Publishable summary

High power Adaptable Laser beams for materials processing HALO www.halo-project.eu

HALO is a collaborative research project supported by the European Commission through its Seventh Framework Programme (FP7). Over its duration the project has been developing technology for the next generation of adaptable materials processing lasers. It brings together large laser manufacturers with key European component suppliers, academic and research organisations and end users of industrial laser systems. The project tackled a wide range of laser technology for processing several important materials, including sheet metal, ceramics and glass. Work has included the simulation of cutting processes, development of new components, experiments with novel laser configurations and the establishment of new processing techniques.

The key advances include:

- Novel components for adaptable beams
    - Capillary tapers to generate a ring-shaped pump beam
    - The first reported isolators to maintain radial and azimuthal polarisation
    - Acousto-optic modulator to select laser mode shape
    - In-cavity acousto-optic Q-switch
    - Segmented waveplates to generate tailored polarisation multi-kW beams
    - S-waveplates to generate radial polarisation using nano-gratings
- Novel 2 µm laser design which can select and combine LG modes
    - 20 W CW output power and Q-switched variant
    - Trials performed demonstrating transparent polymer cutting
- Meta-models developed for metal, glass and liquid-jet cutting
    - New beam characteristics defined for optimised processes
    - HALO IT-tool with convenient GUI for user-friendly application
    - Reduced dross and roughness using standard optics in steel cutting
    - Reduced micro-cracking ps-pulse glass cutting process defined and validated
    - Higher damage threshold nozzle design identified for liquid jet cutting (LJC)
    - Reduced splashing regime for LJC proposed and validated
- Improved understanding of metal cutting using high-speed videography
    - Data implemented in meta-model with HALO IT-tool
- Improved glass cutting processes with ultra-short pulsed lasers using novel beam shapes and multi-spot beam patterns
    - Solved problem of rear-side damage for selected cutting regimes
    - Reduced micro-cracking and improved cut quality
    - Increased cutting speeds setting new state-of-the-art
- Identified optimised polarisation for sheet metal cutting
    - "Shell" pattern polarisation distribution calculated and realised experimentally
    - Dross significantly improved and cut edge quality improved
    - Production feed rate doubled setting new state-of-the-art
- LJC process for sapphire identified
    - Patent applied for on progressive cutting process strategy
    - New state-of-the-art defined for edge quality.

Components

Capillary tapers
A set of capillary fibre tapers were used to produce a ring-shaped pump profile to spatially excite Laguerre-Gaussian ring modes in the end-pumped Ho:YAG rod laser made by ORC (see below). The capillary tapers connected a standard 105/125 µm multimode pump fibre to a fluorine clad capillary fibre with low loss. Tapers were made with several different aspect ratio capillary fibres ranging from 100/200/235 µm to 160/200/217 µm (air/silica/fluorine doped cladding) designed to excite different order LG modes.

Optical isolator
A Faraday isolator designed to operate on and maintain radial and azimuthal polarisation in a Laguerre Gaussian ring mode was demonstrated in HALO. An isolation of >22 dB with an insertion loss of <0.4dB was demonstrated. The consortium believes that this is the first time this has been demonstrated.

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3-port acousto-optic switch
The 3-port acousto-optic switch with a single input fibre and two output fibres was designed for high power operation and used to selectively pump the ORC Ho:YAG rod laser with either a standard multimode fibre or with a capillary fibre through one of the tapers described above. By using the AO switch to control the amount of power in each pump fibre, the user can choose between a TEM_{00}, a particular LG mode or a combination of both. This flexibility offers the opportunity to optimise the mode shape for the particular materials processing application of interest.

Acousto-optic Q-switch
To Q-switch the Ho:YAG rod laser a high power polarisation indep-endent acousto-optic (AO) Q-switch was developed by Gooch and Housego (UK). To enable high-power operation the AO modulator (AOM) used a quartz crystal as the AO interaction material. A novel design was developed to mitigate the natural birefringence of the quartz crystal.

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Segmented waveplates
To manipulate the polarisation of a laser beam external to the laser cavity a series of segmented waveplates with a high laser induced damage threshold were developed, including radial ("dartboard") and striped ("shell") designs. These were used by Trumpf to optimise the polarisation distribution at the cut front of a high power laser used for metal cutting achieving record breaking speeds for steel cutting with a 1 µm laser (see later).

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S-waveplates
The ORC has recently developed a continuously space-variant half-wave plate (S-waveplate) that allows a linearly-polarised laser beam in the two-micron wavelength band to be converted into a radially-polarised (or azimuthally-polarised) doughnut mode with both high efficiency and very high polarisation purity. The S-waveplate was fabricated using a femtosecond laser to write nano-structure gratings in a silica glass window. The grating structures induce birefringence with slow and fast axes aligned parallel and perpendicular to the grating direction respectively, allowing the

construction of a two-dimensional array of microscopic half-wave plates aligned in a manner designed to produce the required position-dependent polarisation rotation.

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Novel laser designs

A novel radially-polarised solid state laser has been developed at the ORC under the HALO project. The laser brings together fibre laser and bulk solid state laser technologies in the form of a hybrid fibre laser pumped bulk laser. In this scheme, the single-mode output beam from a cladding pumped Tm-doped silica fibre laser operating at 1.91 µm is re-formatted using a specially-designed passive fibre with an annular guide to produce an output beam with a doughnut-shaped near-field beam profile.

This multimode ring-shaped beam is used to end pump a bulk solid-state laser based on Ho:YAG, which operates at ~2.1 µm. By carefully matching the transverse spatial profile of the pump and hence the inverted region with the intensity profile of the desired laser mode, a series of different doughnut laser modes can be selectively excited including a radially polarised doughnut mode and higher order Laguerre Gaussian doughnut modes.

The slope efficiencies with respect to incident pump power are typically ~65% for all modes with output power up to 19 W, limited by available pump power.

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Meta-modelling

Meta-modelling enables the derivation of rules for the design of optical components to enable high quality laser cutting. In HALO, meta-modelling was used throughout the project to improve sheet metal cutting, brittle material cutting and liquid jet cutting.

As an example of the method, one potential route for improving metal cutting which was investigated was the use of elliptical beams. As is well-known from recent publications, the most prominent measure to improve cut quality is to increase the angle of incidence of the laser radiation at the cutting front. A straight-forward design rule for an appropriate optical component is to choose an elliptical beam instead of a circular one, in order to increase the angle of inclination while maintaining a small kerf width. However, simple application of this plausible rule fails, since its applicability is restricted to a bounded region of parameter settings. In HALO, tailored meta-modelling approaches were developed and applied to accomplish the request for determination of applicability regions for successful design thinking.

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High speed imaging and analysis

One important HALO task performed at Luleå University of Technology (LTU) was to develop and apply a high speed imaging (HSI) methodology for the validation of the simulations and meta-models that have been developed by Fraunhofer ILT. This includes HSI of drop ejection, dross formation and cutting front melt where different analysis methods are applied, particularly for understanding of dynamic phenomena.

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The HALO IT-tool

The use of the meta-modelling in HALO was very successful, but it is difficult for the user to visualise and keep track of all the different variables and their potential effects. Consequently an IT-tool with a user-friendly GUI was developed within the project. This included a range of different software code modules (partly with embedded data), namely a laser cutting model, a parameter meta-model, a cutting database, cut front streak images and a cut quality optimization tool. These models are integrated to a common IT-based planning and evaluation tool (the HALO IT-tool) in the form of an interactive procedure that enables the user, via the specially designed GUI, to communicate between the different modules, to transfer data and to operate the different modules simultaneously in a multi-tasking manner.

The HALO IT-tool is tailored for experts with a certain background in laser cutting, who can apply the IT-tool for themselves but it also serves clients with less expertise who are untrained on the HALO IT-tool. Trained users can assist clients such as laser system or optical component manufacturers as well as companies (especially SMEs) applying laser cutting. A user guide is also available on request, and a short video showing how the tool works is online at the HALO website: http://halo-project.eu/documents/further-technical-info/

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Glass cutting

In the HALO project Trumpf investigated the influence of beam shape and pulse duration on the cutting speed and quality of alumina-silicate glass processed with ultrafast lasers. The high intensities of the ultra-short laser pulses initiate non-linear absorption. A steep temporal increase in the pulse intensity is required to minimize the amount of energy propagating through the material and causing damage at the rear side. This could be verified by single pulse ablation experiments. For pulse durations of 1 and 0.4 ps the ablation threshold fluences were lower than for 6 ps. The primary rear-side damage could be prevented with shorter pulse durations, however the process efficiency could not be enhanced.

The analysis of multi-spot experiments showed, that the ablation rate as well as the quality can be improved by using multi-spots. By adjusting the angle of a linear multi-spot pattern to the scan direction, the optimum configurations regarding quality and process time were identified. However, the best orientation angle regarding quality generated a spatial line overlap and the best orientation angle regarding process time resulted in well separated lines.

The polygon arrangement proved that it is possible to use the best of both configurations by a approximated circular arrangement where the spots are well separated in the centre of the groove and overlap at the edge of the groove. A comparison of the energy specific volume of the process with and without DOE showed that multi-spot arrangements show a quantitative advantage, i.e. improved energy specific volume.

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Metal cutting

During the HALO project, in the sheet metal cutting sub-project, work was focused on investigating the impact of various configurations of beam, including elliptical beams, radial polarisation and tailored laser beam polarisation. The most successful was the tailored polarisation, as expected from the simulations. Since current industrial solid state lasers are randomly polarised, an optimised polarisation distribution has the potential to drastically increase the absorption rate.

Optimising the polarisation means to orientate the electric field of the incoming laser beam at every point of incidence towards the local cut front normal. Therefore, a detailed analysis of the cutting kerf geometry was necessary. To realise the new polarisation distribution, so-called segmented waveplates were fabricated by Gooch and Housego (UK), in which each stripe of the electric field of an incoming linear polarised beam can be orientated individually. To investigate the impact of the optimised polarisation, cutting experiments in 15 mm stainless steel were performed, with excellent results. Cut edge quality was improved, dross was clearly reduced and feed rate was doubled.

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Liquid-jet cutting

Application of liquid jet technology to the novel laser processing of hard-to-machine materials, e.g. sapphire, has demonstrated promising results in terms of feasibility and speed. Moreover, the surface quality has been highly appreciated by customers; surface roughness values <500 nm have been achieved.

In relation to the material thickness, two different strategies for cutting sapphire have been identified. For structures with thickness <1 mm, the market acceptable cutting speed has been achieved by applying a single cut technique. In contrast, for sapphire samples >1 mm, a newly developed approach using parallel cuts has been applied. Further improvement in the surface quality, in particular decreased chipping, has been achieved by means of so-called "progressive cutting". For this recently developed process, Synova has filed a patent "Processing strategy" (application number 15002232.5). This process will be exploited internally to facilitate high quality sapphire processing and to win more customers for Synova technology in the coming years.

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Further information

For more information on any of the HALO topics please visit the website (www.halo-project.eu) or contact:

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