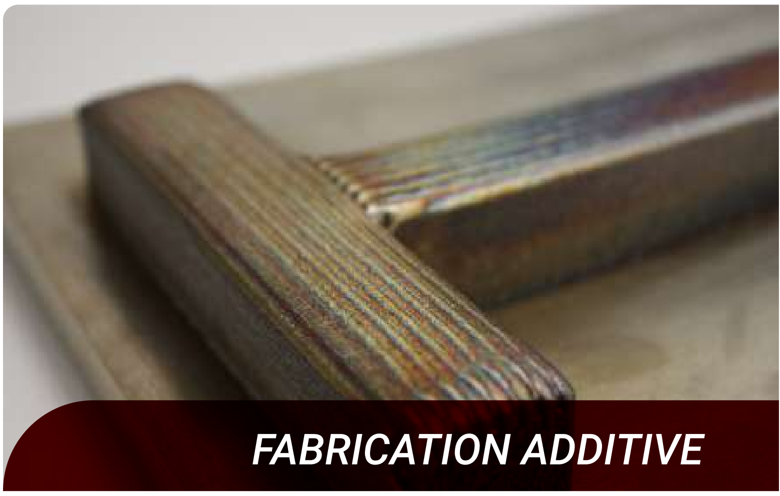
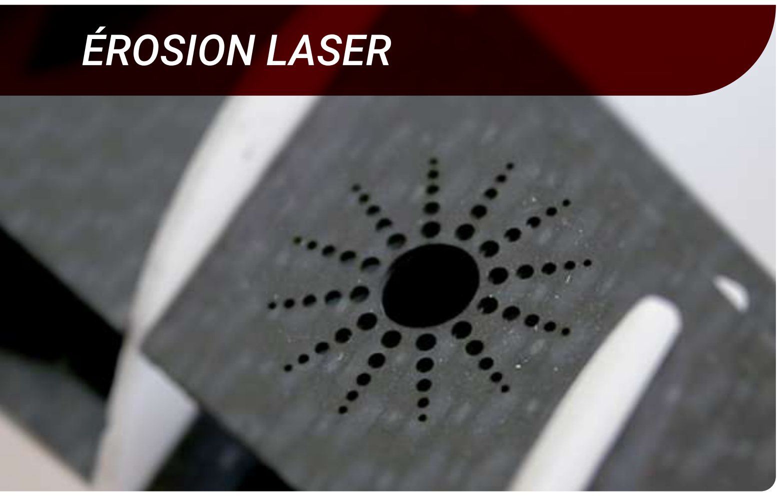




4 EXPERTISES



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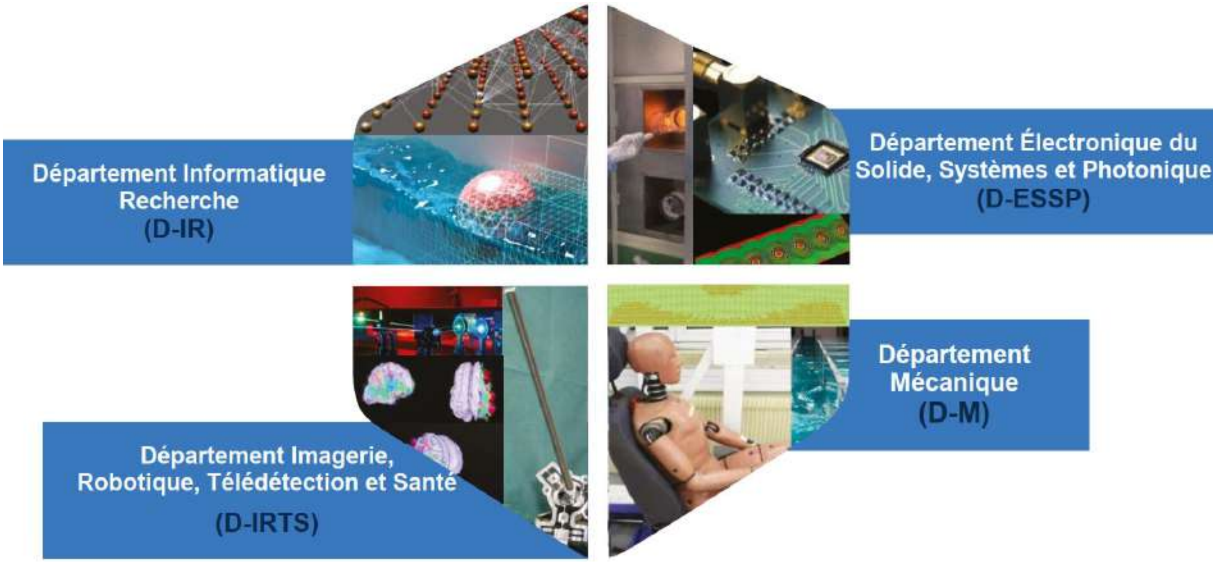

- **Ces moyens expérimentaux sont structurés autour de 7 plateformes :**

C3Fab : Elaboration et de caractérisation de composants, cellules PV et capteurs

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- **Recherches en photonique et sur les procédés laser avancés**

Elles concernent en particulier le **Département Électronique du Solide, Systèmes & Photonique** (D-ESSP) et plus spécifiquement **l'équipe IPP (Instrumentation et Procédés Photoniques)** avec les axes Procédés Laser Avancés, Nanoscopie Multimodale et Optique Biomédicale.

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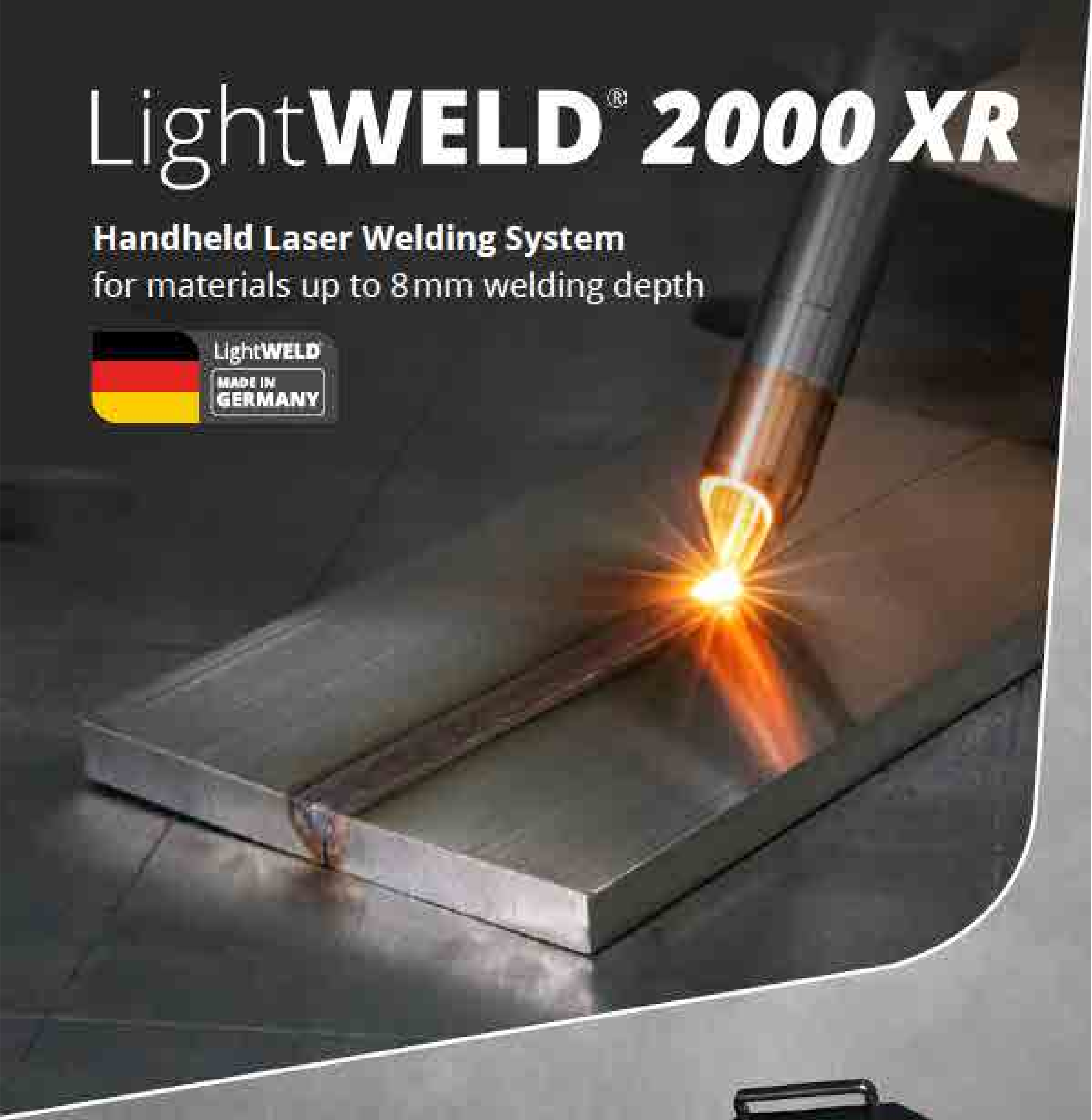

IPG PHOTONICS

MERCREDI 24 SEPTEMBRE / WEDNESDAY 24th SEPTEMBER

▶ SESSION PLÉNIÈRE D'OUVERTURE / PLENARY OPENING SESSION

Auditorium S. Veil / Modérateur : John LOPEZ

08:30	Accueil café / Welcoming coffee		
09:00	Ouverture / Opening talk		
09:20	Jochen STOLLENWERK Fraunhofer ILT	Technologies basées sur le laser pour le développement de technologies clés pour la fusion nucléaire *Laser based technologies for the development of key technologies for nuclear fusion*	EN
09:50	Eveline REINHEIMER PORSCHE	Surveillance des processus : avons-nous vraiment besoin de l'IA ? *Process monitoring- Do we really need AI?*	EN
10:20	Klaus LÖFFLER PRECITEC	Technologie des batteries : comment l'Europe peut-elle rattraper son retard ? *Battery Technology: how Europe can catch-up?*	EN
10:50	Pause-café / Coffee break		

▶ SESSION SÉCURITÉ LASER / LASER SAFETY SESSION

Auditorium S. Veil / Modérateur : Ludovic LESCIEUX

11:30	Franck RIGOLET IREPA LASER	Le marquage CE est-il une assurance sécurité ? *Is the CE marking a guarantee of safety?*	FR
11:50	Mathieu VAUTROT WEARE TECH	Évaluation des risques environnementaux du laser femtoseconde dans l'industrie *Assessing environmental risks of femtosecond laser technology in the industry*	FR
12:10	David LAWTON KENTEC CORPORATION	Problèmes liés à la sécurité laser des systèmes de soudage laser portatifs *Issues with laser safety of handheld laser welding systems*	EN
12:30	Pause déjeuner / Lunch break		

▶ SESSION MICRO-USINAGE LASER / LASER MICROMACHINING SESSION

Amphithéâtre P. Pflimlin / Modérateurs : Sylvain LECLER

11:30	Célia MILLON RAYVEN LASER	Lasers ultrarapides à semi-conducteurs à base d'holmium pour la science et l'industrie *Holmium-based solid-state ultrafast lasers for science and industry*	EN
11:50	Théo GUILBERTEAU ALPhANOV - CELIA	Interaction laser ultrabref avec faisceau de Bessel dans la silice fondue en régime mono-impulsionnelle, rafale-MHz & GHz *Ultrafast laser bessel beam interaction with fused silica in single pulse, MHz-burst, and GHz-burst*	EN
12:10	Dimitris KARNAKIS OXFORD LASERS	Technologies de perçage laser ultra-courtes pour le verre traversant via la fabrication dans des inter poseurs de verre personnalisés *Ultrashort laser drilling technologies for through glass via fabrication in customised glass interposers*	EN
12:30	Pause déjeuner / Lunch break		

▶ SESSION FABRICATION ADDITIVE / ADDITIVE MANUFACTURING SESSION

Auditorium S. Veil / Modérateurs : Bogumila SKIBA

14:00	Andre ELTZE LASERLINE	Les lasers à diodes bleues plus puissants et d'une meilleure qualité de faisceau ouvrent la voie à de nouvelles applications pour ces lasers à haute efficacité *Blue diode lasers with higher output power and better beam quality open new applications for these highly efficient lasers*
14:20	Leila SELLAMI UTBM	Caractérisation micromécanique des interfaces traitées par laser *Micromechanical characterization of laser-treated interfaces*
14:40	Jean-Louis LAURONT INNOVIDEA	Systèmes d'imagerie dans le SWIR, le NIR et le visible pour la surveillance thermique des procédés de revêtement par laser *Shortwave infrared, near infrared, and visible light imaging systems for thermal monitoring of laser cladding processes*
15:00	Clémentine MAURIER CAILABS	Les nouvelles applications des procédés laser et comment elles bénéficient de la mise en forme du faisceau laser *New applications in laser processing and how they profit from beam-shaping*
15:20	Pause-café / Coffee break	

▶ SESSION MICRO-USINAGE LASER / LASER MICROMACHINING SESSION

Auditorium S. Veil / Modérateurs : Emmanuel CHALUMEAU

15:50	Romain DUBREUIL GF MACHINING SOLUTIONS	Micro-usinage laser de haute précision: cavités à parois verticales *Pioneering precision: vertical wall cavity through laser micromachining*
16:10	Eric BELSKI AEROTECH	Quantification de l'efficacité du mode rafale MHz dans le traitement laser ultrarapide à 5 axes *Quantifying the efficacy of MHz-burst mode in 5-Axis ultrafast laser processing*
16:30	Wilfried VOGEL OPHIR SPIRICON EUROPE	Mesure de l'indice de qualité M^2 : technologies actuelles et défis cachés *Measuring the quality indicator M2: Current technologies and hidden challenges*
16:50	Emmanuel PASCAL PI FRANCE	Influence de la cartographie 2D sur la cartographie 1D sur les pièces micro-usinées laser précision *Influence of 2D mapping over 1D mapping on laser micromachined parts accuracy*
17:10	Fin de journée / End of the day	

▶ SESSION MICRO-USINAGE LASER / LASER MICROMACHINING SESSION

Amphithéâtre P. Pflimlin / Modérateurs : Frédéric MERMET

14:00	Sara KIRCHNER IRT SAINT EXUPERY	Procédé laser semi-autonome pour la préparation de surface avant collage *Semi-autonomous laser process for surface preparation before bonding*
14:20	Jan MUYS PRC LASER EUROPE	Élimination des revêtements LowE par ablation laser *Removal of LowE coatings by laser ablation*
14:40	Vincent ROUFFIANGE AMPLITUDE	Laser femtoseconde haute puissance et division de faisceau : challenges et opportunités *High-power femtosecond laser and beam splitting: challenges and opportunities for industrial applications*
15:00	Isabelle GEOFFRAY CEA	Des procédés lasers pour la fabrication des cibles *Laser processes: powerful tools for targets fabrication*
15:20	Pause-café / Coffee break	
15:50	Sylvain GEORGES MANUTECH USD	Optimisation de la polarisation circulaire pour des structures de surface périodiques bidimensionnelles induites par laser (2D-LIPSS) pour des texturations à grand champ *Optimizing circular polarization for two-dimensional laser-induced periodic surface structures (2D-LIPSS) in large-field texturing*
16:10	Anika LANGEBECK BIAS	Ajustement de la mouillabilité de surface par des structures auto-organisées *Tailoring surface wettability through self-organized surface structures*
16:30	Carlos Esteban CIFUENTES CEA – INSTITUT FRESNEL	Découpe Laser Ultrarapide à Fréquence en MHz : gestion thermique pour la préparation d'échantillons de céramiques nucléaires *Ultrafast laser cutting at MHz repetition rates: nuclear ceramic sample preparation through thermal management*
16:50	Vaibhav NAIN IREPA LASER	Développement d'un modèle numérique d'ablation laser à grande échelle avec des impulsions femtosecondes de MHz/GHz *Development of a numerical model of large-scale laser ablation with MHz/GHz bursts of femtosecond pulses*
17:10	Fin de journée / End of the day	

▶ SOIRÉE NETWORKING / NETWORKING EVENING

18:20	Rendez-vous à l'arrêt de tram « Langstross » / Meet at the "Langstross" tram stop
18:30	**Visite guidée de Strasbourg à pied** / Guided tour of Strasbourg on foot
19:30	**Apéritif à la Villa Quai Sturm** / Aperitif at Villa Quai Sturm
20:30	**Dîner à la Villa Quai Sturm** / Dinner at Villa Quai Sturm
23:00	Fin de la soirée networking / End of the networking evening

JEUDI 25 SEPTEMBRE / THURSDAY 25th SEPTEMBER

▶ SESSION APPRENTISSAGE MACHINE / MACHINE LEARNING SESSION

Auditorium S. Veil / Modérateur : Marc FAUCON

08:30	Accueil café / Welcoming coffee	
9:00	Tiphaine GUERRY IREIS - HEF	Optimisation bayésienne dynamique pour le développement de processus laser ultrarapides *Dynamic bayesian optimization for efficient ultrafast laser process development*
9:20	Markus KOGEL-HOLLACHER PRECITEC	Chaînes de production photonique - Méthodes d'IA pour les données de traitement et la lumière façonnée pour un meilleur traitement des matériaux par laser *Photonic production chains - AI methods for process data and shaped light for better laser material processing*
9:40	Eric MOTTAY H-NU	Ablation du silicium pour l'analyse de défauts de circuits intégrés : apport de l'apprentissage automatique *Machine learning assisted ablation of silicon for integrated circuit fault analysis*
10:00	Sébastien LANDON QIOVA	Intelligence artificielle et mise en forme de faisceau par modulateur de phase : la combinaison gagnante pour une optimisation complète des outils laser digitaux *Artificial intelligence and spatial light modulators: the winning pair for fully optimized digital laser tools*
10:20	Loïc MOSSER ICUBE	Vers un contrôle en ligne de la texturation de surface par laser à impulsions ultracourtes *Towards online monitoring of ultrashort pulse laser surface texturing*
10:40	Pause-café / Coffee break	

▶ SESSION SOUDAGE LASER / LASER WELDING SESSION

Amphithéâtre P. Pflimlin / Modérateur : Emric VERWAERDE

9:00	Victor HAYOT ICAM	Intégration des technologies modernes de soudage au laser dans la prédiction basée sur les paramètres des géométries de soudage au laser *Integrating modern laser welding technologies in parameter-based prediction of laser weld geometries*
9:20	Andre ANDREEV TRUMPF	Approche holistique du Can-Cap Welding avec des optiques de traitement en combinaison avec la célèbre technologie Brightline Weld - Mesure capillaire conviviale et fiable avec VisionLine OCT Detect *Holistic approach of Can-Cap Welding with processing optics in combination with the famous Brightline Weld technology - User friendly and reliable capillary measurement with VisionLine OCT Detect*
9:40	Audrey BOURRIEZ COHERENT	Technologie innovante de soudage laser pour la production de batteries *Innovative laser welding technology for battery production*
10:00	Sébastien LAFAYE LASER RHÔNE ALPES & Alexandre MATHIEU LABORATOIRE INTERDISCIPLINAIRE CARNOT DE BOURGOGNE	Soudage laser hétérogène entre titane et acier inoxydable : 10 ans d'études *Dissimilar laser welding of titanium to stainless steel: ten years of studies*
10:20	Emric VERWAERDE LASER CHEVAL	Quels outils d'assistance pour le soudage laser ? *Which assistance tools for laser welding?*
10:40	Pause-café / Coffee break	

▶ TABLE-RONDE / PANEL SESSION

Auditorium S. Veil / Modérateur : Gwenn PALLIER

11:10	Table ronde thématique : Transition énergétique / Thematic panel session: Energy transition
12:20	Pause déjeuner / Lunch break

▶ SESSION PLÉNIÈRE DE CLOTURE / PLENARY CLOSING SESSION

Auditorium S. Veil / Modérateur : Markus KOGEL-HOLLACHER

14:00	**François WEISBUCH** **GLOBAL FOUNDRIES**	Une introduction à la microlithographie : une technologie clé pour l'industrie des semi-conducteurs *An Introduction to microlithography: a key enabling technology for the semiconductor industry*
14:30	**Matthieu LANCRY** **UNIVERSITÉ PARIS-SACLAY**	Fonctionnalisation des verres par laser femtoseconde pour des capteurs optiques à haute température – tendances, limites et opportunités *Functionalizing optical glasses by femtosecond laser for high temperature sensing – trends, limits and opportunities*
15:00	**Andreas HEIDER** **BOSCH**	Soudage laser du cuivre pour les applications de mobilité électrique - Défis et limites de la production en série *Laser welding of copper for e-mobility applications – Challenges and limits in serial production*
15:30	**Sylvain LECLER** **ICUBE**	Micro-usinage par laser : du nanojet photonique au femtoseconde *Laser micro-machining : from photonic nanojet to femtosecond*
16:00	Discours de cloture / Closing talk	

Laser based technologies for the development of key technologies for nuclear fusion

Dr. Jochen Stollenwerk[1]*, Prof. Dr. Constantin Haefner [2]

1-Fraunhofer Institute for Laser Technology ILT, Germany
2-Fraunhofer-Gesellschaft e.V., Germany
**jochen.stollenwerk@ilt.fraunhofer.de*

In December 2022 with the world's first time ever ignition of a burning plasma through inertial confinement of a dense plasma, fusion energy has garnered global attention. Plasma confinement and ignition were driven by the world's largest and most energetic laser in this experiment: the National Ignition Facility in the United States. In the last 24 months, this experiment has been successfully repeated several times and is an important step in the development of fusion as an energy source. For the realization of fusion as a new energy source several steps have to be taken. One of them is developing solutions for key technologies like plasma facing components, laser driver, final optics etc. considering economic aspects as well as upscaling issues.

The Fraunhofer-Gesellschaft is generally tasked with advancing technologies and bringing them to market for the benefit of industry and society. In 2021, a first market study led by the Fraunhofer Institute for Laser Technology ILT identified the difficulty of building a fusion industry capable of delivering a power plant, which requires the establishment of robust supply chains. European Industry is leading in a lot of the laser and optical technologies. Especially Germany is a world exporter of lasers as about over 40% of the market shares in Europe with respect to photonics market. The development of laser-based technology für fusion energy is a huge opportunity for the European industry to enter a new application market and to develop new generations of laser and optic, which can be used also for further applications.

Fraunhofer ILT plays a significant role in advancing fusion research for both approaches: magnetic confinement (MCF) and inertial confinement (ICF) by developing innovative laser systems and technologies. Fraunhofer ILT's contributions include the design of high-precision laser components, optimization of laser pulse delivery techniques, the development and adjustment of new materials for plasma facing components, the development of new target technologies for IFE and the development of cutting and joining technologies for different fusion components. In cooperation with the industry and other research institution Fraunhofer ILT started the first projects within the German research program "Fusion 2040". Within this program Fraunhofer ILT started projects to develop new generation of diodes, optics and laser concepts to enable the development of new diode pumped driver laser in close collaboration with the leading industry. By using Laser Powder Bed Fusion (LPBF), a process invented by Fraunhofer ILT scientists, and Laser Material Deposition Fraunhofer ILT helps to develop a new generation of plasma facing components, necessary for both fusion approaches MCF and ICF. Furthermore, the talk will give an overview of the activities that have already been launched by the Fraunhofer ILT to support the development of fusion key technologies.

Process monitoring- Do we really need AI?

Eveline Reinheimer[1]
1-Dr. Ing. h.c. F. Porsche AG

**eveline.reinheimer@porsche.de*

The use of artificial intelligence is constantly increasing in laser welding process monitoring - but is it necessary in every case or are statistical evaluation methods sufficient? The aim is to take a critical look at the hype surrounding AI and weigh up the use of AI in order to enable the best possible process monitoring using the example of welding on hairpins.

Photonic production chains - AI methods for process data and shaped light for better laser material processing

Markus Kogel-Hollacher,[1,2], Jens Reiser[1], Thomas Nicolay[2], Joachim Schwarz[3], Geoffrey Bruno[4]

1 - Precitec GmbH & Co. KG, Draisstrasse 1, 76571 Gaggenau, Germany
2 - Precitec Optronik GmbH, Schleussnerstrasse 54, 63263 Neu-Isenburg, Germany
3- Precitec Vision GmbH & Co. KG, Rotfarb 4, 8413 Neftenbach, Switzerland
3 – Enovasense, 10 Rue du Général de Gaulle, 94110 Arcueil, France
**mkh@precitec.de*

Photonic production chains represent a transformative approach to manufacturing, leveraging the unique properties lasers for material processing. The integration of artificial intelligence (AI) into these processes further enhances efficiency and adaptability, paving the way for more intricate designs and optimized production outcomes. This became even clearer in the context of battery and e-mobility applications.

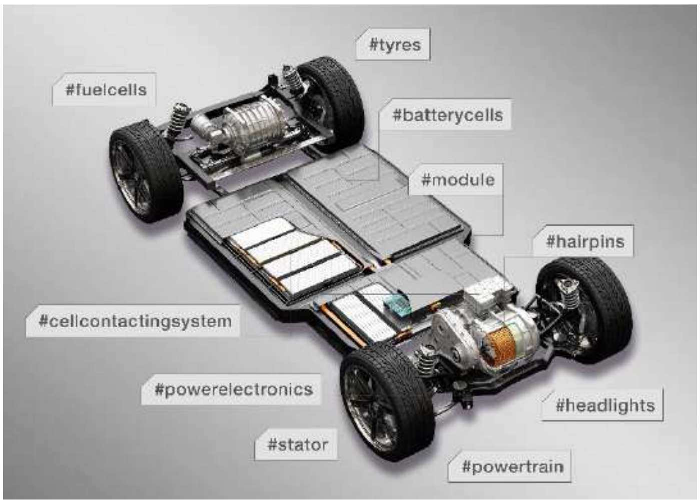

Figure 3 : Overview of typical laser welding applications in e-mobility

AI-driven methods in photonic production chains enable real-time monitoring, adaptive control, and predictive maintenance of laser systems. By analyzing vast amounts of data from the manufacturing process, AI can dynamically adjust laser parameters such as power, pulse duration, and beam shape, ensuring optimal performance and reducing material waste. Machine learning algorithms also facilitate defect detection and quality assurance, making the process more reliable and less dependent on manual intervention.

Shaped light, a technique involving the manipulation of laser beam profiles, plays a critical role in enhancing the precision and versatility of laser material processing. By customizing the intensity distribution of the laser beam, shaped light allows for more controlled energy deposition, enabling the processing of a wide range of materials with varying properties. This capability is particularly useful in applications such as micro-machining, additive manufacturing, and surface texturing, where precision is paramount.

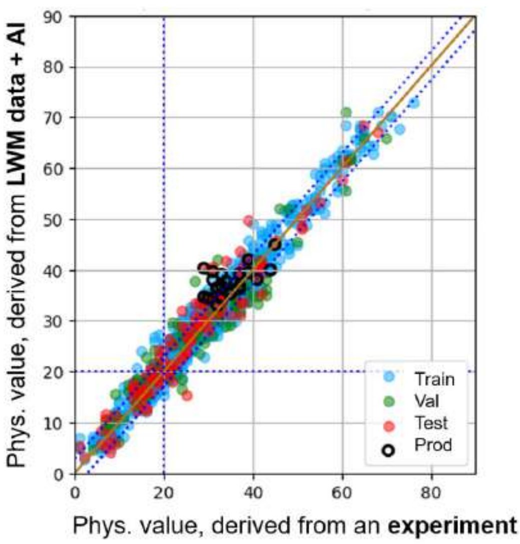

Figure 4 : AI based data evaluation; Application: Foil welding; Penetration depth approx. 100µm; 1200 0Samples, ~120 Test Samples; R2 93.4%

The combination of AI methods and shaped light in photonic production chains leads to a highly adaptable and intelligent manufacturing system. This integration not only improves the accuracy and speed of production but also opens new possibilities for creating advanced materials and components. This presentation for PLI 2025 will provide an insight into Precitec's activities in recent years, being able to more than concept proof the advantages of these individual approaches, but also their combination.

La sécurité des appareils laser à usage manuel

***Franck Rigolet*[1]**

1- IREPA LASER, Pôle API – Parc d'Innovation 320 Boulevard Sébastien Brant, 67400 Illkirch, France

**fr@irepa-laser.com*

En quelques mois, les appareils laser à usage manuel (soudage, décapage, découpe) se sont largement répandus dans l'industrie, y compris dans des secteurs jusqu'alors peu familiers avec cette technologie. Cette adoption rapide s'est accompagnée de nouveaux risques pour les utilisateurs, mettant en tension le cadre européen de protection des travailleurs et soulevant des interrogations sur l'application des directives relatives aux machines et aux équipements de protection individuelle (EPI).

Or, la sécurité des utilisateurs ne peut reposer uniquement sur leur vigilance ou sur l'application de protocoles stricts. Il est essentiel que les fabricants, importateurs et revendeurs assument pleinement leur responsabilité en mettant sur le marché des équipements conformes aux normes de sécurité en vigueur. Les certificats et marquages CE ne garantissent pas toujours un niveau de protection suffisant, rendant d'autant plus crucial le respect rigoureux des exigences réglementaires dès la conception et la commercialisation des appareils laser et de leurs protecteurs.

À travers des exemples concrets, nous mettrons en lumière les obligations des fabricants et les enjeux de la conformité pour assurer une réelle sécurité des utilisateurs.

Assessing environmental risks of femtosecond laser technology in the industry

Mathieu Vautrot*[1], Charles Rouchon[2], Valentin Maffeis[2], Julien Granier[3]

1-WEARE TECH Groupe MECACHROME, 20 rue Professeur Benoit Lauras, 42000 Saint Etienne, France
2-IREIS-HEF, 7 rue Salvador Dali, 42000 St-Etienne, France
3-Manutech USD, Bâtiment des Hautes Technologies, 20 rue Professeur Benoit Lauras, 42000 St-Etienne, France
**mathieu.vautrot@mecachrome.com*

The femtosecond laser industry is rapidly growing due to the technology offering unparalleled precision and new prospects for micromachining, engraving, cutting, and surface functionalization. However, as the utilization of femtosecond lasers becomes more widespread, it is crucial to evaluate and address potential environmental risks associated with their application. In addition to the well-known danger of direct exposure to the beam, the presence of X-rays, fumes and nanoparticles can also be a concern. Anticipating future policies in that regard could be of interest for both manufacturers and end-users.

Laser ablation is the principle behind engraving and cutting. Depending on the targeted materials, fumes of (nano)particles are emitted. In some cases, particles, sized between 1 and 100 nm, can be ejected faster than 1000 $m.s^{-1}$ [1,2]. In our setup with stainless steel, we obtained particles sized between 400 nm and more than 1 µm as shown in Figure 1 (a). Due to their low mass, initial velocity, and supposed charge, it is highly likely that they can partially evade even the best aspiration systems. After some particles' collections from common materials, we assessed the concentration of those airborne particles in a real work environment and propose a comparison with current legal concentrations of fumes.

X-ray generated by the plasma caused by the focusing of a femtosecond laser beam on almost any material are generally low in energy (5-20 keV) causing their penetration depth in organic tissue to be around a millimeter or less [3]. Nonetheless, higher fluences are reached by modern lasers, resulting in increasingly higher X-rays fluxes, warranting proper safety measures [4-5] as shown in Figure 1 (b). In this work, x-ray emission has been measured for common materials up to 20 J/cm^2 in different setups.

Finally, some advice and recommendations are given for the use of a laser in the industry with correct conditions.

(a)

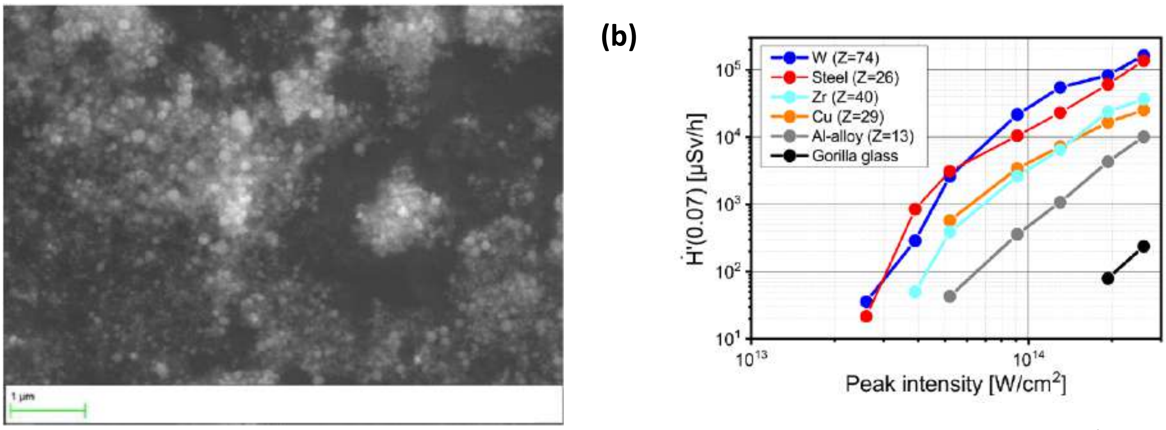

Figure 1 (a) Image obtained from scanning electron microscopy of nanoparticles (b) Measured dose rates of X-rays (Ḣ'(0.07)) in dependence on the material and the laser peak intensity [5]

[1] M. Spellauge, C. Doñate-Buendía, S. Barcikowski, B. Gökce and H. P. Huber, Comparison of ultrashort pulse ablation of gold in air and water by time-resolved experiments, Light: Science & Applications, 11, 68-80, (2022)
[2] J. Perrière, C. Boulmer-Leborgne, R. Benzerga and S. Tricot, Nanoparticle formation by femtosecond laser ablation, Journal of Physics D: Applied Physics, 40, 7069-7076, (2007)
[3] A. Baguckis, A. Plukis, J. Reklaitis, V. Remeikis, L. Giniūnas and M. Vengris, Generation of plasma X-ray sources via high repetition rate femtosecond laser pulses, Applied Physics B: Lasers and Optics, 123, 290-296, (2017)
[4] H. Legall, C. Schwanke, S. Pentzien, G. Dittmar, J. Bonse and J. Krüger, X-ray emission as a potential hazard during ultrashort pulse laser material processing, Applied Physics A: Materials Science and Processing, 124, 407-414 (2018)
[5] H. Legall, C. Schwanke, J. Bonse and J. Krüger, X-ray radiation protection aspects during ultrashort laser processing, J. Laser Appl. 32, 022004 (2020)

Issues with laser safety of hand held laser welding systems

David Lawton[1], Bonnie Simmons[2], Tom MacMullin[3]

1- European Market Development Manager Kentek Corporation, 5 Jarado Way, Boscawen, NH 03303 USA

Corresponding author: dlawton@kenteklaserstore.com

With the advent of fibre lasers, recent years have seen an explosive growth in powerful multi-kW Handheld laser welding systems which offer significant and tangible benefits over traditional methods including ease of use, minimal set up costs, quick and simple training, fast and flexible processing and almost no post-process finishing but still delivering high quality results.

Open beam laser systems for material processing have traditionally been used in controlled and often fully enclosed environments but, by their nature have exposed beams and are also being found in unconventional situations including outdoors and open 'shop floors' within industrial manufacturing.

Standards exist for both laser and welding to assist with the management and control of NIR radiation including containment and training/safety of personnel that work with and around the application, however, there is no natural bridge between the two.

Furthermore, the current Standards and Norms for Laser Personal Protective Equipment (PPE) are struggling to keep up with the emerging laser welding technology. Even with newly published ISO welding standards, there are still 'holes' and unfamiliar 'challenges' with the current international safety standards especially for the blend of laser and welding.

In this paper, the authors will explain the holes and challenges in more detail including referencing specific international standards and how, as a well-respected and trusted laser and welding safety solution provider, they have had to change and tailor their approach to overcome the issues they currently face.

Using real world examples with evidence, the authors will demonstrate how current approaches for PPE may not be safe for the user(s) and how the unique challenge of laser safety with handheld laser welding systems should be approached within the current framework of standards and norms.

Holmium-based solid-state ultrafast lasers for science and industry

Michael Müller[1,2], Célia Millon[1,2], Anna Suzuki[2], Boldizar Kassai[2], Yicheng Wang[2], and Clara J. Saraceno[2]
[1]RayVen Laser, Ruhr-University Bochum, Universitätsstraße 150, 44801 Bochum, Germany
[2]Photonics and Ultrafast Laser Sciences, Ruhr-University Bochum, Universitätsstraße 150, 44801 Bochum, Germany
**Michael.mueller@rayvenlaser.com*

Ultrafast lasers at 2 µm wavelength have scientific, medical, and industrial use. For example, the long wavelength enables in-volume modification and backside-machining using the transparency window of semiconductors [1]. On the contrary, strong absorption of 2 µm radiation in polymers allows for efficient surface ablation [2]. Ultrafast 2 µm-range lasers can be obtained by parametric conversion of near-infrared drivers, or from Thulium (Tm)- or Holmium (Ho)-based lasers. The latter two allow for simple and compact sources that fulfill most applications' needs. While Tm-doped fiber lasers excel at low energy and very-high average power [3], Ho-based solid-state lasers offer high pulse energy and high average power [4,5].

In this contribution we present on robust implementations and the applications of holmium-based ultrafast solid-state lasers for scientific and industrial users. First, we introduce a low-noise oscillator for amplifier seeding or direct application. Second, we present on the development status of an amplifier system. Lastly, we discuss first material processing tests with such an amplifier system.

The oscillator, technically similar to Ref. [6], is rigidly assembled into a compact, dust-tight, and water-cooled aluminum housing for long-term stable alignment, as shown in the first panel of Fig. 1. The oscillator emits pulses with 102 fs duration (FWHM) at 71 MHz repetition rate and at an average power of 1 W. The optical spectrum and the phase noise of the fundamental radio-frequency peak are displayed in the other two panels of Fig. 1. The $sech^2$-shaped spectrum is a sign of clean soliton operation. The phase noise of the laser is low as revealed by the integrated timing jitter of only 350 fs in the frequency span 1 MHz to 100 Hz.

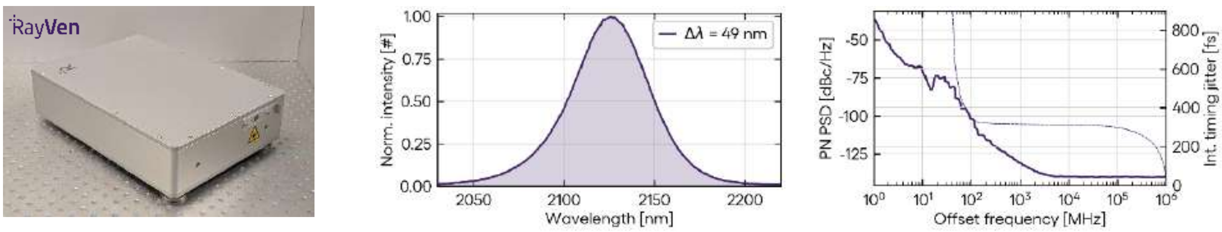

Fig. 1 Photograph of the oscillator (left), the optical spectrum (middle) and the phase noise power spectral density (right).

The chirped-pulse amplifier under construction is based on Holmium-doped CALGO, too, and follows the same design principles as for the oscillator. It is expected to mirror the specifications of the existing research system [7], which delivers 10 W average power and 100 µJ pulse energy for a 10 nm-wide spectrum centered at 2090 nm. The compressed pulse duration is on the order of 750 fs. Packaging of the system is ongoing, and the status will be reported.

Processing tests on silicon and PMMA were conducted using the research system. The results are shown in Fig 2. A 70 µm-wide line was scribed on a silicon wafer and cleaving along this line lead to a clean edge. On PMMA a line of just below 10 µm width was ablated at the surface with a more detailed analysis being underway. However, both examples show that there is potential for ultrafast 2.1 µm lasers in precision materials processing.

Fig. 2 Processing tests: Scribe in silicon wafer (left), cleaved wafer edge (middle), and scribe in PMMA (right).

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Ultrafast Laser Bessel Beam Interaction with Fused Silica in Single Pulse, MHz-Burst, and GHz-Burst

Guilberteau, T.[1,2,*] ; Balage, P.[1] ; Lafargue, M[1,3].; Lopez, J[1].; Gemini, L.[2]; Manek-Hönninger, I.[1]

1. CELIA UMR 5107, 33405 Talence, France

2. ALPhANOV, Rue François Mitterrand, 33400 Talence, France

3. Amplitude, Cité de la Photonique, 11 Avenue de Canteranne, 33600 Pessac, France

**theo.guilberteau@u-bordeaux.fr*

In this study, we show the use of spatial Bessel-beam shaping to produce high-aspect-ratio micro-channels in different regimes - single pulse, MHz-burst or GHz-burst. We investigated the influence of pulse energy and temporal shaping on the elongated bulk modification shape and the inner wall quality. Then, we used selective chemical etching to produce micro-channels. The results in terms of etching rate and micro-channel morphology are discussed regarding laser parameters and compared to previous results published in the scientific literature [1,2]. Our findings constitute a significant contribution to advancing micro drilling and sub-surface structuring of transparent dielectrics, especially for applications requiring high-precision material removal. Moreover, we demonstrate single step and chemical-free micro-channel drilling using a single GHz-burst, which is extremely interesting for applications like Through Glass Via (TGV) fabrication in thick glass.

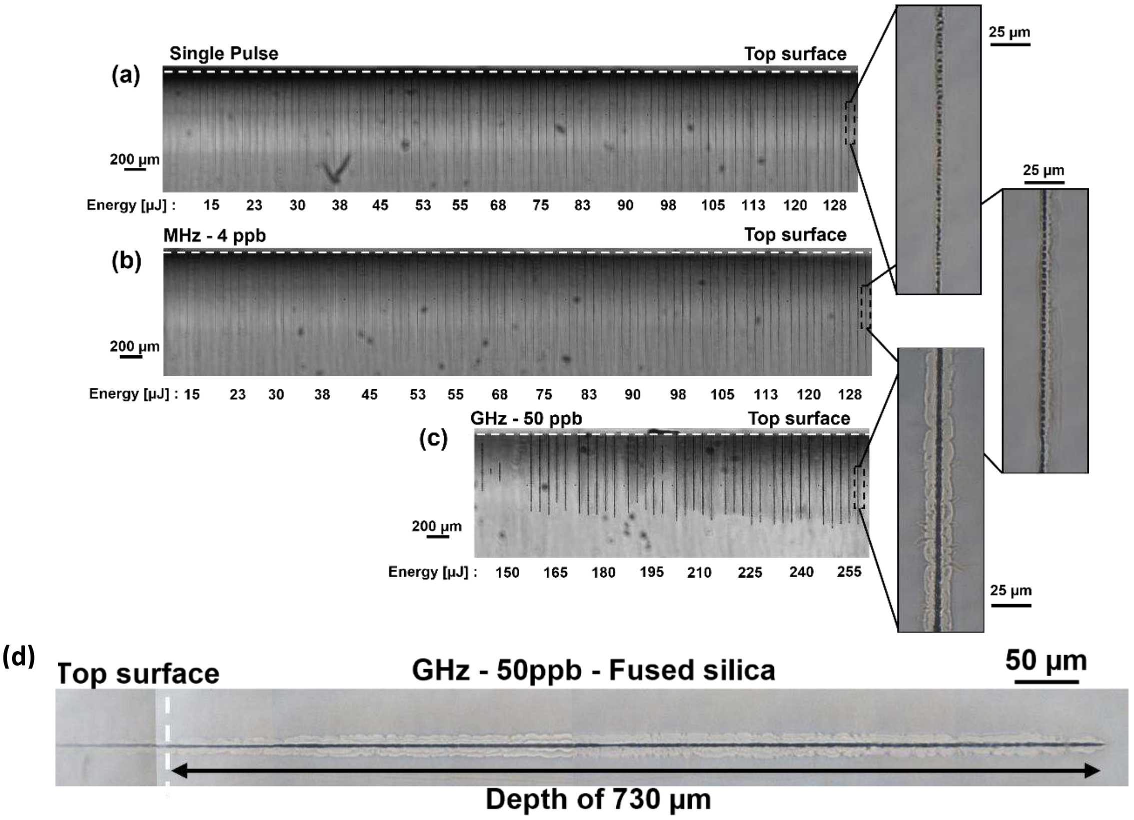

Fig. 1 Optical microscope side views of modifications obtained in fused silica after laser irradiation with a single pulse or burst, respectively, at an energy ranging from 15 to 255 µJ, (a) Single-pulse mode, (b) 4 ppb MHz-burst and (c) 50 ppb GHz-burst. (d) Void microstructure obtained in fused silica with one single GHz-burst (50 ppb) of 255 µJ without chemical etching. Top surface is on the left. The pitch between two modifications of same energy is 50 µm. The white line at the top of each microscope image represents the top surface. The inserts on the right are a zoom of the highest energy modification delimited by a rectangle of black lines.

Example References

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Ultrashort laser drilling technologies for through glass via fabrication in customised glass interposers

Mostafa Hassan, Dimitris Karnakis*

Oxford Lasers Ltd, Unit 8 Moorbrook Park, Didcot, Oxfordshire OX11 7HP, United Kingdom
**dimitris.karnakis@oxfordlasers.com*

Tier-1 semiconductor 2.5D advanced packaging can integrate different types of die like logic, analog, RF, etc. interconnected on a shared interposer substrate (organic, silicon, ceramic or glass) to achieve high performance and avoid limitations from monolithic chip designs. Glass interposers specifically offer key advantages at low cost. Glass is transparent, inert, stable across a wide temperature and humidity range and lossless as an insulator. Recently market interest has emerged for customised glass interposers in lower tier companies specialising in high value, lower volume applications. Laser drilling through glass vias (TGVs) for interconnection is challenging given glass' brittleness and is frequently accompanied by unwanted cracking and chipping due to thermal stress. Additionally, the TGV surface quality can be poor with crater edge defects, scattered laser debris and compromised performance if not polished away in a post process step.

This paper discusses advantages and limitations of ultrashort TGV laser drilling of boroflat33 glass (0.3mm thick) using three different ultrashort laser drilling techniques based on 1030nm laser amplifiers (20W Satsuma, 40W Carbide) with GHz/MHz burst pulsing capability: (i) single-mode percussion or trepanning laser drilling, (ii) percussion GHz-burst drilling and (iii) selective laser-assisted chemical etching. All three techniques find valuable niches for TGV sizes ranging 20-100µm depending on throughput and quality requirements. Single-mode percussion or trepanning is flexible and simple to integrate but produces unwanted laser debris around the via crater and thermal stress which can lead to glass fracturing and microcracking (fig.1a). Temporal pulse shaping with burst pulsing offers high drilling rates and near-zero taper, smooth crack-free TGVs (fig.1b) but at the expense of surface quality. Selective laser-assisted chemical etching produces smooth vias with no post-process requirements however this technique cannot easily control the TGV 3D shape. Examples of indicative TGVs and the merits of each technology will be presented in more detail.

(a) (b)

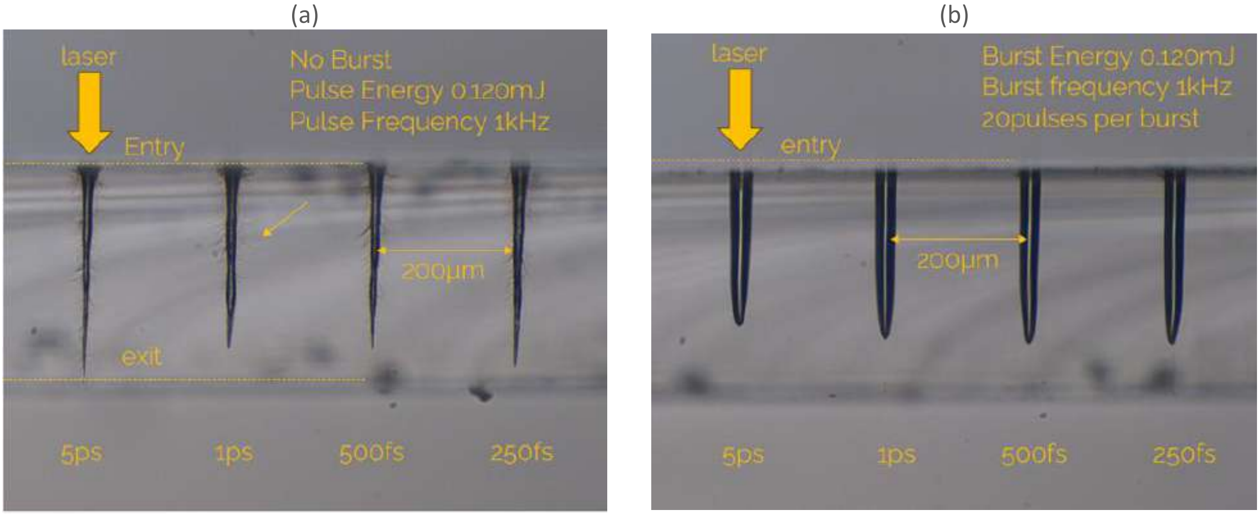

Figure 1 Optical microscope images of sectioned TGVs in ultrashort percussion laser drilled borofloat33 glass (0.3mm thick) with (a) single-mode (no burst), 120µJ per pulse at 1kHz from 250fs to 5ps showing cracking around the borehole and (b) GHz burst pulsing using the same laser energy and frequency but distributed in 20 sub-pulses in each burst. Smoother borehole walls without evidence of microcracking can be produced at near zero taper which is advantageous. Total drill time for both cases is 1sec.

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Blue diode lasers with higher output power and better beam quality open new applications for these highly efficient lasers

Andre Eltze, Luisa-Marie Schäfer-Heine, Daniel Huh, Mathias Schlett

Laserline GmbH, Germany
**andre.eltze@laserline.com*

Blue diode lasers have reached new performance levels, with continuous-wave output powers now available up to 6 kW, making them the most powerful industrial blue lasers to date. Operating at a wavelength of around 445 nm, these lasers achieve absorption in copper alloys that is almost ten times higher than that of near infrared (NIR) lasers, significantly reducing the energy required for material processing and allowing for precise heat input. This makes them ideal for heat conduction welding, keyhole welding and cladding as well as additive manufacturing (AM) applications, often in the production of high-density copper components for battery technology and power electronics. The ability to achieve high absorption also enhances the efficiency of manufacturing processes for power electronics and e-mobility applications. In the welding of busbars (figure 1(a)), for example, the improved absorption leads to exceptionally stable and uniform melt pools, effectively eliminating spatter and porosity while ensuring excellent electrical conductivity. In additive manufacturing, blue diode lasers offer a major advantage for copper-based materials, with powder efficiencies exceeding 80%, thus significantly reducing material waste and improving process sustainability. The high energy efficiency of diode lasers and precise control enable CO_2-reduced production processes across various industrial sectors, making them an environmentally and economically attractive alternative to conventional laser systems.

In addition to increased power, novel blue diode lasers with exceptionally good beam quality (4 mm mrad and better) further expand their application range, particularly in powder bed 3D printing (figure 1(b)). The high brightness and superior focusability of these lasers enable the fabrication of extremely fine details and intricate geometries, which is essential for industries requiring high precision and surface quality, such as aerospace, medical technology, and high-performance electronics made from pure copper. The improved beam quality also enables scanner based welding applications and joining of thin foils for battery production. The ability to process highly reflective and thermally conductive materials, such as pure copper and copper alloys, with minimal defects extends the usability of blue diode lasers beyond traditional welding and cladding. These advancements solidify blue diode lasers as a transformative technology in advanced manufacturing, paving the way for increased adoption in next-generation production techniques.

Figure 1.

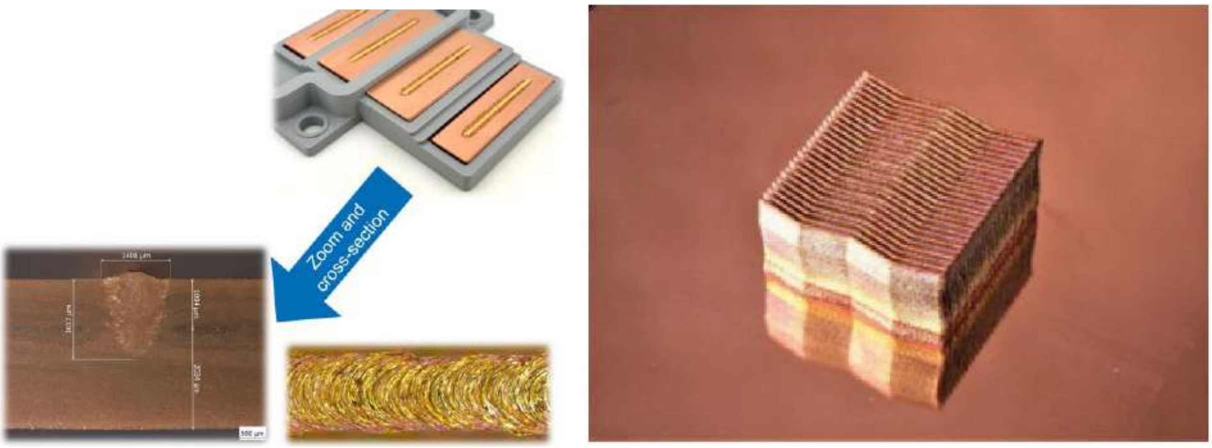

Figure 1 (a) welding of busbars. 1 mm on 2 mm copper @ 3.6 kW - Figure 1 (b) powder bed 3D printing of pure copper. 350 W, 250 layers, size: 21x21x10 mm³

Micromechanical characterization of laser-treated interfaces

Leila SELLAMI[1], Sophie COSTIL[1], Eric BOURILLOT[2], Léa LE-JOINCOUR[3]

1- *University of Technology of Belfort Montbéliard*
2- *University of Burgundy EUROPE*
3- *University of Technology of Troyes*
**leila.sellami@utbm.fr*

Laser texturing is an efficient and environmentally friendly method for preparing surfaces, providing improved performance with increased productivity and lower environmental impact. Adaptable to various materials and uses, it improves the resistance and adhesion of coatings by custom modifying the roughness and chemical composition of the surface. However, many obstacles remain to be overcome regarding the phenomena induced during the laser-matter interaction, however brief it may be (microstructural changes, stresses/deformations, etc.). Such changes can in fact directly influence the service life of the system (coated substrate), hence the need to evaluate them in order to control them as best as possible and to be able to optimize the process in a context of cost reduction and sustainability.

The aim of this study is therefore to analyze in detail the evolutions of the microstructure and the local mechanical state (particularly in terms of impacts) of the material. By means of various characterization methods, conventional (XRD, EBSD) but also more recent (scanning microwave microscopy SMM), a more or less precise analysis of the surface then becomes possible. Indeed, the lateral resolution of the order of a few nanometers of the SMM allows more precise detection in depth (of the order of ten microns depending on the choice of frequency) to compare to the millimeters analyzed by XRD. Thus, depending on the laser treatment strategies, all surface changes can be investigated from a morphological (microscopy), structural and mechanical point of view.

Given their wide industrial exploitation, nickel or titanium based materials will then be particularly studied. A comparison of massive materials or even those resulting from additive manufacturing (SLM: Selective Laser Melting) is considered.

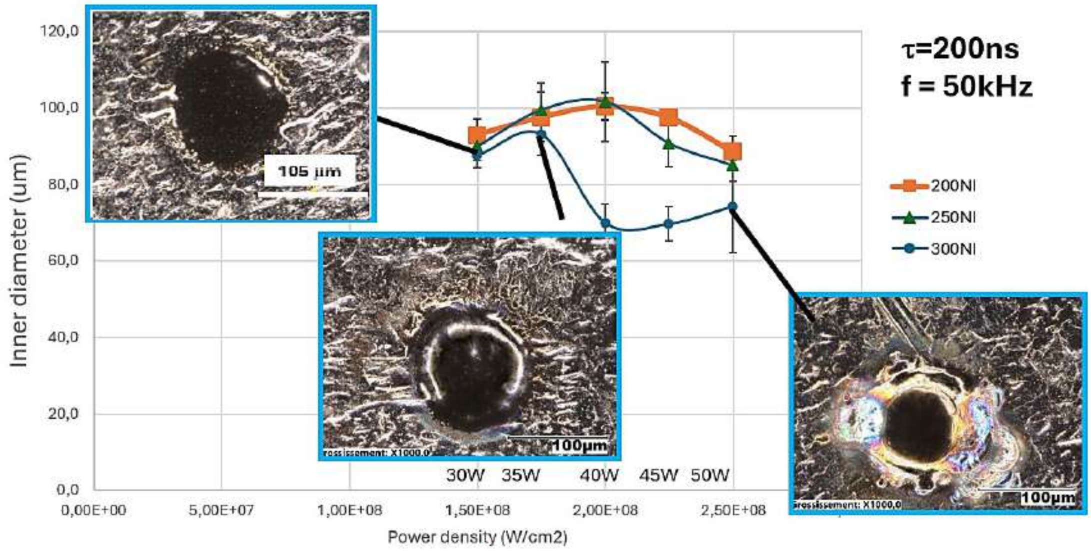

Figure 1 Laser parameters effect (power) on the inner diameter of the impacts in nickel

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Shortwave infrared, near-infrared, and visible light imaging systems for thermal monitoring of laser cladding processes

Dmytro Havrylov*[1], Gentry Wood[2], Patricio F. Mendez[3]

1-Xiris Automation Inc., Canada
2-Apollo-Clad Laser Cladding, Canada
3-Canadian Centre for Welding and Joining, University of Alberta, Canada
**dhavrylov@xiris.com*

Laser cladding is an advanced process for applying high-performance coatings that resist wear and corrosion. With increasing demands for higher productivity and the rise of direct energy deposition (DED) additive manufacturing (AM), adaptive process control is becoming essential. Monitoring the thermal behaviour of the molten clad pool is a promising way to achieve this. Key areas of focus include the melt pool's shape, the quality of the clad bead, and the flow of powder.

Midwave infrared (MWIR) cameras are commonly used for thermal monitoring in laser cladding; however, they often have lower resolution and require specialized non-glass optics. Shortwave infrared (SWIR) cameras offer a potential solution by combining the benefits of both MWIR and visible light cameras. This study compares the performance of visible (VIS), near-infrared (NIR), and SWIR cameras in the context of laser cladding. Tests were conducted using Inconel 625 powder on Inconel 718, 4140, and 4330V alloy steels, as well as spherical tungsten carbide in a Ni-B-Si matrix on 4330V. The setup included an ytterbium fibre laser with a 1070 nm wavelength.

In the SWIR range, thermal emissions from the melt pool, cooling clad bead, and powder flow were clearly captured, whereas in the VIS and NIR ranges, only the powder flow was visible. A SWIR camera was used to capture the melt pool's dimensions, including length, width, and area, and the data were analysed using a Blob algorithm. The study also explored how variations in laser power, travel speed, and powder feed rate influenced the Inconel 625 melt pool. Results showed that the melt pool's length and area were more sensitive to changes in process parameters than its width.

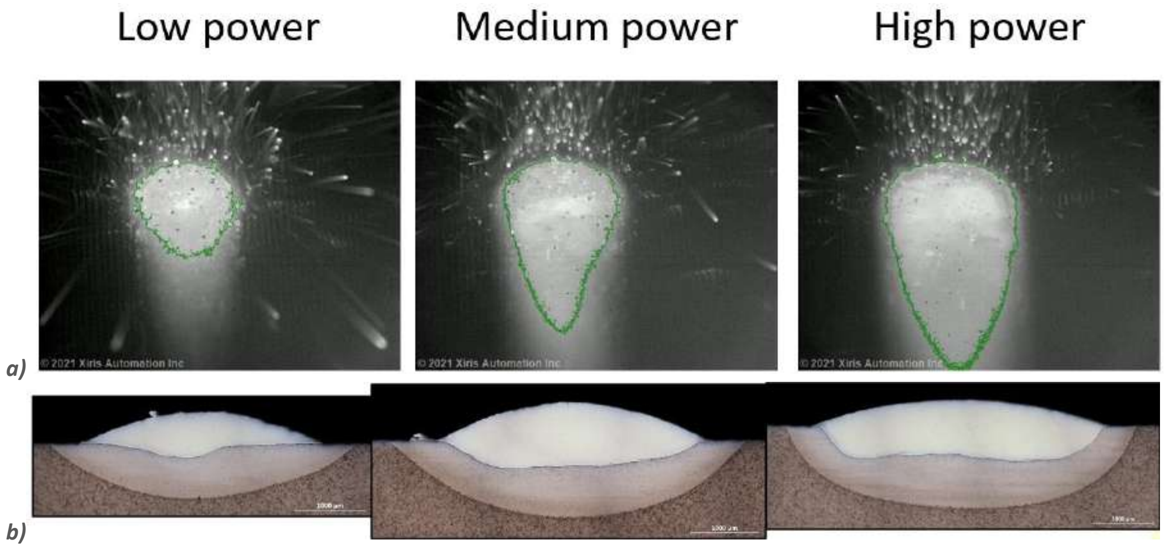

Figure 1 (a) The observed melt pools for three different laser power modes. The melt pools are segmented and measured using Xiris Blob Tool. The increased power resulted in excessively large, elongated melt pools. (b) The cross sections of the clad beads corresponding to the process parameters used. The defective clad beads with high dilution correspond to the excessively large melt pools for medium and high power from Figure 1(a).

New applications in laser processing and how they profit from beam-shaping

Dmitry Nuzdhi[1], Adeline Orieux[1], Gwenn Pallier[1], Guillaume Labroille[1]

1- Cailabs, France
**gwenn@cailabs.com*

Lasers have revolutionized industry for decades and are now widely used in the manufacturing of various products, from watches and smartphones to cars, airplanes, and even jeans! However, the laser ecosystem - particularly in Europe - is facing challenges, partly due to the slowdown in the automotive sector.

In this paper, we will explore the fastest-growing markets, such as consumer electronics and semiconductors, as well as emerging long-term opportunities like data storage and nuclear fusion. These industries require innovative laser processes ranging from micro-processing and welding to surface treatment and additive manufacturing.

We will highlight the role of beam shaping in optimizing these processes. Specifically, we will discuss how femtosecond lasers, combined with top-hat square beam shaping and beam splitting, can increase surface texturing speed by a factor of 200. We will also explore quality improvement in micro-processing such as conicity reduction. We will also examine how a fast-switching system between a large-diameter ring and the preserved Gaussian profile of a machine laser can boost PBF-LB/M printing speeds by a factor of 5. In additive manufacturing, we will explore the advantages of coaxial wire-feed DED using an annular beam shape. Finally, we will address the challenges in laser welding, including managing larger gaps, reducing porosity and spatter, and minimizing scrap rates. Surface treatment with top-hat and more complex beam profiles will also be discussed.

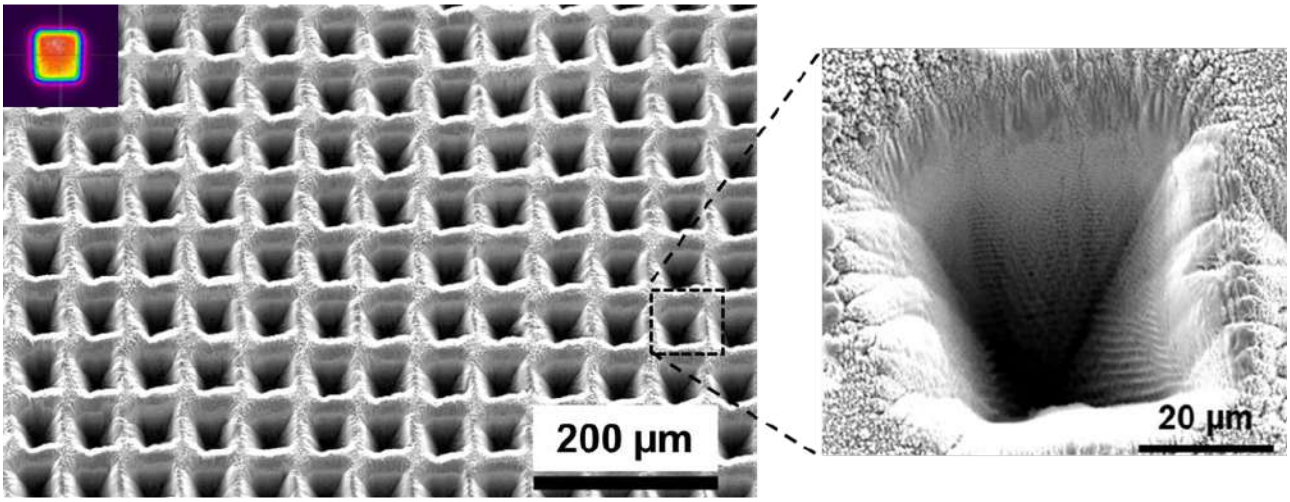

Figure 1 Percussion drilling with a square top-hat at 400µJ, 1030nm presenting reduced taper

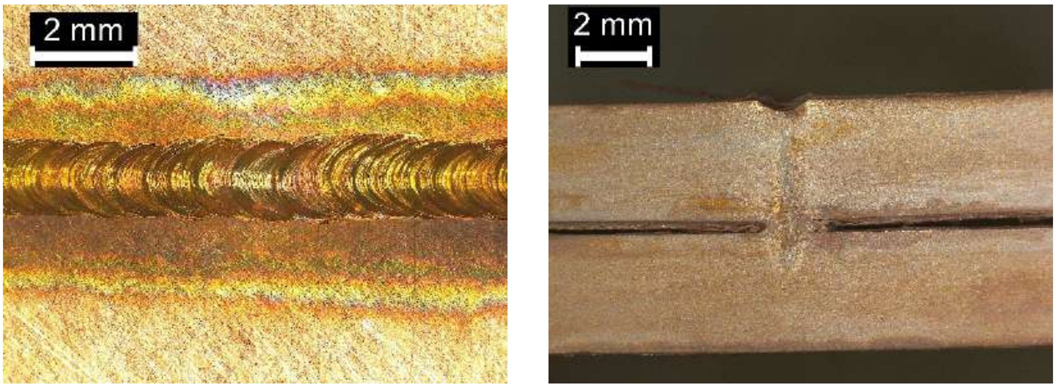

Figure 2 – 3mm/3mm overlap joint Laser Welding 3m/min, 8kW with 0.4mm gap displaying a 4.6mm penetration depth

"Pioneering Precision: Vertical Wall Cavity through Laser Micromachining"

Davide Lotto, Julien Viel, Romain Dubreuil

**romain.dubreuil@georgfischer.com*

Over the past decade, laser µmachining has evolved significantly, transitioning from a niche solution confined to high-tech laboratories into a viable alternative to conventional subtractive machining processes. This advancement has been driven by breakthroughs in femtosecond laser technology and the development of advanced 5-axis scanners, enabling complex processes such as vertical micro-drilling and cutting.
However, one area that has seen limited progress due to the inherently non-deterministic nature of laser ablation is the machining of precise microcavities. This challenge has been characterized by three key issues :

- **Inconsistent accuracy**, constrained by machining strategies and the precision of laser systems.
- **Inability to create vertical walls**, limiting geometric versatility.
- **Rounded corners**, which impede the production of sharp edges and intricate designs.

Charmilles has committed extensive R&D efforts to overcome these limitations. Users of high-accuracy milling and die-skinning machine tools are increasingly focused on reducing energy consumption and CO2 footprint, areas where laser technology offers a real competitive advantage.
Leveraging high-precision laser platforms such as the LASER S 500 U and the advanced process and toolpath generation capabilities of LaserSUITE360, we have successfully demonstrated the ability to machine microcavities with unparalleled precision. This includes achieving perfectly vertical walls and maintaining exceptional overall accuracy within the cavity.

This presentation will showcase application examples that highlight the expanded possibilities for high-accuracy machining, particularly in tungsten carbide.

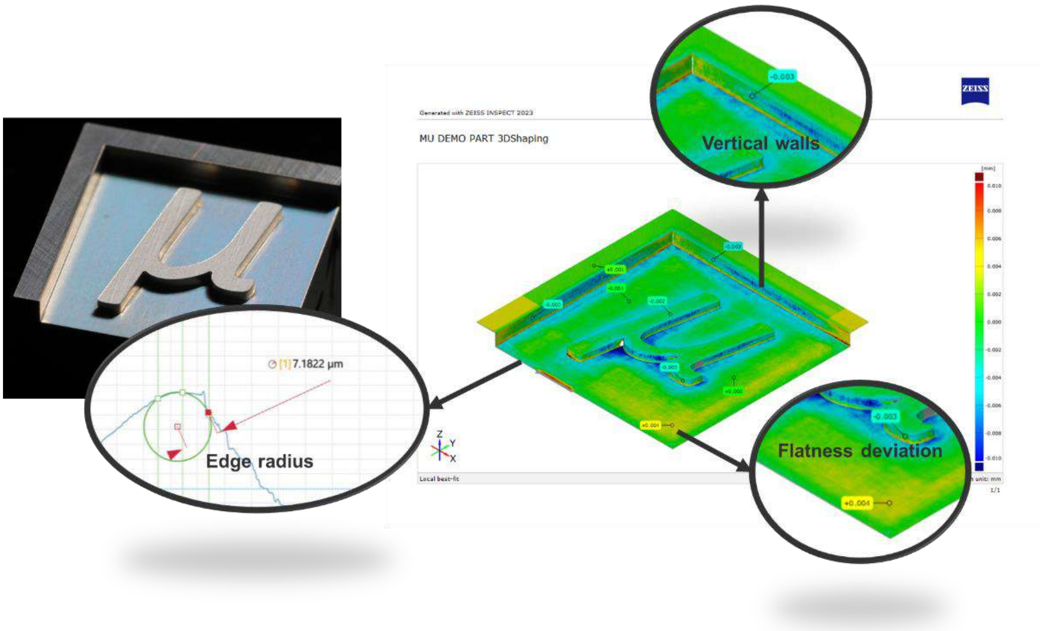

Figure 1: µmachining demonstrator

These patented innovations aim to broaden the adoption of laser micromachining across a wide range of applications, including tooling manufacturing, semiconductors, and even watchmaking.

Quantifying the efficacy of MHz-burst mode in 5-Axis ultrafast laser processing

***Eric Belski*[1], *Bryan Germann*[1]**

1- Aerotech, Inc.

Ultrafast lasers are widely used in precision micromachining due to their ability to deliver high-resolution material removal with minimal thermal effects. Recently, major laser manufacturers have introduced MHz- and GHz-burst mode capabilities, where each primary laser pulse is subdivided into a series of lower peak power pulses that collectively sum to the same energy as a single pulse. While experimental studies suggest that burst mode can improve ablation efficiency for select materials—particularly those with reduced free-electron density—there is limited evidence for its efficacy for metal machining. Furthermore, there is little comparative analysis of how burst modes from different manufacturers influence material removal rates and surface quality in ultrafast laser drilling.

This work systematically benchmarks MHz-burst mode against single pulse mode in 5-axis ultrafast laser micromachining, specifically evaluating its impact on blind hole drilling in stainless steel. Recent findings [1] demonstrate that a position-based pulse control mechanism, wherein the number of pulses emitted per spatial location is precisely controlled, significantly enhances ablation efficiency. By allowing a predefined number of pulses (e.g., 1, 5, 10 or 20) at each position-based firing event, material removal rates can be optimized while maintaining high-quality hole characteristics, including controlled sidewall taper, minimal surface charring and smooth bottom surface finish. This controlled approach is functionally analogous to burst mode, where pulse packets enable deeper penetration and faster material removal without increasing the average power.

By directly comparing burst mode with single pulse mode under identical machining conditions, this study quantifies tradeoffs between processing speed and feature quality. Blind holes serve as an ideal test case, allowing detailed examination of entrance edge integrity, sidewall formation and floor smoothness as key quality metrics. While previous studies primarily report either efficiency [2,3] or quality [4-6], this work seeks to establish a comprehensive understanding of their interplay in a controlled 5-axis micromachining environment. The results provide practical insights into optimizing MHz-burst mode for metal processing applications, informing future industrial adoption of this technique.

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Measuring the quality indicator M²:
Current technologies and hidden challenges

Wilfried Vogel
Area Sales Manager, MKS|Ophir, France
Wilfried.vogel@mksinst.com

Focusability plays a key role in the assessment of laser quality: According to ISO standard 11146, this is described by the diffraction index M². It indicates how far the profile of the laser beam deviates from that of the ideal Gaussian beam. Measuring the M² is a core part of the standard quality verification process performed by the laser manufacturer. However, laser users - especially in medical applications, semiconductor and micro machining process as well as in the defense sector - are also increasingly interested in checking this quality indicator as it significantly influences the results of their laser processes.

That said, the M² is not the only parameter to consider when conducting a fine analysis of the laser beam. Astigmatism is also an important parameter for users. Although this parameter - which indicates the deviation between the focus position in the x and y directions - is not defined in the ISO standard, it is required by many users and calculated by sophisticated M² measuring devices. In the past years, especially users of femtosecond UV-lasers with longer Rayleigh lengths experienced difficulties in precisely measuring astigmatism.

This presentation outlines why measuring the M² and related parameters such as astigmatism is key in receiving high-quality results, explains recent findings and presents measurement methods that are suitable for manufacturers and end users alike.

Mesure de l'indice de qualité M² : technologies actuelles et défis cachés

La focalisation joue un rôle essentiel dans l'évaluation de la qualité du laser : selon la norme ISO 11146, elle est décrite par l'indice de diffraction M². Il indique dans quelle mesure le profil du faisceau laser s'écarte de celui du faisceau gaussien idéal. La mesure du M² est un élément essentiel du processus de contrôle de qualité standard effectué par le fabricant de laser. Cependant, les utilisateurs de laser, en particulier dans le traitement dans les applications médicales, le semiconducteur, le micro-usinage et certains applications de défense sont également de plus en plus intéressés par le contrôle de cet indicateur de qualité car il influence considérablement les résultats de leurs processus laser.

Ceci étant dit, le M² n'est pas le seul paramètre qui compte lorsque l'on souhaite effectuer une analyse fine du faisceau laser. L'astigmatisme est également un paramètre d'intérêt pour les utilisateurs finaux. Bien que ce paramètre ne soit pas défini par la norme ISO, c'est un prérequis pour beaucoup d'utilisateur et c'est un des résultats issus des systèmes de mesure de M² sophistiqués. Ces dernières années, les utilisateurs de lasers UV femtosecondes avec des longueurs de Rayleigh plus longues ont particulièrement éprouvé des difficultés à mesurer précisément l'astigmatisme.

Cette présentation explique pourquoi la mesure du M² et des paramètres associés tels que l'astigmatisme est essentielle pour obtenir des résultats de haute qualité, explique les découvertes récentes et présente des méthodes de mesure adaptées aux fabricants et aux utilisateurs finaux.

Influence of 2D mapping over 1D mapping on laser micromachined parts accuracy

Clifford Jolliffe*[1], Alexandre Barthlen[1], Priyank Agarwal[1], Raphael Grifone[1]

1-Physik Instrumente, Germany
**c.jolliffe@pi.ws*

A key requirement within a laser micromachining machine is the need to produce accurate positioning, which ultimately reduces errors in manufacturing and improves the quality of produced parts. Positioning may either involve the workpiece or the laser beam delivery head, using a motion platform made up of CNC tables, or alternatively, manipulating the beam directly onto the workpiece via a set of mirrors (i.e., Galvo Scanner). Some systems may use both methods in a hybrid format. In the former case, CNC tables are typically joined together in a format that produces a Cartesian motion layout, generating motion in the X and Y axes. Additional tables may be connected or associated, allowing motion in the vertical (Z) and angular (A, B) directions. With respect to the XY linear motion created by CNC tables, the stage characteristics can be previewed from the CNC table manufacturer’s data sheets. These attributes include linear errors (repeatability, accuracy, straightness, flatness) and angular errors (pitch, roll, yaw). It should be noted that such specifications are only met when the stage is laid flat and fully supported by a surface, which will also have its own specification requirements.

To produce motion in both the X and Y directions, the second (Y) table is placed on top of the first (X) and aligned to a desired criterion. This alignment may be challenging, and a best-effort approach may be employed for multiple reasons, i.e. the skill level of the aligner may also be a contributing factor. After alignment, the second (Y) table is unlikely to be fully supported by the CNC table beneath, causing its specification to no longer comply with its associated data sheet. As such, the accumulation of the table errors may far exceed the requirements needed for a precision micromachining system.

One method to reduce some errors is using one-dimensional linear mapping, also referred to as 1D linear calibration. A typical approach is to use a laser interferometer that accurately measures and generates correction data along the machine's linear axes at discrete steps across the travel range of interest. This data is used to calculate deviations between the commanded position and the actual position. The correction data is then used within the motion or CNC controller to adjust the commanded position to closely match the real corrected position. As a ‘linear’ correction, this method can only address errors that cause a linear discrepancy. Additionally, any errors that are not repeatable due to the quality of the CNC tables or unstable environmental factors (such as heat or vibration) will limit the capability. For best results, mapping in 1D should be carried out on the final assembly of the stages. This method is commonly used to improve system precision.

There are several limitations to the results achieved by a 1D approach. Although it is the go-to method for improving accuracy, micromachining processes are not restricted to simple straight-line motion (even such motion can be corrupted by off-centre detrimental table effects). More often, the process is 2D (or beyond). Point-to-point positioning over a two-dimensional field or contouring motion along complex paths or geometries linked to the firing of the laser is essential. Laser drilling, for the creation of circular or elliptical holes after rapid in-position movement, is an example. Additional distortion becomes apparent when a hybrid system is considered, as the CNC tables extend the 2D fields of the smaller ‘field of view’ of the laser scanner. Such scanners undoubtedly have a 2D calibration correction already applied [1]. This suggests that applying a 2D correction to the tables would be beneficial to the final part accuracy, and a simple estimation of stacked table errors intimates surprising figures.

Mapping a two-dimensional CNC table is a more complex process than calibrating a single axis. It addresses positional accuracy, angular errors, and potential interactions between the X and Y axes. The challenges involved include the time taken to measure a 2D grid compared to that of a single axis. In addition, the tooling and optics required to measure a 2D pattern may be significantly more complex. Consideration is given to the performance improvements over 1D calibration and the specific errors that can and cannot be addressed. A new automated procedure will be detailed, explaining how this has been introduced into a high-volume production line for building multi-axis laser micromachining and metrology systems, allowing significant reductions in delivery schedules and production costs. Finally, an analysis of laser-machined parts using this methodology will be presented to show part accuracy.

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[2] A. Author, B. Author, and C. Author, Title of paper, Journal Name, vol., pp. start-end, (year)
[3] A. Author, Title of book (Publisher), Chapter, (year)

Semi-autonomous laser process for surface preparation before bonding

Jean-Baptiste Duga[1], Andrés Lombana[1], Sara Kirchner[1], Julie Lecomte[1], Laurent Ferres[1], Selen Unaldi[2], Thomas Balutch[3], Colin Debras[1,4], Maxime Péron[1,5], Nicolas Cuvillier[1,6]*

1-IRT Saint Exupéry, France
2-Airbus, France
3-Naval Group, France
4-Thales Alenia Space, France
5-ArianeGroup, France
6-Safran Composites, France
**sara.kirchner@irt-saintexupery.com*

In both the aeronautical and aerospace industries, as well as in the marine and offshore sectors, replacing riveted and screwed connections with adhesive bonding plays a crucial role in reducing structural weight. Bonding also offers significant potential for multi-material assemblies while ensuring a more uniform distribution of stress. However, the quality of a bonded assembly cannot be reliably inspected after bonding. Therefore, it is crucial to ensure a high-performance and robust surface preparation process to achieve the required adhesion strength. Laser surface preparation has emerged as a promising alternative to traditional cleaning and pickling methods, which rely on chemical baths. These laser-based processes can achieve, and in some cases even exceed, the mechanical performance of bonded assemblies obtained with classical processes. For almost a decade, IRT Saint Exupéry has been actively studying surface preparation with nanosecond IR laser, focusing on identifying and understanding key process parameters. In parallel, efforts have been made to transfer this technology to automated platforms capable of treating representative technological specimens. Ensuring the robustness of laser processes for bonding requires a comprehensive approach, including sensitivity analysis of influential factors and the integration of advanced online process monitoring technologies.

The industrial objective is to process parts with complex geometries, which introduce intrinsic challenges such as defocusing (deviation between theoretical and actual geometry). Since defocus tolerances for maintaining the mechanical performance of bonded joints are relatively low, a dedicated working distance regulation system has been developed. This system, based on a lens coaxial rangefinder coupled with a linear axis, ensures sufficient precision with regard to the required tolerances. Additionally, two control and monitoring technologies—based on imaging and plasma spectroscopy—are implemented to assess the maintenance of the working distance and verify the conformity of the surface treatment.

Surface cleanliness is a key factor in ensuring strong adhesive bonding. While laser treatment effectively removes surface contaminants, ensuring effective cleanliness remains crucial. To address this, an *in situ* LIBS system, specifically developed by IRT for its applications, enables real-time detection of surface contamination, through spectroscopy of the plasma generated during surface preparation before bonding. The developed acquisition strategies enable the detection of multiple types of surface contamination during the same laser treatment.

Recent developments, undertaken by IRT Saint Exupéry and IRT Jules Verne, address the industrial need for first-time-right processes. A Human-Machine Interface (HMI) has been developed, which enables two key functions. Firstly, it integrates all process data, including robot trajectory, working distance measurement via telemetry, and non-destructive testing (NDT) data. This allows for the identification of defective areas relative to specified tolerances, as well as their nature. Secondly, the HMI facilitates automatic feedback control of the laser treatment on defective zones, enabling re-treatment and ensuring that the part meets specifications upon process completion. These developments have resulted in a monitored, data-driven, and corrective process that meets industrial requirements and has reached a sufficient level of maturity for transfer. The integration of real-time data and automated correction capabilities ensures enhanced process reliability, reduced defect rates, and improved overall efficiency.

Removal of LowE coatings by laser ablation

Jan Muys

PRC Laser Europe N.V., Belgium
jan.muys@prclaser.com

Low-emissivity (Low-E) coatings are widely applied in architectural and automotive glazing to reduce heat transfer by reflecting infrared (IR) radiation while maintaining high visible light transmittance. These coatings significantly improve energy efficiency in buildings. However, during window manufacturing and integration processes, localized removal of Low-E layers is often required. This is necessary to facilitate the application of edge seals in insulating glass units (IGUs), enable digital or ceramic printing, or permit electromagnetic (EM) wave transmission for wireless technologies such as 5G or RFID. Conventional removal methods—including mechanical abrasion and chemical etching—pose several drawbacks, such as surface damage to the underlying glass, tool wear, limited precision, environmental concerns, and process inflexibility.

Recent advancements in ultra-short pulsed laser (USPL) technology have introduced laser ablation as a promising alternative. Laser ablation relies on the delivery of extremely short and intense light pulses that exceed the material's ablation threshold fluence, causing rapid ionization and direct phase transition from solid to plasma without significant heat diffusion to the surroundings. This cold, non-contact process offers precise material removal with minimal thermal or mechanical impact on the substrate, making it particularly suitable for delicate or high-value glass products.

The laser ablation process can be finely controlled by adjusting several parameters, including laser wavelength, pulse duration (typically in the femtosecond to picosecond range), peak power, intensity profile, and the geometry of the focused beam. The laser energy is typically delivered via a galvanometric scanner, which raster-scans the beam over the target area. The challenge lies in scaling this inherently microscopic process to large-area applications typical in industrial settings. This requires the development of optimized scan strategies, synchronization between the scanning system and workpiece movement, and effective handling of by-products such as ablated material, dust, and fumes.

Low-E coatings differ significantly in their composition and structure, being produced either by pyrolytic methods (on-line) or magnetron sputtering (off-line), resulting in varying thicknesses, material stacks (e.g., silver, metal oxides), and optical/electromagnetic properties. Each variant requires tailored laser processing parameters to achieve clean and selective removal without damaging adjacent layers or the glass surface. Engineering efforts must therefore focus on the development of adaptive process control, advanced beam delivery systems, and robust material characterization to support consistent performance across diverse coating types.

While initial investment in USPL systems remains relatively high, the ongoing trend in laser technology—characterized by increasing power output and decreasing cost per watt—is rapidly improving the cost-effectiveness and scalability of laser ablation for industrial applications. Given its process advantages, environmental safety, and adaptability, laser-based Low-E removal is poised to become the preferred technology in the glass manufacturing sector.

Scaling Ablation Processes with Multibeam and Femtosecond Laser: Challenges and Opportunities for Industrial Applications.

***Marie Fleureau*[1]*, Eric Audouard*[1]*, Benoit Morin*[1]*, Frédéric Mermet*[2]*, Jean Michel Romano*[2]*, Amina Arahouni*[2]**

1-Amplitude Laser, 11 Avenue de Canteranne, Pessac, France
2-IREPA LASER, Parc de l'innovation, Illkirch, France
marie.fleureau@amplitude-laser.com

Nowadays, industrial femtosecond laser systems are capable of reaching up to 300 W average power and kilowatt-level was already demonstrated. To fully exploit the potential of those systems, innovative solutions in beam engineering must be adopted to overcome existing limitations.

The optimal approach to improve the throughput of femtosecond laser remains to be determined. Therefore, in this study, we explored the capabilities of multibeam configurations combined with a femtosecond laser system for material ablation. By employing advanced beam-splitting techniques, the study evaluates ablation rates, thermal effects, and precision across metals, ceramics, polymers and composites. This work aims to give a preliminary direction on the beam manipulation strategies required to optimize the use of high-power femtosecond laser systems in industrial applications.

The experimental setup associates a high-power femtosecond laser, a Tangor 300 W from Amplitude, with a water-cooled Spatial Light Modulator (SLM), to enable precise multibeam pattern generation and control. The laser, operating at a central wavelength of 1030 nm, delivering ultrashort pulses with a pulse duration of 500 fs, and a repetition rate of 100 kHz producing a maximum energy of 3 mJ. During this campaign, the laser power was limited to 100 W and 3 mJ to preserve the SLM from damages.

The SLM was programmed to generate a line of spots from 1 to 50 spots in the scanning direction and the generated beams were directed to a galvo scanner equipped with a 100 mm focalization lens. For each SLM configuration, trenches with a variation in fluence (spot fluence, ranging from 1J/cm² up to 80 J/cm²) were realized. A variation in the number of pulses was also tested. This study aims to highlight the interest of beam splitting to increase the throughput while maintaining high process quality.

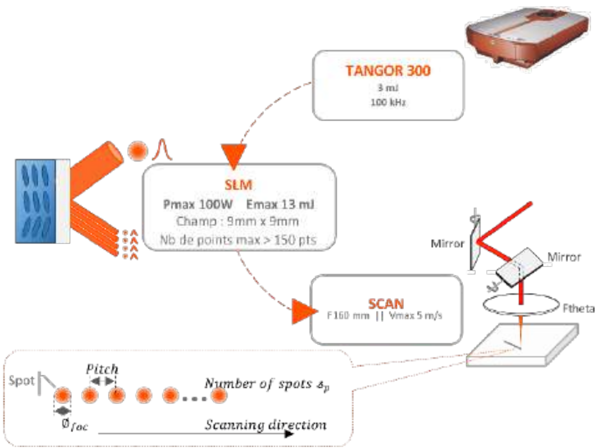

Figure 1 : Schematic of the set-up.

Laser processes: powerful tools for targets fabrication

Isabelle Geoffray[1*], Rémy Bourdenet[1]

1- CEA, DAM, centre de Valduc, 21120 Is Sur Tille, France
**isabelle.geoffray@cea.fr*

The LMJ laser is a major scientific facility dedicated to High-Energy Density Physics Experiments. The laser / target interactions produce dense and hot plasmas in a few nanoseconds only.

Targets are designed and manufactured by the CEA. Their fabrication is a continuous challenge, as they are composed of many – specific and innovative – materials shaped and assembled in a sub-millimeter range. They must meet stringent specifications, which requires the development of high-tech fabrication processes. In this field, laser micro-machining processes offer reliable and accurate solutions, whether it is for 2D or 3D micro-machining, drilling, selective ablation or micro-welding.

During this oral talk, we give an overview of the latest developments in laser micro-machining of targets components, involving both nanosecond pulses (excimer laser) and ultrashort pulses (femtosecond laser). We will emphasize on the quality, accuracy and specificity of our machining – that require a deep understanding of the materials and processes involved.

Optimizing Circular Polarization for Two-Dimensional Laser-Induced Periodic Surface Structures (2D-LIPSS) in Large-Field Texturing

Sylvain GEORGES[1,2], Yoan DI MAIO[1], Julien GARNIER[1], Xxx SEDAO[2], Jean-Philippe COLOMBIER[2]*

1- ***GIE Manutech-USD, FRANCE***

2- ***Université Jean Monnet, CNRS, IOGS, Laboratoire Hubert Curien UMR 5516, F-42023 St-Etienne, FRANCE***

* *sylvain.georges@manutech-usd.fr*

Femtosecond laser-induced periodic surface structures (LIPSS) have profoundly transformed the field of surface texturing, enabling the creation of functionalized patterns at sub-micrometer scales. Traditionally, LIPSS exhibits a one-dimensional periodicity, aligned perpendicular or colinear to the linear polarization of the laser beam. These structures result from interference phenomena at the laser-material interface, generating localized intensity regions, referred to as "hot spots", which define well-structured periodic patterns [1]. However, when the polarization state of the beam is modified to circular polarization, two-dimensional periodic structures, known as 2D-LIPSS, emerge. These structures are periodically rotationally symmetrical in the (x, y) plane, with a period close to the wavelength (see Figure 1 a and c). This results in a unique isotropic symmetry, opening to new possibilities for applications in various fields such as tribology [2], anti-reflection coatings [3], and even antibacterial treatments [4].

In the context of this study, conducted in collaboration with Manutech-USD and the Hubert Curien laboratory, the shaping of beams in circular polarization was explored, which is essential for mastering vortex beams. Several scientific and technical challenges were addressed. The use of a polarimeter enabled precise measurement of the Stokes vectors, ensuring accurate assessment of the circular polarization rate. Polarization degradation was then pointed out over the whole laser beam path and compensation was applied for a perfect polarization control at the working plane. The feasibility of generating 2D-LIPSS on various metallic materials, such as titanium, nickel, iron chromium, stainless steel, and copper, was demonstrated. Finally, the stability of circular polarization over the scanner lens field was studied.

To ensure homogeneous patterns over larger surfaces, a dedicated optical configuration was designed to stabilize circular polarization and minimize variations over large fields. This approach could improve the maintenance of pattern contrast and uniformity, thus paving the way for industrial and scientific applications at larger scales where precision and quality of structures are crucial for optimal performance.

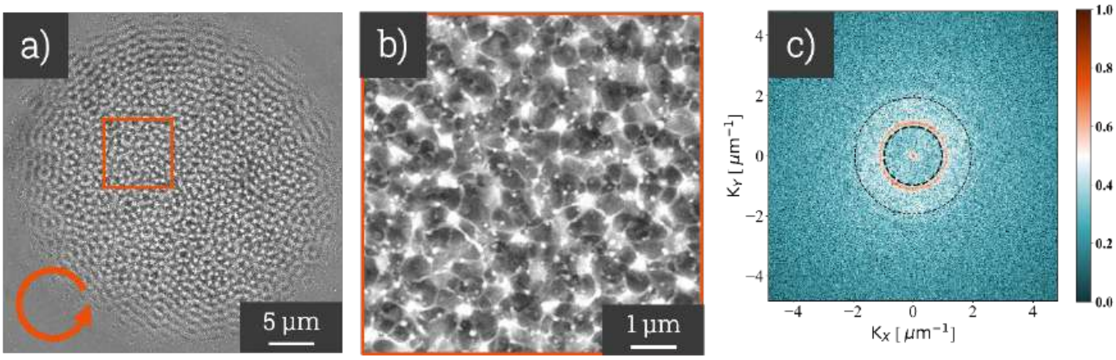

Figure 1 (a) Scanning Electron Microscope (SEM) image of a crater formed by 50 femtosecond laser pulses with circular polarization at an average fluence of 0.28 J/cm². (b) A 5× magnified view of the orange-framed region in (a), highlighting the fine details of the substructures within the crater. (c) Fourier transform of the SEM image in (a), showing the periodicity of the generated structures, with a period of around 1 µm, corresponding to the laser wavelength.

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Tailoring surface wettability through self-organized surface structures

Anika Langebeck[1], Lewin Rathmann[1], Yasmine Bouraoui[1], Tim Radel[1,2]*

1-BIAS – Bremer Institut für angewandte Strahltechnik GmbH, Germany
2-MAPEX – Center for Materials and Processes – University of Bremen, Germany
**langebeck@bias.de*

The wetting behavior of surfaces is strongly influenced by their structural characteristics. In this regard, surface wettability can be tailored by introducing periodic structures on functional surfaces, a process commonly achieved through laser-based material processing. Among the various laser-induced structures, self-organized surface structures can be efficiently generated via a single-step procedure. Depending on the applied laser fluence, ultra-short pulsed lasers can generate laser induced periodic surface structures (LIPSS), grooves, or spikes.

LIPSS can be utilized to create hydrophilic surfaces; however, these nanostructures exhibit limited resistance to mechanical stresses [1]. To enhance their mechanical robustness, laser hardening of LIPSS presents a promising solution. Studies indicate that laser hardening alters the previously structured surfaces (Figure 1 a-d), impacting their wetting behavior. Specifically, as the laser power during hardening increases, the contact angle of a single droplet on the surface increases, diminishing the surface's wettability. This phenomenon is attributed to changes in the aspect ratio of the LIPSS. A higher aspect ratio typically results in lower contact angles, but as the laser power intensifies, this ratio decreases, leading to increased contact angles (Figure 1 e) [2]. Further, changes of the chemical surface condition are possible. Thus, a balance must be chosen between hardness and wettability when applying laser hardening to LIPSS.

For oleophilic applications, higher laser fluence is used to generate larger-scale spikes [3], which are more effective than LIPSS for retaining larger volumes of liquid within the structure's cavities. While the formation mechanisms and properties of LIPSS have been extensively studied, there is comparatively limited research on the formation of spikes. The present study investigates the influence of the number of laser pulses on spike formation. Experimental results reveal a clear relationship between pulse count and the growth and morphology of the spikes, with both the spatial wavelength and depth of the structures increasing as the number of pulses rises. This provides a basis for structuring larger areas with spikes to achieve tailored oleophilic behaviors, with potential applications across various industries.

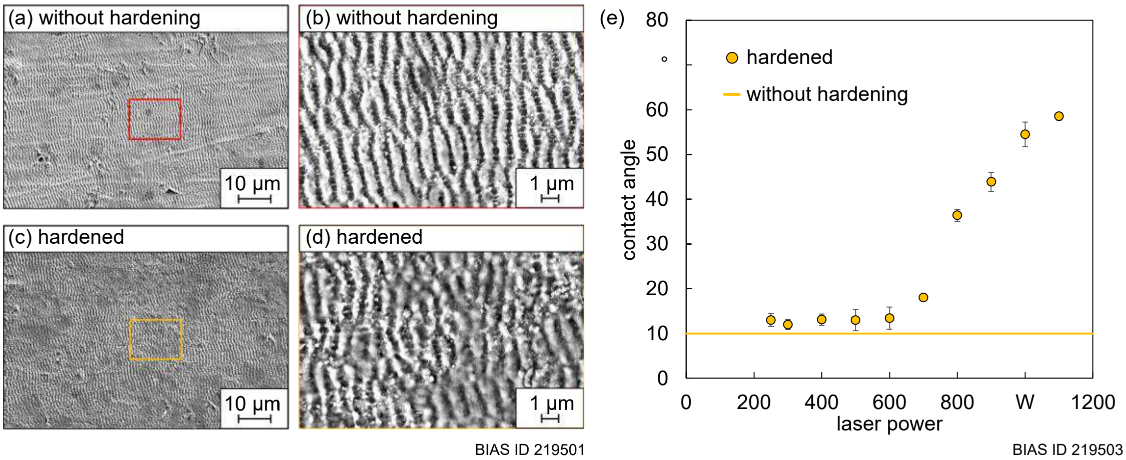

Figure 1 (a-b) SEM images of LIPSS without and (c-d) with subsequent hardening. (e) Contact angle of LIPSS depending on laser power used for hardening.

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Ultrafast Laser Cutting at MHz Repetition Rates: Nuclear Ceramic Sample Preparation through Thermal Management

C.E. Cifuentes Quintal*[1,2], T. Doualle[1], Y. Pontillon[1], L. Gallais[2]

1- CEA, DES, IRESNE, DEC, Cadarache F-13108 Saint-Paul-Lez-Durance, France
2- Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, Marseille, France
**Carlos-Esteban.CIFUENTESQUINTAL@cea.fr*

As nuclear technologies evolve, the demand for precise and efficient methods to prepare ceramic fuel specimens grows ever more critical. Traditional mechanical machining often struggles with radioactive handling constraints and risks of microstructural damage. In response, this study presents an exploration of ultrafast laser cutting at MHz repetition rates—offering a contact-free, high-throughput solution for nuclear ceramic micromachining. In parallel, we investigate additional laser machining approaches that involve varying wavelengths (515 nm and 1030 nm) and pulse durations ranging from femtoseconds to nanoseconds, aiming to refine ablation quality and thermal management across different operating regimes.

Our approach emphasizes thermal management, integrating high-speed thermographic monitoring with finite element heat transfer simulations to track spatio-temporal temperature distributions. By correlating experimental data with model predictions, we delineate optimal process windows that mitigate heat accumulation and suppress the heat-affected zone (HAZ). This fine-tuning is particularly crucial for nuclear ceramics (e.g., UO_2), where microstructural integrity directly impacts the reliability of subsequent post-irradiation examinations.

Preliminary findings suggest that ultrashort pulses at MHz repetition rates can yield relatively precise cuts with limited thermal damage, provided process parameters are carefully optimized. Initial observations indicate reproducible cut edges and a lower risk of cracking or unwanted phase transformations compared to conventional methods. While these results are promising for sample preparation in hot laboratory environments, further investigations are necessary to fully characterize scalability and consistency. Nevertheless, this approach has the potential to inform broader applications of ultrafast laser cutting in advanced manufacturing contexts, pending additional research and validation.

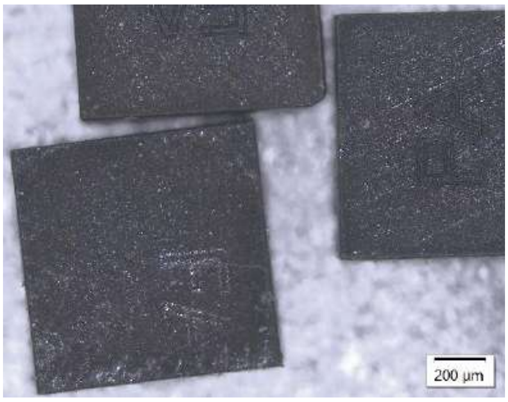

Figure 1 Laser-cut UO_2 ceramic squares produced with 300 fs pulses at 1030 nm. The cutting parameters included a beam waist (1/e²) of 13.5 µm, a fluence of 4.12 J/cm² at 0.333MkHz, a scanning speed of 0.5 m/s.

Development of a numerical model of large-scale Laser Ablation with MHz/GHz bursts of Femtosecond Pulses

Authors: Vaibhav Nain [1], Thierry Engel[1,2], Frédéric Mermet[1,3], Jean-Michel Romano[1,3]

[1] IREPA LASER, Parc d'Innovation, Pôle API, 67400 Illkirch, France

[2] INSA Strasbourg, 24 blvd de la Victoire, 67084 Strasbourg cédex

[3] LaserSurf?laboratoire commun entre IREPA LASER et iCube?Illkirch?France

Femtosecond laser pulses are commonly used to ablate materials, producing a high-quality surface finish. Such laser ablation processes are yet slow, limiting the transfer of the technology toward large-scale industrial applications. A promising way to increase productivity is to improve the ablation removal rate of materials by using bursts of femtosecond pulses. Indeed, laser manufacturers have recently been developing high average power lasers and the capacity to generate bursts of pulses with intra-burst frequencies in the MHz and even GHz regime. A downside of such processes is the overheating of materials, reducing the resulting quality.

A laser ablation model for MHz and GHz bursts for a fs laser pulse is developed on COMSOL Multiphysics®. A heat transfer module with a surface heat source is employed to model input laser energy. The deformed geometry physics is utilized to simulate the material removal during laser ablation. Temperature-dependent absorptivity and thermal properties are considered in the model to capture the process physics accurately. Experiments are conducted for single and multi-tracks on Stainless Steel (SS) to remove large materials. Finally, the numerical model is successfully compared with experimental data.

Keywords: femtosecond ablation, burst mode, stainless steel, simulation, COMSOL

Dynamic Bayesian optimization for efficient ultrafast laser process development

Valentin Maffeis*[1], Tiphaine Guerry[1], Bertrand Nicolet[1]

1-IREIS-HEF, 7 rue Salvador Dali, 42000 St-Etienne, France
**vmaffeis@hef.group*

Femtosecond lasers are powerful tools for micromachining, engraving, and surface treatment, offering precise control over a wide range of parameters, including frequency, energy, scan speed, burst mode, beam size, polarization, and pulse-to-pulse overlap. When combined with other technologies such as Physical Vapor Deposition (PVD), which also involves numerous variables like temperature, pressure, and degassing time, the optimization space becomes vast and complex. This "hyperspace" of parameters presents a challenge in finding optimal solutions, often requiring the expertise of skilled technicians in both fields.

The manual evaluation of parameter sets is resource-intensive and costly, which leads experienced engineers to rely on intuition and a deep understanding of the system to speed up development. Known solutions are often targeted directly, leaving little room for exploration. As the range of parameters available to users has significantly expanded in recent years—such as the introduction of complex burst envelopes and beam shaping—this can result in suboptimal processes being used due to the lack of time for thorough exploration.

To address this, we are working on implementing a computer-guided framework to streamline, accelerate, and broaden our laser process optimization. Bayesian optimization is particularly well-suited for black-box problems where evaluating the objective function is expensive. By modeling the system's behavior probabilistically, the algorithm predicts the most promising and exploratory parameter combinations, enabling more efficient navigation of the optimization space than traditional methods.

In this presentation, we will discuss how we have implemented Bayesian optimization to optimize ultrafast laser processes. We will explore the challenges and best practices in managing the many variables involved and share insights into the shortcomings and limitations of our current approach. Furthermore, we will describe the dynamic system we've developed, allowing for on-the-fly adjustments of parameters and scoring methods to accommodate unforeseen tasks, such as balancing quality and speed, adding new parameters, or optimizing specific performance metrics. Ultimately, this system lays the foundation for a self-optimizing process that can significantly reduce development time and enhance results.

(a)

(b)

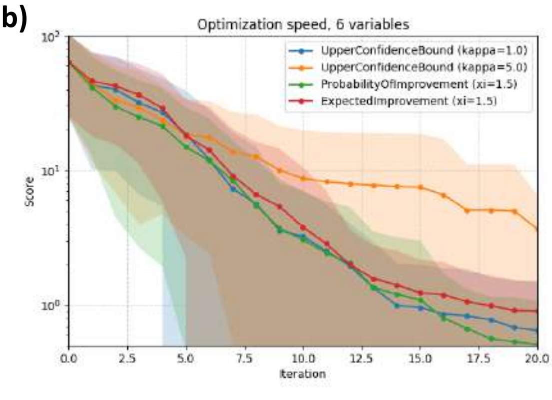

Figure 1 (a) Typical parameter grid used for laser process optimization, shown here for coloring purposes on copper and titanium. (b) Convergence plot for a 6-variable optimization of a test function, comparing different acquisition functions for Bayesian optimization.

Photonic production chains - AI methods for process data and shaped light for better laser material processing

Markus Kogel-Hollacher,[1,2], Jens Reiser[1], Thomas Nicolay[2], Joachim Schwarz[3], Geoffrey Bruno[4]

1 - Precitec GmbH & Co. KG, Draisstrasse 1, 76571 Gaggenau, Germany
2 - Precitec Optronik GmbH, Schleussnerstrasse 54, 63263 Neu-Isenburg, Germany
3- Precitec Vision GmbH & Co. KG, Rotfarb 4, 8413 Neftenbach, Switzerland
3 – Enovasense, 10 Rue du Général de Gaulle, 94110 Arcueil, France
**mkh@precitec.de*

Photonic production chains represent a transformative approach to manufacturing, leveraging the unique properties lasers for material processing. The integration of artificial intelligence (AI) into these processes further enhances efficiency and adaptability, paving the way for more intricate designs and optimized production outcomes. This became even clearer in the context of battery and e-mobility applications.

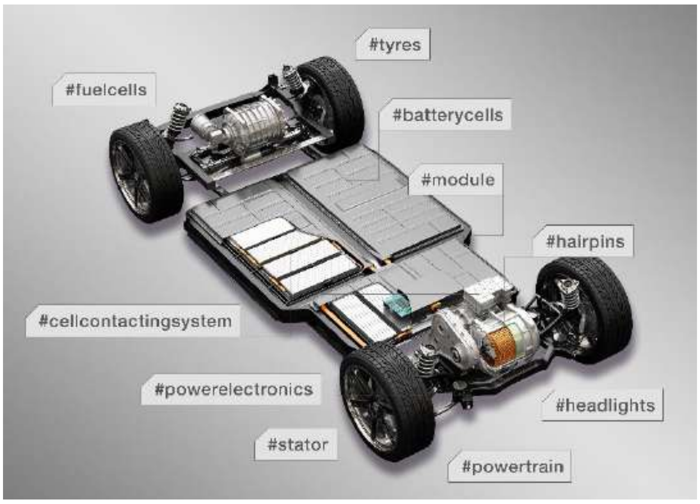

Figure 3 : Overview of typical laser welding applications in e-mobility

AI-driven methods in photonic production chains enable real-time monitoring, adaptive control, and predictive maintenance of laser systems. By analyzing vast amounts of data from the manufacturing process, AI can dynamically adjust laser parameters such as power, pulse duration, and beam shape, ensuring optimal performance and reducing material waste. Machine learning algorithms also facilitate defect detection and quality assurance, making the process more reliable and less dependent on manual intervention.

Shaped light, a technique involving the manipulation of laser beam profiles, plays a critical role in enhancing the precision and versatility of laser material processing. By customizing the intensity distribution of the laser beam, shaped light allows for more controlled energy deposition, enabling the processing of a wide range of materials with varying properties. This capability is particularly useful in applications such as micro-machining, additive manufacturing, and surface texturing, where precision is paramount.

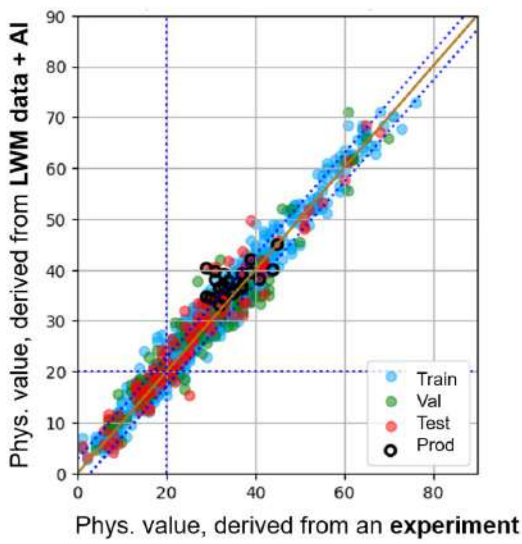

Figure 4 : AI based data evaluation; Application: Foil welding; Penetration depth approx. 100µm; 1200 0Samples, ~120 Test Samples; R2 93.4%

The combination of AI methods and shaped light in photonic production chains leads to a highly adaptable and intelligent manufacturing system. This integration not only improves the accuracy and speed of production but also opens new possibilities for creating advanced materials and components. This presentation for PLI 2025 will provide an insight into Precitec's activities in recent years, being able to more than concept proof the advantages of these individual approaches, but also their combination.

Machine Learning Assisted Ablation of Silicon for Integrated Circuit Fault Analysis

Eric Mottay[1], Wahib Migan Barkat[2], 2 Emile Barjou[2], Anthony Bertrand[2], Girolamo Mincuzzi[2]

1- h-nu, France
2-Alphanov, France

Corresponding author email address : eric.mottay@h-nu.net

Ensuring the safety and reliability of integrated circuits is of paramount importance, during or after manufacturing. Manufacturing defects such as bonding defects, internal cracks, delamination or junction leakages can severely decrease the production yield. In harsh environments, such as space applications, ionization and electrostatic discharges or radiation can induce catastrophic damage or severely reduce the lifetime of the component. Failure Analysis is the process of collecting and analyzing failure data, usually to identify the root cause of an integrated circuit malfunction.

Photoemission microscopy uses the very low level infrared light emitted by transistors to probe circuits under real conditions. To access the integrated circuit, decapsulation and thinning of the silicon chip must be performed to gain access to the underlying circuitry. In a typical application, laser ablation reduces the silicon thickness from 3-400 µm to less than 50 µm, while maintaining a good surface quality.

Femtosecond laser ablation allows for high precision, high accuracy micromachining. However, the quality of the ablation depends on a number of parameters (laser parameters, spot size, scan speed, etc…) that are difficult to simultaneously optimize. Machine learning is an attractive method to predict and optimize the ablation depth and surface roughness during silicon wafer thinning. However, it requires extensive and time-consuming data acquisition. To address this challenge, we developed an automated acquisition protocol using a confocal profilometer, capturing topographical data from hundreds of ablation images across silicon and steel samples. We apply regression algorithm to predict ablation depth and surface roughness, as well as a hybrid generative adversarial network to predict surface texture The predictions closely match actual measurements, opening the way towards implementing real-time optimization of the thinning process

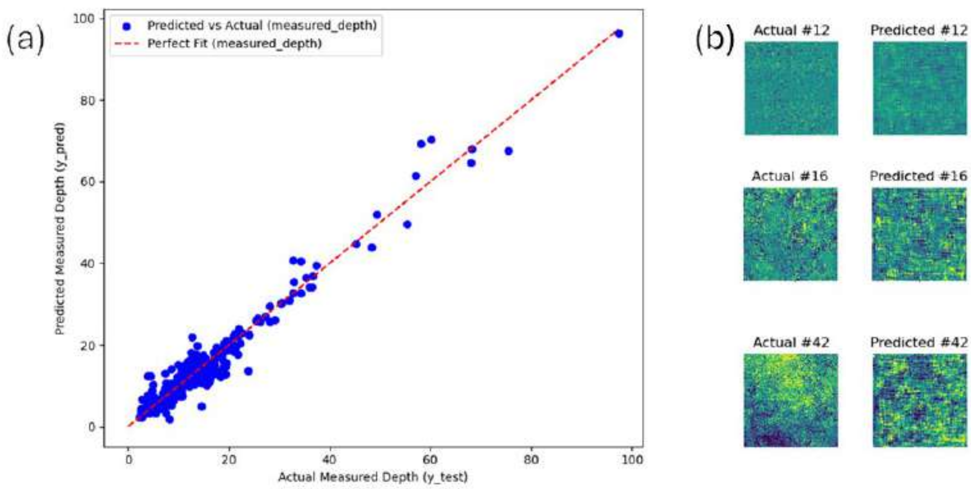

Figure 1 (a) Predicted vs Actual ablation depth across test dataset (b) Examples predicted vs actual surface textures

Artificial intelligence and spatial light modulators: the winning pair for fully optimized digital laser tools.

Sébastien LANDON[1], Florent THIBAULT[1]

1-QiOVA company, France
*[*s.landon@qiova.fr](mailto:s.landon@qiova.fr)*

QiOVA develops advanced laser solutions for marking and surface treatment, leveraging its patented multibeam technology to achieve processing speeds many times faster than conventional laser systems. Key application areas include product serialization (pharmaceuticals, electronics, medical devices, industry), high-end decoration (luxury goods), and surface functionalization (transportation).

At the core of this innovation lies an active, software-controlled Spatial Light Modulator (LCoS-SLM – Liquid Crystal on Silicon SLM). By leveraging this real-time adaptive optical interface, Artificial Intelligence (AI) unlocks new possibilities for software-driven laser beam optimization. AI-powered algorithms dynamically adjust beam profiles, providing unprecedented control, flexibility, and adaptability to real-world conditions – such as input laser beam quality - rather than relying on predefined models.

This talk will explore recent advances in integrating deep learning and evolutionary optimization techniques with SLMs to shape and enhance laser beams with minimal hardware adjustments. Practical demonstrations will illustrate applications in precision marking and surface treatment and highlight the advantages of this fully digital and reconfigurable approach, paving the way for more efficient and intelligent laser systems.

Towards online monitoring of ultrashort pulse laser surface texturing

Loïc Mosser [1,2,4], Jean-Michel Romano[2,3], Thierry Engel[1,3], Frédéric Mermet[2,3], Laurent Barbé [1,2], François Geiskopf [1,2,4], Pierre Renaud [1,2,4], Sylvain Lecler [1,2,4]

1-ICube laboratory, University of Strasbourg, CNRS, INSA Strasbourg, France
2-LaserSurf, joint lab between IREPA LASER and ICube laboratory, Illkirch, France
3-IREPA LASER, Parc d'Innovation, Pôle API, 67400 Illkirch, France
4- INSA Strasbourg, 24 blvd de la Victoire, 67084 Strasbourg cédex, France
**mosserl@unistra.fr*

Laser texturing is of growing interest as it finds applications in areas such as wettability control, tribology, coloring and also in the medical field. Incorrect settings of the texturing process can lead to thermal accumulation, increasing the temperature of the textured surface by several hundred degrees. As a consequence, failures like surface oxidation [1] or unwanted microstructures can be observed [2].

Lasersurf, a joint laboratory between IREPA LASER and ICube laboratory, aims to find methods for supervising the laser texturing process, in order to avoid these process failures. In this respect, thermal build-up modelling [3-4], associated with thermal measurements could lead to supervise the laser texturing process.

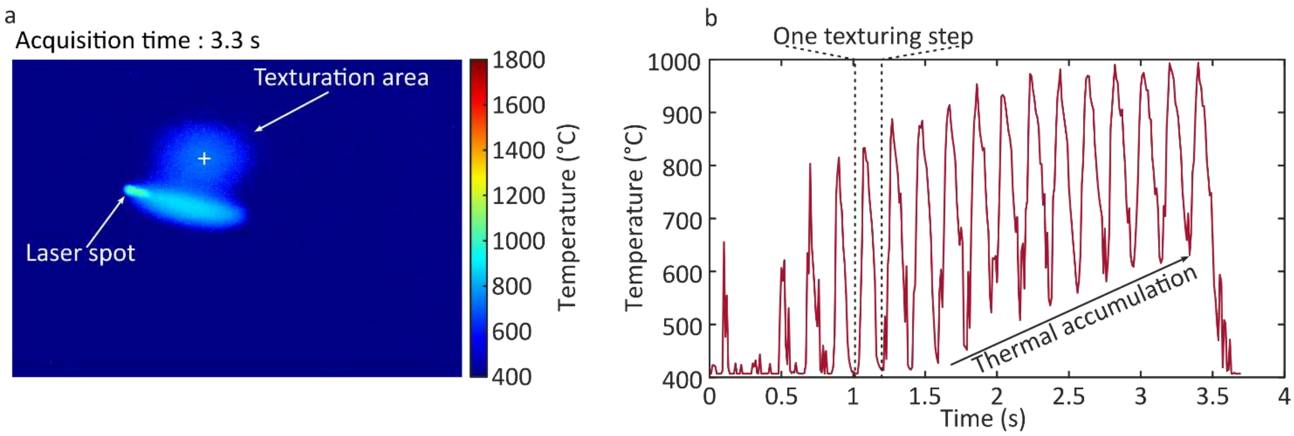

Figure 11 : Thermal camera image acquired during a laser texturing process on stainless steel (a) with temperature measurement acquired at a point (white cross) over time (b)

Experiments on metallic surfaces are achieved using an Amplitude Tangerine femtosecond IR laser (300 fs). We describe the results obtained after integration of an InGaAs XIR-1800 thermal camera to acquire thermal images during surface texturing (Figure 1-a). The thermal map can be captured every 10 ms. Thus, it is possible to track the texturing process and the surface temperature accumulation during the passage of the laser. We demonstrate that thermal accumulation can be detected and monitored (Figure 1-b). In our case, the surface reaches a temperature of 630°C after successive laser passes. The impact of the multi-beam for parallelization strategy on the thermal accumulation will be discussed.

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[2] : S. Richter, S. Döring, F. Burmeister, F. Zimmermann, A. Tünnermann, et S. Nolte, « Formation of periodic disruptions induced by heat accumulation of femtosecond laser pulses », *Opt. Express*, vol. 21, nº 13, p. 15452, juill. 2013, doi: 10.1364/OE.21.015452.

[3] : L. L. Taylor, R. E. Scott, et J. Qiao, « Integrating two-temperature and classical heat accumulation models to predict femtosecond laser processing of silicon », *Opt. Mater. Express*, vol. 8, nº 3, p. 648, mars 2018, doi: 10.1364/OME.8.000648.

[4] : L. L. Taylor, J. Qiao, et J. Qiao, « Optimization of femtosecond laser processing of silicon via numerical modeling », *Opt. Mater. Express*, vol. 6, nº 9, p. 2745, sept. 2016, doi: 10.1364/OME.6.002745

Integrating modern laser welding technologies in parameter-based prediction of laser weld geometries

Victor HAYOT*[1-3], Andre ALVES FERREIRA[2], Frédérique MACHI[2], Sylvain LECLER[3,4], Grégoire CHABROL[1,3]

1-Icam site de Strasbourg Europe, France
2-IREPA LASER, Illkirch, France
3-Laboratoire ICube, University of Strasbourg, CNRS, Strasbourg, France
4-INSA Strasbourg, France
**victor.hayot@icam.fr*

Laser welding has become a key manufacturing process in modern industries, offering unmatched flexibility, speed, and efficiency. Its ability to create welds with a high depth-to-width ratio in keyhole mode makes it particularly valuable for joining overlapping parts. However, optimizing welding parameters to achieve desired joint properties remains a complex task, as intricate interplays influence weld quality among thermodynamics, laser-material interactions, fluid flow, and other non-linear phenomena. These challenges are further compounded by the increasing complexity introduced by advanced laser welding technologies. Understanding and quantifying the link between process parameters and weld outcomes is crucial, particularly when dealing with various materials.

A parameter-based approach has been proposed to tackle this complexity, using reduced parameters that combine the main process' variables, such as laser power, scanning speed, and spot diameter as Power Density and Specific Point Energy (Esp). These variables have proven effective in isolating the effects of individual parameters, providing a clearer relationship between process settings and weld characteristics like penetration depth. While this methodology has been validated for traditional laser beams and scanning patterns, its applicability to novel beam shaping techniques and advanced trajectories, such as BrightLine fibre or laser oscillation strategies, remains untested.

This study extends the parameter-based approach to account for modern laser welding configurations. The method addresses the complexities of contemporary welding processes by introducing additional parameters—including fibre diameter, oscillation patterns, and power distribution. Experiments were conducted using cutting-edge laser welding systems on steel and stainless steel substrates, focusing on the relationship between Specific Point Energy and weld cross-sectional geometry. Results confirm that the extended methodology enhances the predictability of weld dimensions when using these new parameters and maintains the relevance of previous data.

TRUMPF Group

Author : Dr Andrey Andreev

Name: "Holistic approach of Can-Cap Welding with processing optics in combination with the famous Brightline Weld technology. User friendly and reliable capillary measurement with VisionLine OCT Detect."

Summary:

The manufacturing process of monolithic power cells generally consists of stirring, coating, tab cutting, winding, press & Hi-pot testing, X-ray inspection, tab welding, soft-connector welding, insulation wrapping, can inserting, can-cap pre-welding, can-cap laser welding, visual inspection, helium inspection, and other processes. The can-cap laser welding is important part of the single cell manufacturing process. The efficiency and yield directly affects the capacity of single cell. Currently, the market mostly uses linear motors with fixed welding heads, which often have integrated coaxial shielding gas nozzles and suction unit, or in some cases, suction unit integrated into the fixture.

With fixed processing optics BEO in combination with the famous BrightLine Weld technology we can get ideal welding results in actual batch production: very smooth welding surface, very low welding spatter, very stable welding depth.
Reasonable laser optical configuration is only a prerequisite for good welding results, the comprehensive effect of shielding gas and suction, the stability of the fixture, the accuracy of the can-cap, etc., all together will eventually affect the welding results which can be monitored by the user friendly and very reliable OCT technology made by TRUMPF.

Contact : andrey.andreev@trumpf.com

COHERENT

Author : Audrey BOURRIEZ

Technologie innovante de soudage laser pour la production de batteries

Dans la production de batteries pour les véhicules électriques, l'assemblage de nombreux feuillards de cuivre ou d'aluminium à un tab de cuivre plaqué Ni a toujours été un défi. Le soudage par ultrasons a été la méthode la plus utilisée, malgré les problèmes de continuité électrique à travers la pile de feuillards.

Une nouvelle approche utilisant la technologie laser et la tête de soudage de Coherent permet aujourd'hui de relever ces défis. Cette méthode permet d'obtenir des soudures de haute qualité et d'éviter les problèmes de dérivation observés avec le soudage par ultrasons, ce qui garantit une connexion électrique idéale avec une conductivité maximale, même pour des piles de feuillards dépassant 120 couches.

La technologie utilise un laser à fibre double cœur réglable qui produit un faisceau central circulaire entouré d'un faisceau annulaire, combiné à la technologie unique d'oscillation de la tête de traitement SmartWeld+. Le CSM-ARM utilise un faisceau central à haute luminosité, tandis que le faisceau annulaire de moindre puissance chauffe doucement le feuillard pour augmenter l'absorption du matériau.

Le cœur de la fibre à haute intensité fournit alors l'énergie nécessaire au soudage à grande vitesse, tandis que le matériau environnant reste souple et élastique, ce qui minimise les turbulences du bain de fusion et prévient les éclaboussures.

Contact : audrey.bourriez@coherent.com

Dissimilar laser welding of titanium to stainless steel: ten years of studies

A. MANNUCCI[1,2], N. HAGLON[1,2], R. BOLOT[1], I. TOMASHCHUK[1], A. MATHIEU[1], R. GONCALVES[2], S. LAFAYE*[2]

1- Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR CNRS-6303, Université de Bourgogne-Franche Comté, 12 rue de la Fonderie, 71200 Le Creusot, France
2- SME Laser Rhône-Alpes, 49-51 Boulevard Paul Langevin, 38600 Fontaine, France
**corresponding author slafaye@laser-rhone-alpes.com*

The FLAMme LabCom was created in 2014 between the LTM team of ICB (UMR 6303, CNRS - Université de Bourgogne) and SME Laser Rhone Alpes, to study dissimilar laser welding of materials as titanium to stainless steel. These assemblies remain very challenging but very interesting for industrial applications. The FLAMme LabCom was financed by ANR during three years and labelled by Nuclear Valley pole. One postdoctoral researcher, two PhD candidates and several internships have contributed to increase the knowledge on dissimilar laser welding materials.

During 2014 to 2018, direct laser welding of titanium to stainless steel was studied. These assemblies show brittle intermetallic compounds as Fe_2Ti, FeTi and $Cr_7Fe_{17}Ti_5$. By applying suitable welding parameters including beam offset regarding to the joint plane, the formation of these phases was reduced to thin interfacial layers, resulting in UTS up to 175 MPa [1].

From 2018, the use of inserts to prevent the contact between melted titanium and stainless steel was studied. Vanadium is a good candidate due to its compatibility with titanium and its solubility in iron. Focusing IR laser beam in butt configuration with a first pass between titanium and vanadium, and second pass between vanadium and stainless steel, allowed obtaining ductile fracture with UTS up to 500 MPa [2]. However, Vanadium is very expensive and not biocompatible in contrary of niobium. The use of niobium inserts in the same two pass configuration resulted in comparable UTS as without insert. Copper is also a good candidate as insert, but its poor UTS lead to poor mechanical resistances. More recently from 2022, Copper-nickel alloy as Cu55Ni45 or copper-aluminium alloy as Cu-6Al-2Ni were applied as inserts, which should be better candidates due to much higher UTS. If Cu-6Al-2Ni/316L junction shows UTS between 400 to 500 MPa, Cu-6Al-2Ni/ Ti6Al4V shows UTS lower than 100 MPa [3]. Using green laser beam provided similar results. Cu55Ni45/316L and Cu55Ni45/ Ti6Al4V junctions show better UTS of 500 MPa and 250 MPa respectively [4]. However, these UTS remains far from that of a junction with vanadium insert. Cu55Ni/X junctions seem to show better UTS with green laser beam. Table 1 shows a summary of UTS obtained by laser welding of the different studied junctions. The best UTS is reached for the welding with vanadium insert.

Junction	**UTS (MPa)**
Ti6Al4V/316L	175
Ti6Al4V/V/316L	500
Cu-6Al-2Ni/316L	400 to 500
Cu-6Al-2Ni/Ti6Al4V	< 100
Cu55Ni/316L	400 to 500
Cu55Ni45/Ti6Al4V	250
Sintered Cu55Ni45/316L	230 to 280

Table 1: summary of UTS obtained by laser welding according to several junctions.

In same time, from 2022, junction between sintered Cu55Ni45 manufactured by powder metallurgy (i.e. Spark Plasma Sintering, SPS), and 316L was studied. Thermocalc calculations showed the lack of intermetallic compounds. Depending on beam offset from joint line, UTS in the range 230-280 MPa were achieved, limited by the mechanical strength of the sintered Cu55Ni45 alloy. Application of HIP should allow improving the UTS of sintered Cu55Ni45 during the coming months.

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[2] Mannucci, A., Tomashchuk, I., Mathieu, A., Bolot, R., Cicala, E., Lafaye, S., Roudeix, C., "Use of pure vanadium and niobium/copper inserts for laser welding of titanium to stainless steel", Journal of Advanced Joining Processes, 1 (2020)
[3] Haglon, N., Bolot R., Tomashchuk, I., Mathieu, A., Lafaye, S., "Dissimilar welding between Cu–6Al–2Ni alloy and stainless steel 316L using continuous ytterbium YAG laser", J Materials: Design and Applications, 238 (2024)
[4] Haglon, N., Bolot R., Tomashchuk, I., Mathieu, A., Lafaye, S., "Dissimilar welding of Cu55Ni45 alloy with Ti-6Al-4V and 316L using a continuous 1030 nm Yb:YAG laser", Procedia CIRP, 124, 403-408 (2024)

Vacuum control applied to copper alloys laser welding.

Cyril Roudeix[1,], Jolan Barat[1]*

1-VLInnovations, FRANCE

** Corresponding author. Tel.: +33-066-3519-683. E-mail address: cyril.roudeix@vlinnovations.fr*

Copper and its alloys are essential materials in many industries due to their excellent electrical and thermal conductivity, corrosion resistance, and formability. However, welding copper presents difficulties due to its high reflectivity, high thermal conductivity, and tendency to porosity. These challenges are exacerbated in the case of copper alloys, which may exhibit complex chemical compositions and variable microstructures, making conventional welding difficult and often unreliable.

VLInnovations has developed innovative vacuum laser welding processes that allow for excellent results on copper and its alloys, pushing the boundaries of weld quality. Our expertise in vacuum laser welding technology, combined with the latest advancements in laser sources, including fiber and disk lasers, allows for precise control of the welding process. This synergy enables us to tailor the laser parameters, such as power, controlled pressure, and beam shape, to the specific alloy being welded, minimizing heat-affected zone size and optimizing grain structure. Furthermore, the vacuum environment significantly reduces the formation of oxides and other contaminants, leading to significantly improved joint strength, ductility, and fatigue resistance. By combining our deep understanding of vacuum science with cutting-edge laser technologies, VLInnovations achieves unprecedented weld qualities for copper and its alloys, opening new possibilities in demanding applications. This presentation reviews the challenges associated with welding copper alloys, the advantages of vacuum laser welding over traditional methods, and these new quality achievements as well as the potential applications in various fields such as electronics, aerospace, and energy.

Figure 1: Brass alloy welding with beam shape without vacuum

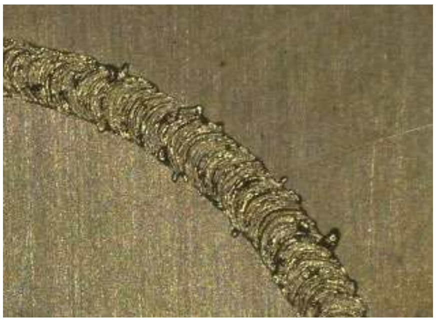

Figure 2: Brass alloy welding with beam shape and vacuum

An Introduction to Microlithography: a Key Enabling Technology for the Semiconductor Industry

François Weisbuch[1]

[1]*GlobalFoundries, Wilschdorfer Landstraße 101, 01109, Dresden, GERMANY*
Francois.weisbuch@globalfoundries.com

In recent decades, lasers have played an essential role in the semiconductor industry. One of the most important applications is advanced optical microlithography, or photolithography, a fundamental step in the chip fabrication process. This step has enabled the patterning of increasingly miniaturized and complex microelectronic devices. Microlithography involves using light to transfer the image of a pattern placed on a photomask onto a photo-sensitive polymer (see Figure 1a). The use of excimer lasers (Deep Ultraviolet, operating at 248 nm and 193 nm) and the recent introduction of EUV sources (Extreme Ultraviolet, operating at 13 nm) have sustained Moore's Law for decades. These technologies have enabled a continuous reduction in transistor size and higher density integration in electronic products [1, 2]. Figure 1b shows that these constant improvements in the ultimate microlithography resolution—the smallest dimension achievable in the photoresist—follow cycles of innovation where shorter wavelengths have been introduced over time. Additionally, the microlithography process has been greatly improved by a series of resolution enhancement techniques, pushing the limits of what can be patterned with a given laser wavelength.

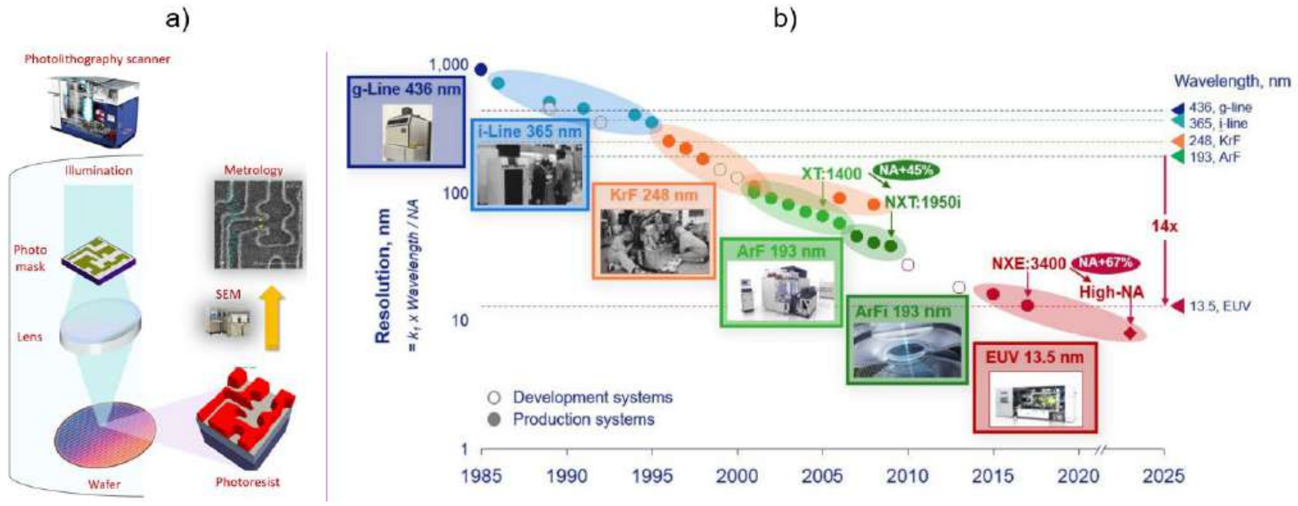

Figure 1. *a) Principle of optical microlithography b) History of projection microlithography technology: a resolution gain of two orders of magnitude over 40 years [1].*

In this presentation, we provide an overview of the microlithography process, emphasizing the importance of the laser and describing the key parameters that govern the performance of this technique for industrial applications. We will then explore the main innovations in this field, such as illumination optimization, Optical Proximity Correction, assist features, and inverse lithography. Scaling this approach to support the manufacturing of millions of transistors on a 300 mm wafer is a very complex task that involves addressing numerous challenges, including patterning variations (such as overlay, photoresist stochastic effects, defectivity, and process fluctuations) and new device complexities. To this end, advanced metrology and sophisticated simulation tools are leveraged to characterize photoresist profiles and anticipate patterning challenges.

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Functionalizing optical glasses by femtosecond laser for high temperature sensing – trends, limits and opportunities

Maxime Cavillon[1], Matthieu Lancry[1]

1- Institut de Chimie Moléculaire et des Matériaux d'Orsay, Université Paris-Saclay, Orsay, France
*[*matthieu.lancry@universite-paris-saclay.fr](mailto:matthieu.lancry@universite-paris-saclay.fr)*

Ultrashort laser pulses focused inside optical glasses enable localized transformations in volume. For example, isotropic index modifications, so-called Type I, can be used to fabricate complex waveguiding structures, gratings, lenses. Another type of transformation, labeled Type II or nanogratings (NGs), corresponds to the formation of sub-diffraction porous nanostructures controllable by light polarization. NGs are birefringent, making them attractive to the development of 3D geometric phase components, waveplates, optical data storage, or fiber-based sensors, e.g., Fiber Bragg gratings (FBGs). Furthermore, NGs exhibit extraordinary thermal stability, withstanding hundreds of hours at 1000°C, making them particularly useful for FBGs operating in harsh environments. To date, fs-Type II FBGs are principally inscribed in telecom, lightly doped, silica core optical fibers. When operating at high temperatures (>800 °C), NGs progressively relax and erase, causing drifts of the monitored property (e.g., Bragg wavelength), and more drastically a loss of signal. Therefore, there is a need to comprehend and predict what drives NGs erasure over a given thermal treatment, to anticipate potential signal degradation. Following this, novel solutions must be envisioned to go beyond current limitations, ultimately set by the intrinsic nature of the glass substrate, usually SiO_2.

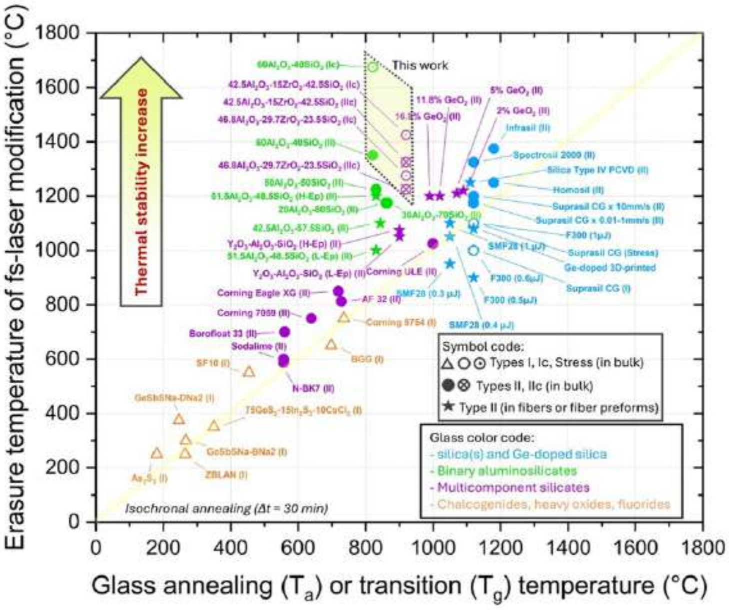


Figure 1 Temperature index changes Δn erasure (for which Δn drops to zero) as a function of glass annealing temperature (T_a). The star shape datapoints are fiber or fiber preform, while other symbols are bulk ones. This collection of works includes both laboratory and commercial glasses. The yellow area is a guide-to-the-eyes pointing out outliers with unexpectedly high thermal stability.

In this context, we will review the impact of laser parameters and glass composition on the thermal stability of refractive index changes imprinted by fs-laser. Over 30 optical glasses and fibers will be investigated, all with varying temperature stability. While laser parameters can slightly impact the overall fs-laser structure thermal stability through modification of the NGs morphology, it has been established that the main driver to NGs erasure is the glass viscosity. However specific glass compositions, including binary SiO_2-Al_2O_3 ones with Al_2O_3 > 50 mol% that can be shaped into optical fibers, do not fall into that predictive trend. The prediction is underestimated by more 300 °C, making them comparatively much more stable to "golden" SiO_2 material. To comprehend such discrepancies, an in-depth analysis of the irradiated structure reveals the formation of a crystal / glass structure composed of precipitated nanocrystals. Upon thermal treatment, complex phase transformations occur, including pore nucleation, crystallization, and chemical migration. Finally, an exploitable refractive index contrast remains imprinted at temperatures higher than 1400°C in the experimental conditions, which may be proved useful in some fiber sensing applications for instance in turbine engines in trains, aircrafts and space vehicles, manufacturing (3D laser additive manufacturing of metal or ceramics parts), nuclear power plants (future reactors and tokamaks), or optical sensing (structural health monitoring, deep drilling).

Laser Welding of Copper for E-Mobility Applications – Challenges and Limits in Serial Production

Dr. Andreas Heider[1], Dr. Lukas Alter[2]

1- Robert Bosch GmbH, Robert-Bosch-Campus 1, 71272 Renningen, Germany
2- Robert Bosch GmbH, Markwiesenstraße 46, 72770 Reutlingen, Germany
**Andreas.heider2@de.bosch.com*

Laser beam welding is a well-established, highly automated, and controlled technique widely used in the automotive and automotive supply sectors. With the shift towards electro-mobility, the requirements and materials utilized in power train applications are evolving, leading to an increased demand for copper materials in industrial applications. Future trends indicate a growing need for enhanced joint performance, including higher current transfer and an increased number of welds per component. Consequently, significant improvements have been made in terms of process efficiency, reliability, and the quality of the resulting welds.

However, welding of copper is generally considered to be difficult, particularly due to its high heat conductivity and low absorptivity using laser sources with a wavelength of 1 µm. This often results in weld defects such as pores, spatters, and significant variations in penetration depth. Additionally, the laser beam welding process for copper is highly sensitive to surface conditions, including oxidation and roughness, which can lead to an unstable welding process and a high incidence of defects. These defects can adversely affect both the mechanical and electrical properties of the weld seam, making it crucial to understand the cause-and-effect relationships of the formation of weld defects in order to develop effective process strategies and new technologies aimed at minimizing or eliminating such defects, particularly in industrial applications.

While spatter formation during copper welding has been the subject of several studies, the underlying mechanisms and cause-and-effect relationships related to pore formation remain inadequately understood. Pore formation can arise from various mechanisms: some pores are attributed to capillary instabilities (process pores), while others result from the interaction of ambient gases with the molten material in the weld zone. Pores can vary significantly in size, quantity, and shape. Recent research conducted by Bosch at the electron synchrotron DESY in Germany has facilitated in-situ observation of the formation of weld defects during welding. Different approaches using different laser sources and weld strategies to achieve high quality welds in copper were analyzed, compared and discussed. Figure 1 shows single frames from a high-speed x-ray analyzes of the formation of pores when welding copper using a green laser. The formation of the bubbles in the rear area of the molten pool and the subsequent mixing of the bubbles in the molten pool can be clearly seen. After solidification, the bubbles remain as pores in the weld.

In addition, a challenge at welding copper is the transfer from the laboratory to the production line. Knowledge of the process fundamentals and interaction mechanisms is essential for the transfer from the laboratory to serial production. A few pragmatic examples are used to discuss the challenges involved in transferring from the laboratory to production.

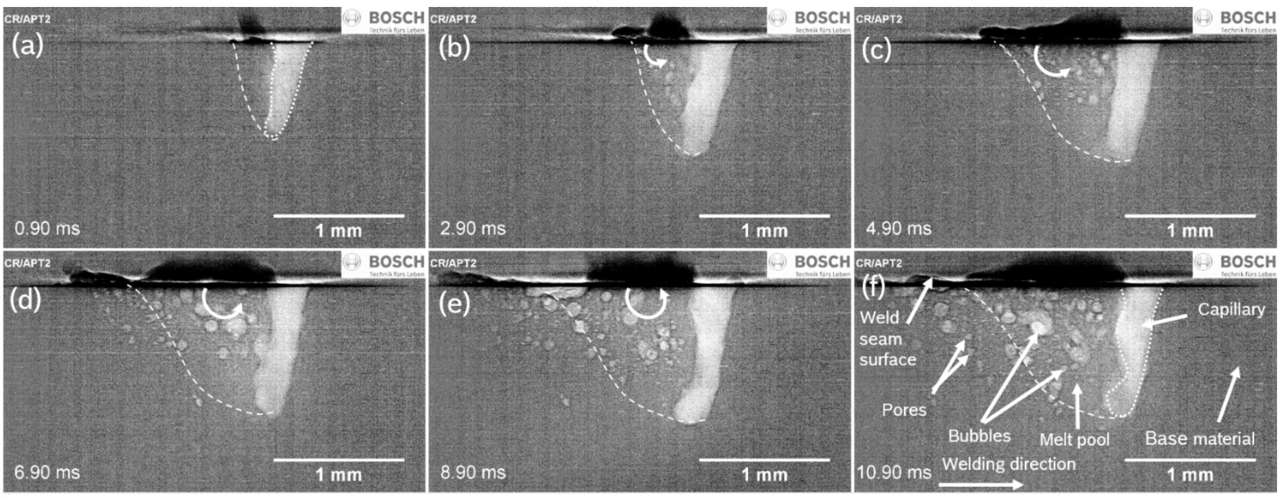


Figure 1 Single frames from high-speed synchrotron X-ray observation of the formation of pores at welding copper using green laser. Parameters green laser: P = 3250 W, v = 0.25 mm/s, df = 300 µm. Ambient gas: Air

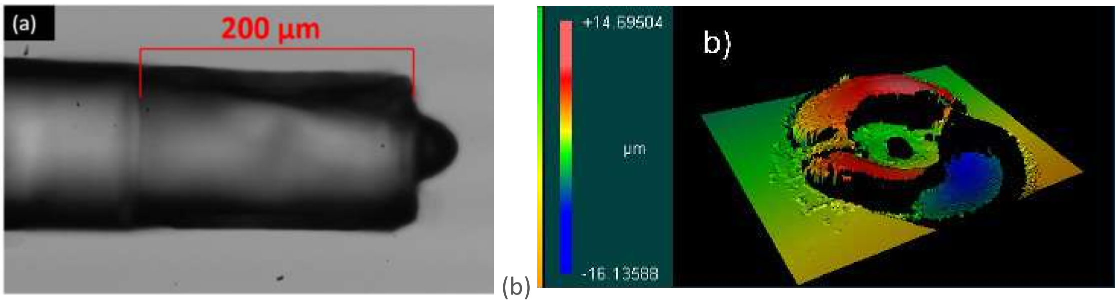
Micro-usinage par laser : du nanojet photonique au femtoseconde
Laser Micro-machining : from photonic nanojet to femtosecond

Sylvain Lecler[1,2*], Tony Hajj[1–2], Baptiste de Azevedo[1-2], Armel Bahouka[3], Fréderic Mermet[3]

1- Université de Strasbourg – CNRS, ICube Illkirch-Graffenstaden, France
2- INSA-Strasbourg, Strasbourg, France
3- IREPA LASER, Illkirch-Graffenstaden, France
**sylvain.lecler@insa-strasbourg.fr*

The development of new technologies is in strong connection with the mastering of new materials and of the technique implemented to process them. In this context the laser can be a wonderful tool especially when the energy deposition can be controlled at a small scale. During long time this laser-matter interactions were highly dependent on the laser wavelength. However, the non-linear response of the materials when submitted to high power density has made decrease this dependence. Therefore, to make the laser a universal tool for material micromachining the key parameter is the power density. For each material there is a power density threshold to reach to benefit of the non-linear response of the material to both decrease the wavelength dependence and increase the spatial resolution. To reach such a power density our team investigate two main ways: concentrate the power in space by photonic jet or concentrate the energy in time using femtosecond pulses.

First, we will show how the power can be spatially concentrated beyond the diffraction limit using the so-called photonic jet. From the first idea with dielectric microspheres, difficult to manipulate, to the current fiber microlenses many developments have been required [1-2]. We will show how a single mode fiber, with a 200 µm spacer and a molded polymer microlens deposited in alignment with the fiber core (as illustrated figure 1a), is able to etch semiconductor and metal at 1 µm scale with a 100 ns near-infrared laser (1064 nm). Only 10 mW is required to etch silicon. The process can be adapted to multicore fibers for parallel processing.



(a) (b)

Figure 1 (a) Microlens and 200 µm spacer in polymer (NOA61) on a single mode silica fiber, able to etch silicon at 2 µm scale with a 1064 nm, 100 ns laser with only 10 mW. (b) Topology of a broken welding spot, top glass plate (400 fs, burst 40 MHz, in a gap)

As we will see, the laser processes using photonic jet are limited to surface structuring, Inversely, femtosecond lasers, concentrating energy in time, make possible to micromachining dielectric materials in volume. The transparent material absorbs the energy only at the focus point where the peak power density is enough. We will show how a 40 MHz burst of 400 fs pulses (at 1030 nm) can be used to enhance the energy deposition in a glass material, how such energy deposition can be used to perform glass welding and not only where the two glasses are in optical contact but in a gap of few micrometers [3-4]. These results come from the Labcom ANR LaserSurf, jointed lab between ICube and IREPA LASER and the ANR Glass Welding.

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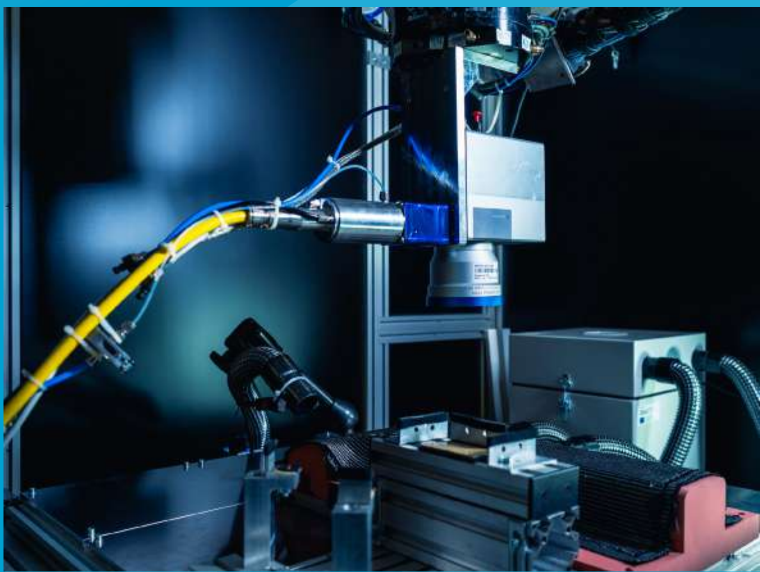

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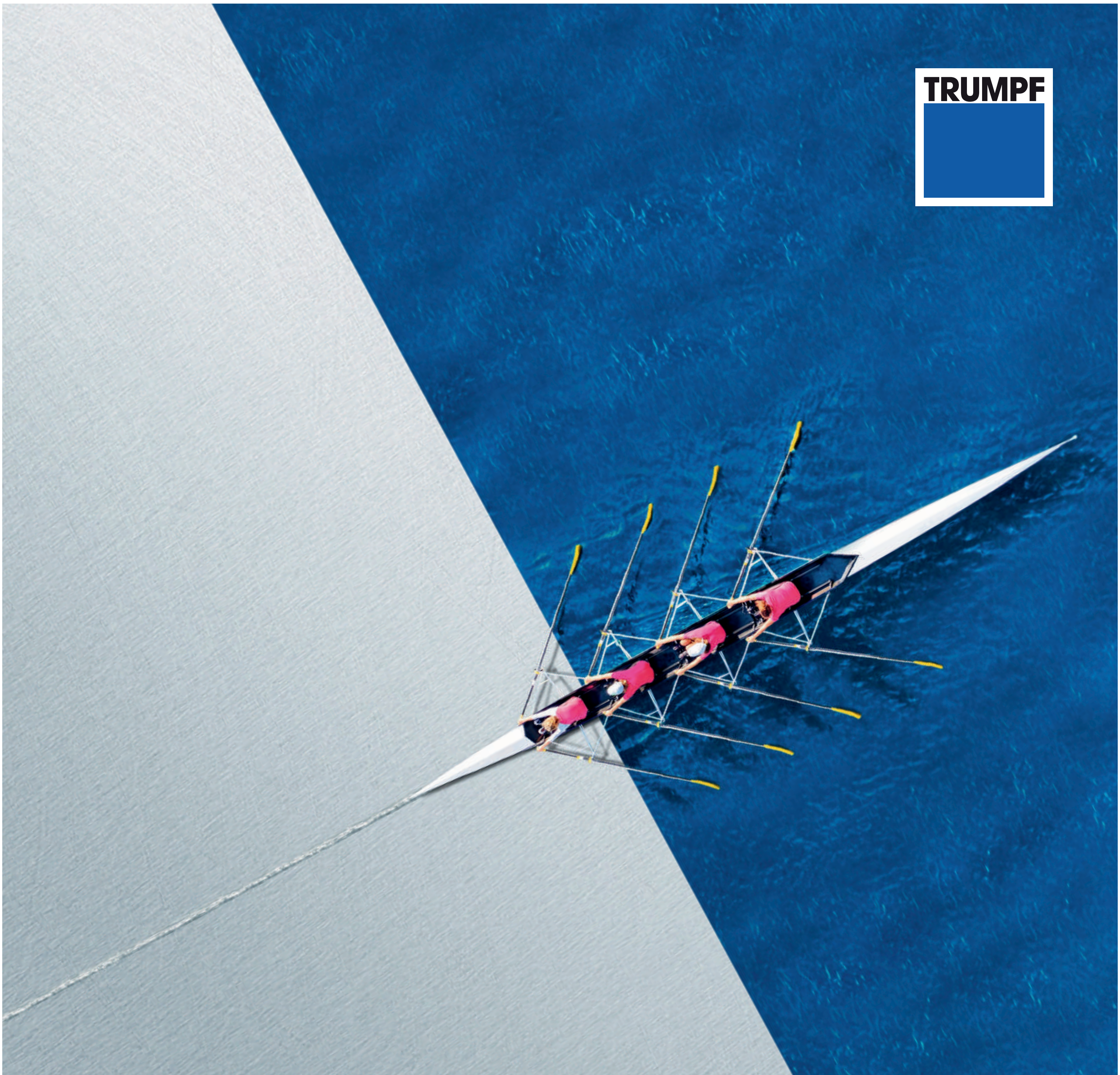
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