CaliBend: a flexible, cost-effective laser module for thermal-assisted bending of high-strength steels

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ABSTRACT

"CaliBend" proposes a direct diode laser approach for thermal assisted processing of steel sheets. Our module aims at enabling bending processes of high-strength steels (HSS) and with minimal bending radii without inducing damage to the metal part. In this work we present a laser source integrated on an industrial servo press for continuous die processing. The metal sheet is heated up locally by laser radiation before the bending stroke. By reaching power densities close to 40 W/mm^2, the bending line of the metal sheet reaches the hot forming temperature regime in under two seconds allowing a faultless while increasing the typically low forming limits of HSS.

Keywords: High strength steel, diode laser, material processing

1. INTRODUCTION

High-strength steels (HSS), i.e. steels with tensile strengths higher than 1000 MPa, are becoming an increased sought solution material for multiple industry fields, ranging from automotive, mining and naval sectors [1]. The increased tensile strength of these materials improves part resistance and thus reduces the risk of part failure, crucial in crash safety for instance. Additionally, a higher part strength allows to reduce the used steel thickness, contributing to an overall part weight reduction. However, HSS present a challenge in terms of industrial processing. Typical cold/ambient temperature processing usually results in cracks and unwanted spring-backs (Figure 1), compromising the part structural properties and limiting the possibilities of HSS applications. The formability of HSS has been investigated in detail and different material and process technological solutions have been proposed [2-4]. Nevertheless, many HSS fail prematurely due to shear during flange tension. The reason for this is the high strain hardening and strain rate sensitivity.

The most usual solution to avoid these processing problems is the preheating of the HSS sheet. However, HSS are particularly demanding in terms of heat treatment, requiring short-term, localized and controlled process temperatures to avert faults and unwanted microstructure changes [2]. In order to avoid a negative influence on the properties of the part, the processing must be carried out below the recrystallisation temperature (approximately T<800 - 900 °C). Laser heating sources are an ideal candidate for these materials as they provide a repeatable, controlled and focused thermal profile. Moreover, as opposed to other heat treatment methodologies such as induction heating, laser sources are less sensitive to source-metal distance variations usually caused by shocks and vibrations present in industrial environments.

The "CaliBend" project unites the know-how of three partners to provide a ready up solution to process HSS steels at the industrial level. One the one hand, Fraunhofer-Institute for Production Technology IPT brings its vast experience in material processing and industrial process integration. On the other hand, Franz Pauli GmbH & Co. KG contributes with its expertise on continuous die processing and industrial servo presses and their tooling. Finally, Monocrom S.L. provides its know-how in diode laser manufacturing and laser solutions for industrial applications.

In the present work we focus on providing a flexible, cost-efficient laser module, the @Met direct diode module, aiming to assist the 90º bend of HSS sheet on an industrial servo press (Schuler MSC 2000) for continuous die processing. Within the progressive die, the sheet metal is heated locally in the machine cycle. It is then fed in hot state to the

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processing stage where it is formed. To match all these goals, we have based our laser module on broad area diode lasers, which are one the most efficient laser sources currently on the market, both in electrooptical (E-O) efficiency and cost.

First, we defined the laser requirements to achieve a faultless processing by using a fiber coupled diode laser test bench. Using these results, we have designed a diode laser module able to deliver 8 kW of optical power in continuous wave (CW) conditions, focused in a line of 200 mm in length and 1 mm of width by means of simple and inexpensive optics. These conditions allow to reach power densities close to 40 W/mm^2, allowing faultless bends in sheets of 2 mm thickness of CR1220Y1500T-MS (1500M) and CR700Y980T-DP (DP1000) with bending radius down to 0.25mm.

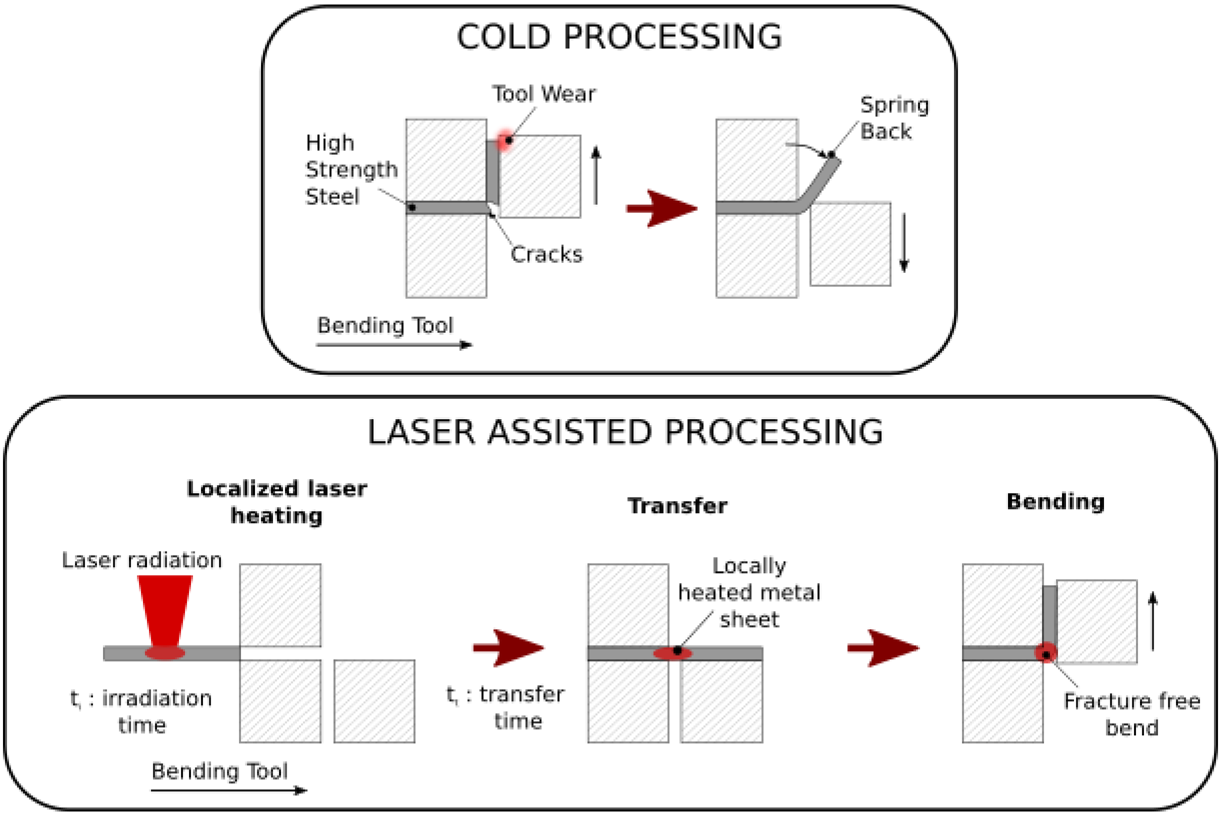

Figure 1. Scheme of the bend of an HSS sheet on a servo press. (Top) Typical issues observed when the steel sheet has not been thermally processed, mainly cracks and strong spring backs of the sheet. (Bottom) Schematic procedure where a laser thermal treatment is applied to the HSS sheet before the processing step. The preheating aims to achieve fracture free bends with reduced spring backs.

2. LASER IRRADIATION PARAMETERS

The first step on the design of the @Met module was to determine all laser source and irradiation parameters in order to achieve faultless 90º bends with minimum changes on the material properties. Additionally, the heating of the bending line must be achieved within a reasonable time frame compatible with industrial upscaling. That is, the irradiation time and transfer time to the bending tool must not decrease significantly the stroke per minute rate of the servo press. We characterized the best combination of laser power density and irradiation time in a test rig in Fraunhofer-Institute for Production Technology IPT, consisting on a punching machine (Boschert, 28t of maximum force) coupled with a fiber laser (LASERLINE LDF 4500-30) with a scanning head (Raylase Superscan III-30). Two types of HSS part materials were tested, 1500M and DP1000, both in sheets of 2mm thickness. The test consisted on a rapid scan of the fiber coupled diode laser along the bending line. The part is then transferred to the bending tool of the punching machine while it remains hot and finally it is bent and inspected. It is important to note that the irradiation pattern on the test rig consists on a circular spot scanned along the bending line of the part. Thus, the scanning speed (5 m/s), spot size and power of the laser was taken into consideration when calculating the power densities applied all over the bending line. Given the high scanning speed compared to the dimensions of the part, it is safe to assume that our treatment behaves close to continuous irradiation, despite slight differences in absorption caused by cyclic overheating.

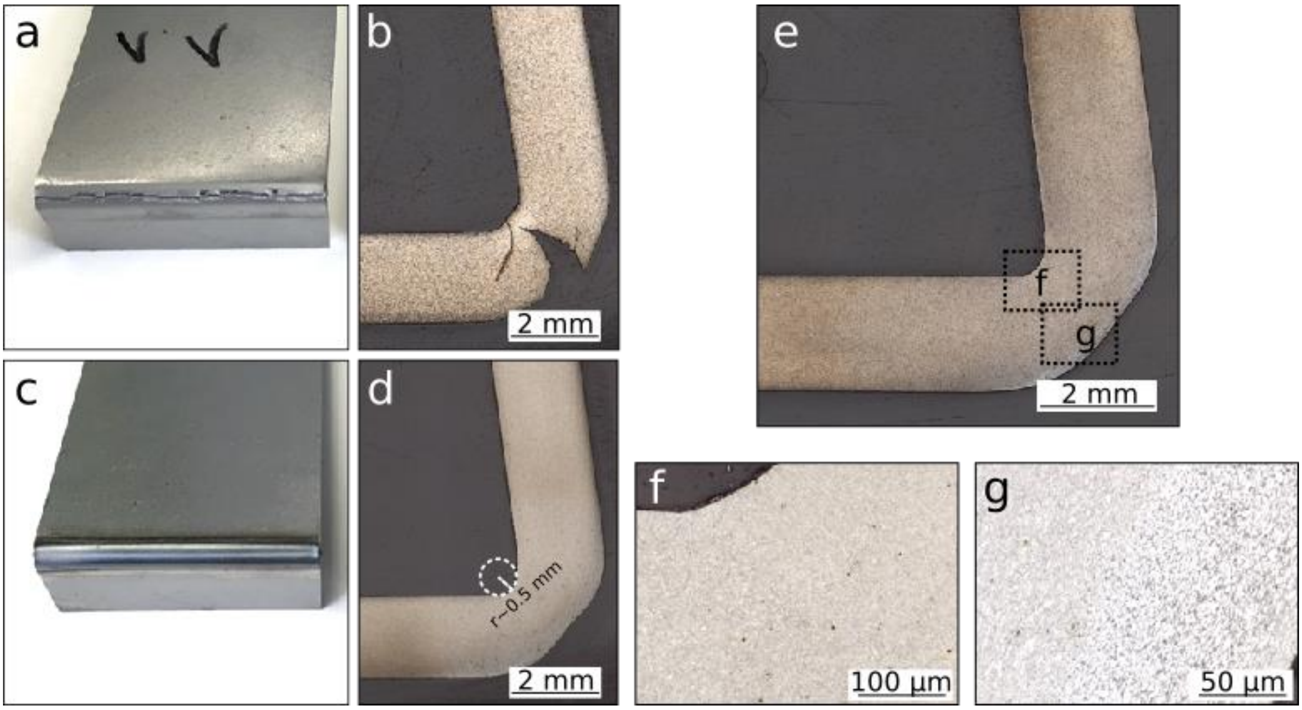

Figure 2. Photographs of 1500M 2mm thickness parts after bending. (a) 1500M part after bending without heat treatment where cracks are visible. (b) Side view of panel a, showing the depth of the crack. (c) 1500M part bent after applying a laser heat treatment consisting on 43 W/mm^2, 1.75s of irradiation time and 0.5s of transfer time to the punching machine. No visible damage is appreciated. (d) Side view of panel c. The bending radius achieved is ~0.5 mm. (e) Enhanced contrast and closer inspection of the heat-treated part. Dotted squares represent the regions of interest of panels f and g. (f) Zoom in of the inner region of the bent zone. Far from the irradiated surface, the grain structure remains the same as the bulk HSS material, i.e. martensitic. (g) Zoom in of the irradiated region of the bent zone. Close to the irradiated surface the microstructure is changed, presenting an austenitic structure.

Figure 2 shows the bending results for 1500M. As seen in Figure 2a and 2b the sheet cracks during the bend without heat treatment, showing the requirement of heat treatments during HSS processing with high degrees of deformation. Figures 2c,d and e show the resulting bends after an optimized thermal treatment consisting on power densities of 43 W/mm^2, irradiation time of 1.75s and transfer time of 0.5s. First and foremost, the part shows no cracks or evident damage and second, a bending radius of 0.5 mm was achieved. Closer inspection of the bending zone allows to observe changes on the microstructure of the steel. Figure 2f, the surface farthest from the irradiation, shows little changes on the grain structure of the HSS, i.e. martensitic microstructure. On the other hand, the irradiated surface (Figure 2g) presents slight differences with an overall austenitic structure close to the irradiation zone.

The tests performed on DP1000 showed similar results, as presented in Figure 3. The cold processed part presented cracks on the bending region although not as deep as in 1500M. On the contrary, the thermally treated sheet was successfully bent reaching a radius of 0.25 mm (Figure 3a and b). The irradiation parameters were similar to those of 1500M, i.e. 40 W/mm^2, irradiation time of 1.75s and transfer time of 0.5s. Inspection of the microstructure of the bent zone showed a grain structure similar to the bulk material on the inner surface while the directly heated surface presented a mixed ferrite and martensitic structure.

The slight and superficial changes on the grain structure of both thermally treated parts confirm that the irradiation parameters used were sufficient to achieve faultless bends without compromising the HSS sheet integrity. On the one hand, the used power densities and irradiation times are enough to reach hot forming temperatures without affecting the bulk structure of the material and only modifying the first 100-200 μm grain structure of the bent region. On the other hand, the irradiation and transfer times used are compatible to usual stroke rates of servo presses (~40 strokes/min) which confirm the upscalability of this laser treatment process for HSS.

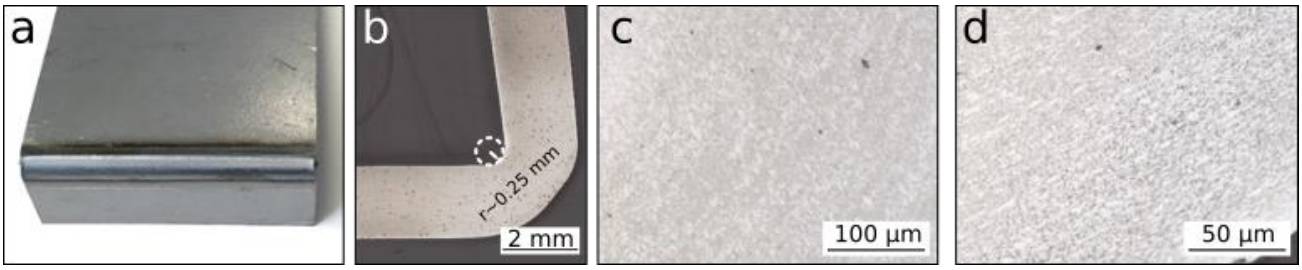

Figure 3. Photographs of bent DP1000 2mm thickness part after laser metal treatment. (a) Bent part after a laser heat treatment consisting on 40 W/mm^2, 1.75s of irradiation time and 0.5s of transfer time to the punching machine. (b) Side view of panel a, showing the bending radius achieved of ~0.25mm. (c) Zoom in of the inner region of the bent zone. Far from the irradiated surface, the grain structure remains the same as bulk DP1000, i.e. martensitic. (d) Zoom in of the irradiated region of the bent zone. Close to the irradiated surface, the microstructure consists on both ferrite and martensitic.

3. @MET DIRECT DIODE MODULE DESIGN

After defining the requirements of irradiation for the correct heat treatment of 1500M and DP1000 parts Monocrom S.L. aimed at the design of a cost effective, flexible laser module easy to integrate on an industrial servo press. The target bending profile was a line of 200mm x 1mm, with a target bending radius of 0.5mm and 0.25mm for 1500M and DP1000, respectively. Our design is based on diode laser systems which present an excellent E-O efficiency and a reduced cost per optical power ratio. To achieve the previous stated 40 W/mm^2 we thus require a module able to deliver 8 kW of optical power in continuous wave (CW) conditions. The selected wavelength of the laser was 940 nm, as it presented both a good absorption rate for HSS and a high E-O efficiency for diode laser bars [5]. We used 8 individual stacks of 1kW of optical power to achieve the required power density and irradiation profile dimensions (Figure 4a). Each of the stacks consists of 8 diode laser bars.

3.1 Optical design

To shape the diode laser beams in a focused line we used commercial fast axis collimator microlenses in order to collimate the fast axis component of the laser emission. Then each of these collimated beams is focused on a single line profile using a cylindrical lens as depicted in Figure 4a and b. On the contrary, the slow axis of the diode laser sources is left uncollimated. To achieve a homogeneous irradiation line profile, we have optimized the spacing between stacks and the focal length of the cylindrical lens. At the chosen focal distance (215mm), the beams overlap owing to their natural slow axis divergence. As a result, the beam profile is a uniform line, with top hat and gaussian contours along and across the irradiation pattern, respectively (Figure 4c). The optical design of the system allows a ± 2 mm depth of focus flexibility without significantly affecting the line profile uniformity. It is important to highlight the low cost of the optical components used as well as the increased flexibility in system integration that our large working distance provides.

3.2 Diode laser stacks

The design and assembly of the diode laser stacks was performed by Monocrom using its proprietary patented solder-free mounting process (*Clamping^{TM}*). This technology overcomes most of the problems of the solder-based techniques [6]. Each laser bar is clamped between two copper heatsink electrodes by applying uniform pressure over the bar contact

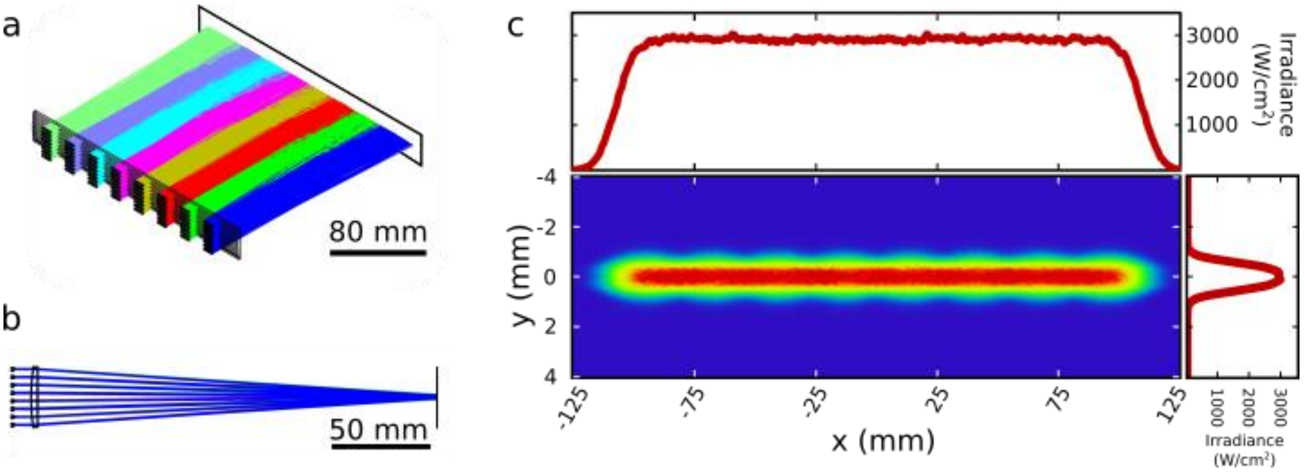

Figure 4 . Optical design of the laser module. (a) Beam layout of the laser module. The module consists of eight stacks built with eight diode laser bars each. The fast axis component of each of the beams is collimated with fast axis collimator lenses. These beams are then focused with a cylindrical lens (f = 215mm). The slow axis component of the beams is not modified by any optical system. (b) Side profile of the beams in panel a showing the fast axis collimation and focusing of the laser beams. (c) Simulated irradiation pattern of the module at the focal distance of the cylindrical lens (f=215 mm). The line has a uniform top hat profile along its length of 200mm (top) and a gaussian profile across its width (right).

surface [7] (see Figure 5). Since the mounting process takes place at room temperature, mounting induced stress by thermal expansion coefficient mismatch is avoided. The laser bar can still expand between the electrodes when heating up avoiding thermal-mechanical induce fatigues during operation, which increases the lifetime of the device.

The elimination of the intermediate layers reduces the thermal resistance between the heatsink and the semiconductor, affected by the homogeneity of the contact. Moreover, since the laser bar is contacted from both sides, cooling takes place also from the n-side (around 20% of the heat is removed from the n-side contact), reducing the thermal load in the p-side of the laser diode bar [8]. This additional heat dissipation capacity allows to use macro channels cooling channels on our heatsinks. In contrast to their micro channeled counterparts, macro channel coolers show less clogging risk of the water channels by particles derived from corrosion or biological agents that appear during storage. Furthermore, our macro channel coolers are not prone to failure due to electro-corrosion effects. As a result, our macro channel cooled heatsinks require low maintenance and possess longer lifetime.

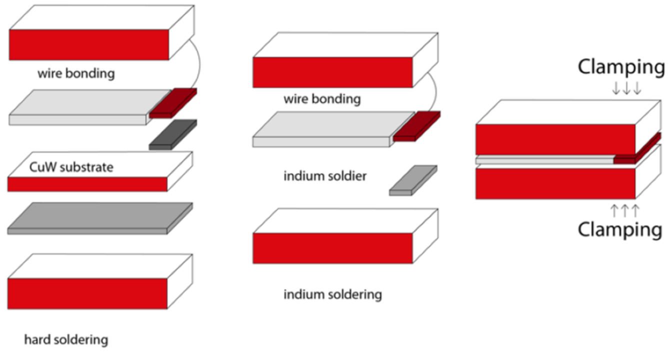

Figure 5. Schematic view for laser bar mounting with (left) hard soldering, (center) soft soldering with indium, and (right) clamping.

Another important benefit offered by this technology is the very low smile achieved. The smile effect consists on the curvature of the diode laser bar due to induced thermal-mechanical stress during the mounting process. Consequently, the smile can reduce the beam quality when using optics by a factor of 2 [8]. Owing to the reduced stress applied on the laser bar of our *Clamping*^{TM} technology, we are able to reduce the smile curvatures by an order of magnitude compared to typical soldered diode laser devices (see Figure 6a and b). This has an impact on the beam quality of our stacks, especially when using microoptics as it is the case of our diode laser module.

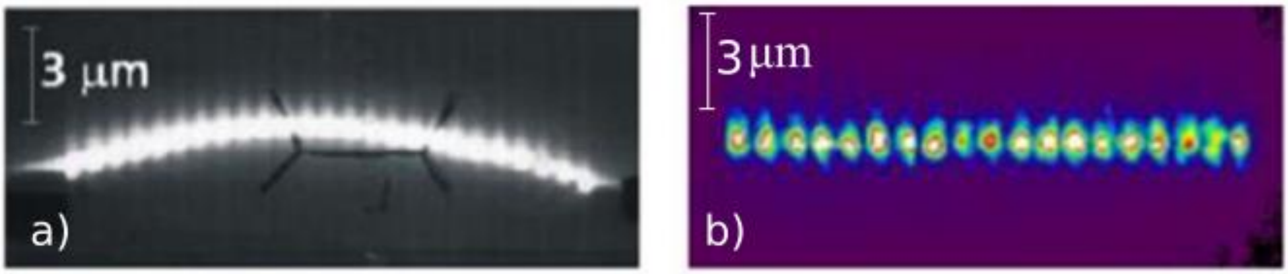

Figure 6 Smile effect on laser diode bars. (a) Enlarged picture of a soldered diode laser bar with a 'smile' of approx. 2 µm [5]. (b) Enlarged picture of a diode laser bar mounted with the Clamping technology, showing a smile under 0.1 µm.

The performance of each of the stacks allows to reach 1 kW of optical power at 125A of electrical current (Figure 7a, blue). At maximum current, the stacks reach an E-O efficiency close to 60% (Figure 7a, orange). The total of eight stacks thus provide 8 kW of optical power and 40 W/mm^2 of power density at the expense of ~13.5 kW of electrical power, underlying the high cost efficiency of our module. Furthermore, the electronic design of the module allows controlling the power of each individual stack. This grants the possibility of generating flexible irradiation profiles, either by shortening the line length or by modulating the optical power irradiated to the part along the line length.

The @Met direct diode laser module (Figure 7b) is compact (240 x 100 x 85 mm) and light (5kg), perfectly suitable to fit in the narrow spaces of a servo press bench. Moreover, the module is airtight, avoiding degradation of its performance due to typical harsh conditions of industrial environments such as fumes or dust.

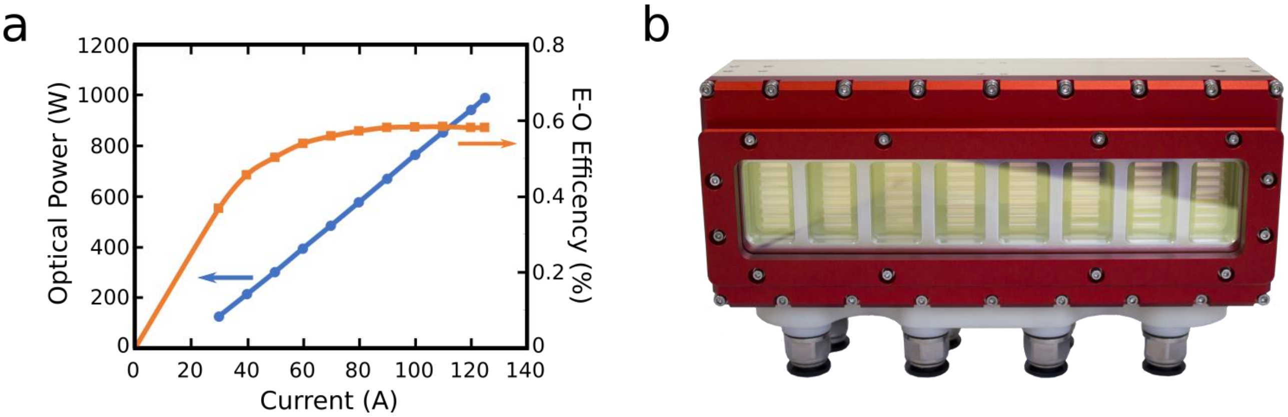

Figure 7. (a) Performance of one of the module's diode laser stack. At 125A the stack reaches 1 kW of optical power (blue line, left axis). The stack Power-Current behavior is completely linear over the operating conditions range. The E-O efficiency reaches 58% at maximum current (orange, right axis). (b) Photograph of the @Met direct diode laser module, showcasing its eight independently working stacks. The dimensions of the module are 240 mm in length, 100 mm in height and 85 mm in depth. The weight of the device is 5 kg.

4. CONCLUSIONS

We have presented cost efficient solution to bend HSS on an industrial servo press for continuous die processing. The @Met direct diode module is a stable, focused and local heat source that enables the preheating of the steel part before its subsequent bending. Fraunhofer-Institute for Production Technology IPT and Franz Pauli GmbH & Co. KG have provided the know-how and experience for the validation of this solution under industrial conditions. In collaboration with our partners, we have optimized the irradiation parameters of the laser source to allow faultless bends in sheets of 2 mm thickness of 1500M and DP1000. By applying power densities close to 40 W/mm^2 during 1.75s, we are able to achieve bending radius down to 0.25mm without significantly affect the mechanical properties of the material. It is important to note, that cold processing of these materials, i.e. without previous heat treatment, results in damaged parts. This highlights the new material and processing possibilities opened with our approach.

With these results we have designed and built the @Met direct diode module, based on diode laser stacks using Monocrom's *Clamping*^{TM} technology. Our module is able to deliver 8 kW of optical power at a wavelength of 940 nm in CW conditions. By focusing its power on a line profile of 200 mm x 1 mm, we reach the desired power densities of 40 W/mm^2. Our optical design allows a uniform irradiation profile with the use of inexpensive optical elements, while achieving a comfortable and flexible working distance larger than 200 mm. Moreover, the @Met direct diode module allows the individual control of each of the stacks, granting the flexibility to apply different irradiation line profiles, either by shortening the irradiation pattern or by modulating its power profile along the bending line.

Owing to the high efficiency of our diode lasers and the simple optics used in our module, the @Met direct diode stands as a highly flexible and efficient tool, ready and easy to integrate in most industrial environments.

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