LightPanther: a tool that permitted the first ever demonstration of a mobile laser ultrasonics system

WHITE PAPER

November 2023

SHOCKLite

Laser Ultrasonics, an advanced hearing device for the industry

While the human ear is usually sensitive to frequencies between 20Hz and 20kHz, there is a wide range of frequencies, such as the ultrasound, that cannot be heard by our fellow human beings.

Ultrasound is defined as the frequencies above 20kHz, which, as stated above, is our hearing limit. Dolphins are the most famous mammals that can hear and communicate via ultrasonic waves as the frequencies they are sensitive to can be as high as 120kHz. But they are not the only ones! In fact, the human's best friends, cats and dogs, can hear ultrasonic frequencies that are as high as 60kHz and 40kHz respectively.

As all waves, the ultrasonic ones can carry very valuable information between living beings, but their contribution does not stop there! In fact, they have become a precious ally for the humans in a wide range of applications, the most famous of them being the ultrasound scan to live monitor fetuses or the sonar ranging.

A more recent application appeared after the emergence of lasers in the 60's: laser ultrasonics. This technique uses two laser sources: a first one, that is an intense pulsed laser, to generate the ultrasonic wave via the buildup of a plasma on the material to inspect and a second one, that is frequency-stabilized, which is coupled to an interferometric setup to detect the wave.

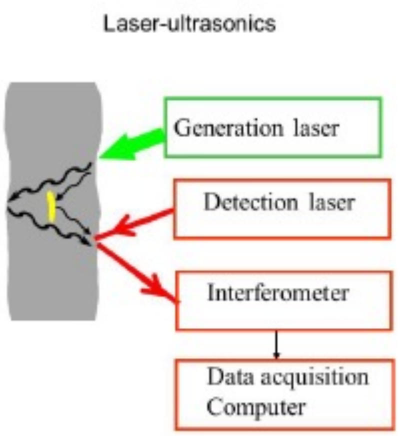

Figure 1 : Laser ultrasonics apparatus [1]

The wave travels back and forth in the part. When it gets to the surface on which the detection laser points, it distorts the surface and the apparatus detects an echo. Laser ultrasonics can be beneficial to characterize certain properties of materials such as their thickness, their composition or the presence of flaws in their structure. In fact, the microscopic properties of the materials will tend to have an effect on the ultrasonic signal signature. For example, a flaw in the material's volume will reflect a part of the wave which will give rise to an additional echo.

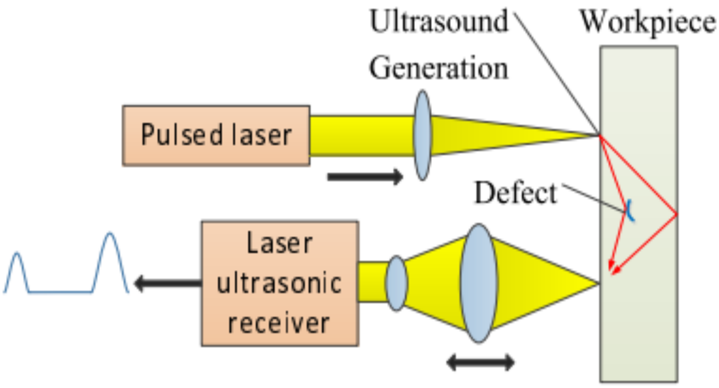

Figure 2 : Laser ultrasonic crack detection principle [2]

The attenuation of the ultrasonic wave after several reflections on the parts' interfaces can also give a valuable insight on the grain size. In fact, the grain dimension has an effect on the scattering of the wave: the bigger the grain size, the higher the attenuation.

An advanced hearing device that is not that flexible

How many grandmas have complained about how unpractical their hearing device is? Well, quite a lot.

The number is, without any doubt (and may be a bit of exaggeration), the same as the one counting the industrials who have complained about the incompatibility of the laser ultrasonics process with their environments. That is mainly due to the fact that the generation laser is generally used in free-space propagation.

While the detection laser is usually a CW or QCW laser (easy regimes to transmit through optical fibers), the generation laser is generally an intense nanosecond pulsed laser (tens to hundreds of mJ). The high level of peak power developed by the latter type of lasers has been a hurdle to couple in optical fibers.

This difficulty made it hard for the process to get a wider exposure in the industry. In fact, free-space propagated beams imply that the laser sources are located close to the materials to analyze and therefore, in industrial environments, close to perturbation sources (heat, vibrations, water etc). Another struggle is related to eye-safety as these class IV lasers have to be completely encapsulated to ensure the workers' safety.

The road to an industrial-friendly system with record-breaking fiber injection performances

As underlined in the previous section, laser ultrasonics is a process that is not well adapted for a use in environments in industrial environments such as hot rolling mills, for example. A necessary candidate to overcome this issue is the use of an optical fiber to transmit the laser energy from the source to the zone to be treated.

Commercial solutions have been existing to inject energetic nanosecond laser beams in optical fibers. However, they struggle to transport the needed laser energy to generate relevant residual stress profiles, as the highest reported transmitted peak powers were in the 10-20MW range. The main enemy of a higher energy transmission is called the dielectric breakdown of the fused silica contained in optical fibers.

A common easy fibering solution usually consists in focusing the beam thanks to a lens without further care except placing the optical fiber after the beam focus to prevent too high fluences on the air-silica interface. Such a technique is usually detrimental for high-energy transmission as only a few modes propagate in the fiber, which can lead to self-focusing. Another possible approach is to homogenize the beam with microlens arrays [3] following the Köhler integrator design, however such a design has also its inconveniences as the array design gives way to an interference pattern, and therefore intensity peaks, at the focus.

In order to overcome these issues, Shocklite, the beam shaping division of Imagine Optic, has been developing during the last few years a unique beam shaping system allowing the injection of more than 60MW in the nanosecond regime in standard single-core silica optical fibers. To obtain this, particular attention was brought to shape the laser beam in the smoothest possible way at the fiber entrance interface. This is thanks to the reduction of the laser beam spatial coherence which allows much lower speckle peaks than before the beam shaping. The resulting speckle contrast decreases from 0.7 down to 0.15.

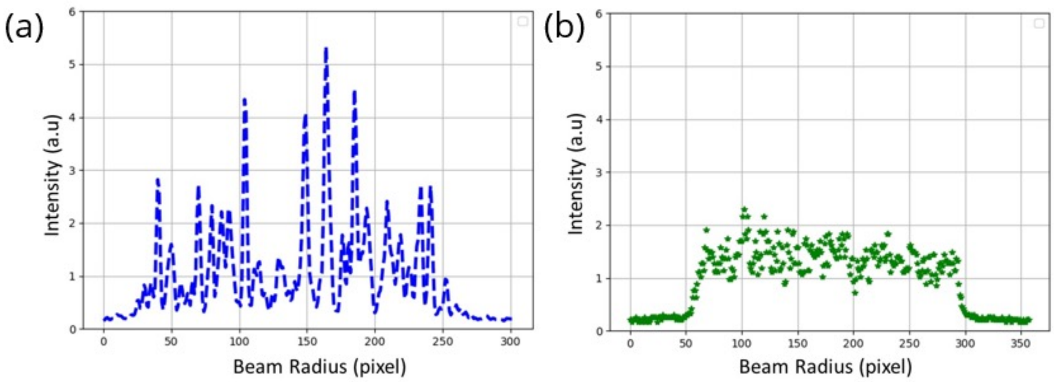

Figure 3: Laser beam profile at the entrance of the optical fiber (a) before beam shaping (b) after beam

As the fibering system is intended for an industrial use, a real-time imaging module was added to the system to live-monitor the fiber entrance facet (and therefore eventual plasmas occurring inside the fiber) and stop the laser in case of any disturbance. This tool enabled us to identify the optical fiber damage threshold for a core diameter of 1.5mm to be at an incident energy of 380mJ (for a repetition rate of 10Hz) which corresponds to a peak power of 63MW at a pulse duration of 6ns. Such energy levels have not damaged a 5m fiber for more than 50 million shots.

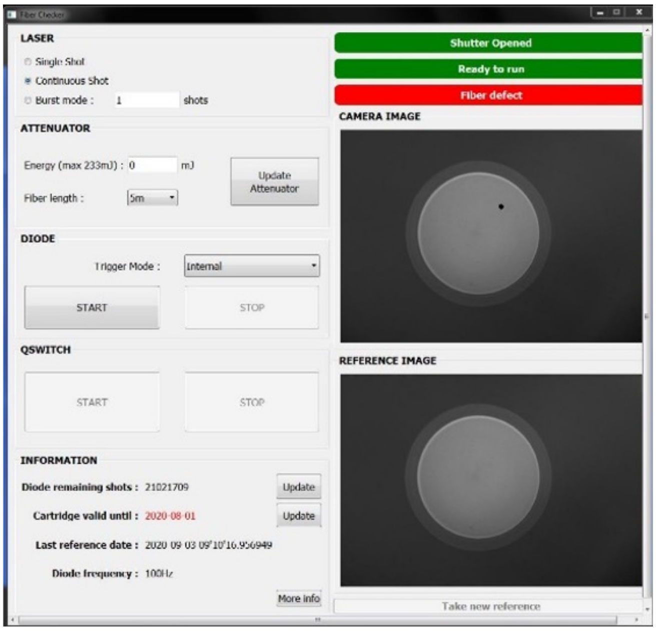

Figure 4 : Optical fiber entrance facet live monitoringafter beam shaping

Half of this energy (190mJ at the fiber output) was used in the scope of the project.

The first-ever demonstration of an all-fibered laser ultrasonics system in industrial conditions

Shocklite (Imagine Optic) and ArcelorMittal Global Research (Maizières-Lès-Metz, France) collaborated very closely in the last 15 years in the frame of two European RFCS projects which were Microcontrol (Grant agreement RFSR-CT-2010-00010) and Microcontrol PLUS (Grant agreement RFSR-CT-2015-00007). This work received financial support from the European Commission under Grant agreement RFSR-CT-2010-00010 "Microcontrol" and Grant Agreement number RFSR-CT-2015-00007 "MicroControl-PLUS.

The main objective of these two projects was to set up the first ever all-fibered laser ultrasonics system in industrial conditions with the aim to characterize the steel properties, namely the grain size and phase transformations, in different locations of a hot-rolling mill. These two data being known, it would then be possible to live-tune the production process parameters (heat, cooling, speed) to make sure the right steel properties would be obtained at the run-out table stage.

Such a closed loop would help prevent the waste of non-compliant steels.

The whole optical path was handled by Shocklite. An optical head ensuring the coaxiality of the generation and detection laser beams was also designed and mounted at the end of the optical chain. This optical module's function was to properly focus the two beams but also to collect the scattered detection laser to be processed in the interferometer.

Figure 5 : Internal view of the optical head

Figure 6 : Laser Ultrasonics apparatus in industrial conditions (ArcelorMittal's factory in

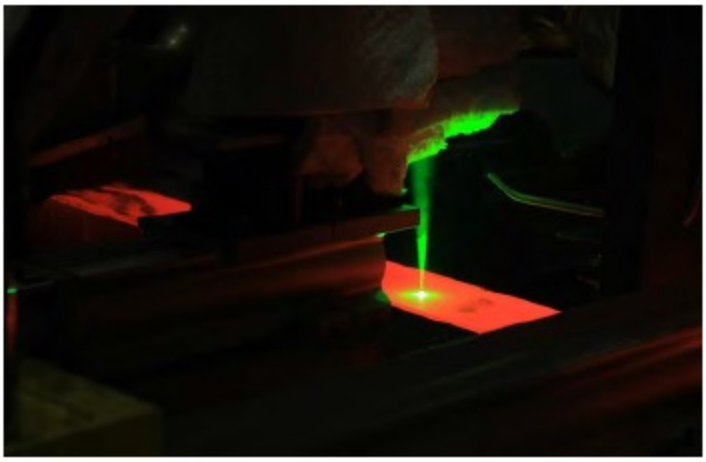

Figure 7 : Optical head located above the steel

Multiple measurements were made on different steel grades. Very good signal-to-noise ratios were obtained as can be seen on Figure 7. Thanks to these signals, accurate ferrite and austenite grain size measurements were made possible. Also, phase transformation predictions could be made as ultrasonic velocity variations were recorded at different stand stages.

Figure 8 : Laser ultrasonic signal obtained with a 5mm-thick steel

In summary

The record-breaking performances of the nanosecond regime energetic laser injection accomplished brought very good quality signals as the high level of transmitted energy ensured powerful ultrasonic waves which could travel back and forth many times in the material. The results obtained within these two projects confirm the possibility of using the fibering system in harsh environments as dust, high temperature and water vapor were perfectly handled by the system.

The energy levels could also open a way for a wider industrial use of intermediate-energetic nanosecond lasers through applications such as laser peening, laser cleaning or laser induced breakdown spectroscopy (LIBS).

References

[1] Jean-Pierre Monchalin, “Laser-ultrasonics : Principles and industrial applications,”

[2] Y. Cheng, Y. Deng, J. Cao, X. Xiong, L. Bai, Z. Li, “Multi-Wave and Hybrid Imaging Techniques: A New Direction for Nondestructive Testing and Structural Health Monitoring.”

[3] Y. Sano, K. Akita, K. Masaki, Y. Ochi, I. Altenberger and B. Scholtes, “Laser Peening without Coating as a Surface Enhancement Technology,” Journal of Laser Micro/Nanoengineering Vol. 1, No. 3 (2006)