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LASER ASSISTED BENDING FOR EFFICIENT LIGHT-WEIGHT-PRODUCTION

Ferdinand Bammer, Thomas Schumi, Andreas Otto, Dieter Schuöcker

Original scientific paper

Laser-assisted bending is an efficient production method of light weight and/or high strength parts. It enables bending of Al-, Mg-, Ti-, and certain steel alloys by heating the bending line shortly before and during the bending process. Two solutions integrated in the lower tool of a bending machine are available: first with diode lasers, second with optics supplied by an external fiber coupled solid state laser. Experiments show that laser assisted bending of Al-parts needs the use of an absorption layer like graphite. In case of high strength steels an accurate temperature control is necessary and some steel-alloys lose strength due to this process. Mg- and Ti-alloys can be bent with this new method usually without complications. Further this new production method is an energy saving method for bending of brittle metals and the ease of operation, which can be compared with simple cold-bending, and it allows going new ways in construction and production of light weight parts.

Keywords: *hot bending, light weight construction, diode laser, solid state lasers*

Laserom potpomognuto savijanje u učinkovitoj proizvodnji dijelova male težine

Izvorni znanstveni članak

Savijanje laserom je uspješna metoda u proizvodnji dijelova male težine i/ili velike čvrstoće. Omogućava savijanje legura Al-, Mg-, Ti- i nekih legura čelika zagrijavanjem linije savijanja neposredno prije i tijekom postupka savijanja. Moguća su dva rješenja integrirana u donjem alatu stroja za savijanje: prvi s diodnim laserima, drugi s vanjskim laserom s čvrstom jezgrom spojenog s optičkim vlaknom. Eksperimenti pokazuju da je za savijanje aluminijskih dijelova laserom potreban apsorbcioni sloj poput grafita. Kod visoko čvrstih čelika potrebno je pomno kontrolirati temperaturu, a neke čelične legure tim procesom gube čvrstoću. Mg- and Ti-legure se ovom novom metodom mogu savijati bez problema. Ovim se novim proizvodnim postupkom olakšava rad i štedi energija kod savijanja krtih metala, što se može usporediti s jednostavnim savijanjem u hladnom stanju, a pruža mogućnost novih načina u konstruiranju i proizvodnji dijelova male težine.

Keywords: *savijanje u toplom stanju, konstrukcija male težine, diodni laser, laseri s čvrstom jezgrom*

1 Introduction

Currently hot-bending of sheet metals is generally avoided. If absolutely necessary, oven-heating is usually used, with the disadvantage of unacceptable heating and cooling times, big energy input, handling problems, and change of material parameters.

Inductive heating is better but it still has the problem of a large heated area and the fact that for thin sheet metals high frequencies are needed for high coupling.

With laser assisted bending the heat input can be concentrated on the forming zone. This was first demonstrated by Schuöcker et al. [1] with a scanned CO_2-Laser for 1 m bending line. Here still problems with efficiency, beam guidance, and absorption were encountered and, even more important, the heating happened outside the bending tool causing again handling problems.

Better suited for this task are diode lasers, with much higher efficiency and absorption. First Geiger et al. [2] demonstrated such a setup with a scanned diode laser.

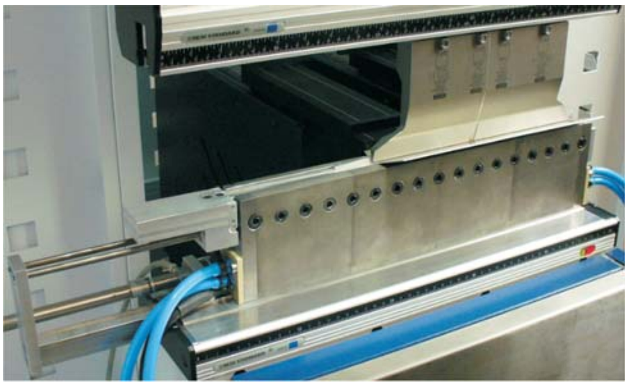

Figure 1 400 mm diode laser assisted bending tool

Figure 2 Diode laser inset with 100 mm length

Recently we published two new methods of laser-assisted bending, both with heating from the lower tool during the bending operation, the first one with diode lasers integrated into the lower tool of a bending press ([3], Fig. 1-2) and the second one with a fiber coupled solid state laser supplying a beam splitter and optical power distributor built into the lower tool (Fig. 3, [4]). Both solutions allow "just-in-time" and "just in place"-delivery of the heat by the following "heating scheme":

First a small cold bending is performed in order to fix the work-piece. Then the press stops and the laser heating starts. At a predefined temperature (measured by a sensor in the upper tool) or time the bending process proceeds while the lasers remain on. Usually the temperature rises further during the bending process. In some cases, e.g. when the bending has to be done very slowly, a control loop keeps

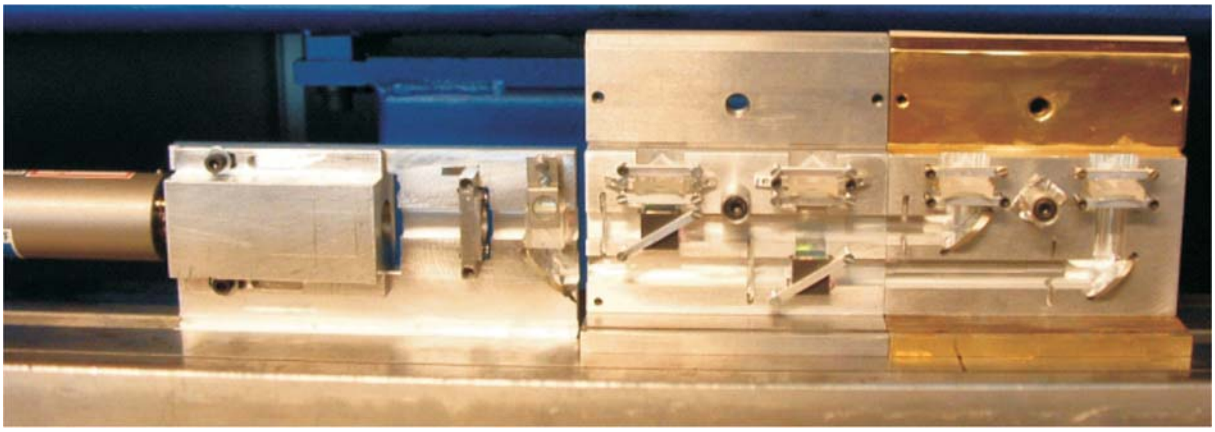

Figure 3 200 mm laser assisted bending with an external laser source (opened lower tool)

the temperature on a predefined level to avoid damage of the work piece.

Note that Laser-assisted bending must not be confused with pure Laser-bending [5], where only with the localized heat concentration, only possible with a laser, and resulting thermal strains a lasting bending deformation is induced.

We present now, after a more detailed description of the two solutions for laser-assisted bending, some considerations and results of this new method applied to Mg-, Al-, Ti-, and Steel-alloys. Especially we consider the energy demand per meter bending line and we discuss, where laser assisted bending will allow putting light-weight-construction into practice.

2 The diode laser solution

Diode laser bars [6] with an optical power of 200 W and a wavelength of 940 nm are used (Fig. 4, [3]). The maximum current for one diode laser bar is 220 A and the voltage drop ~2 V. The diode laser bars are soldered on micro channel coolers, eight of which fit into a lower tool for 100 mm

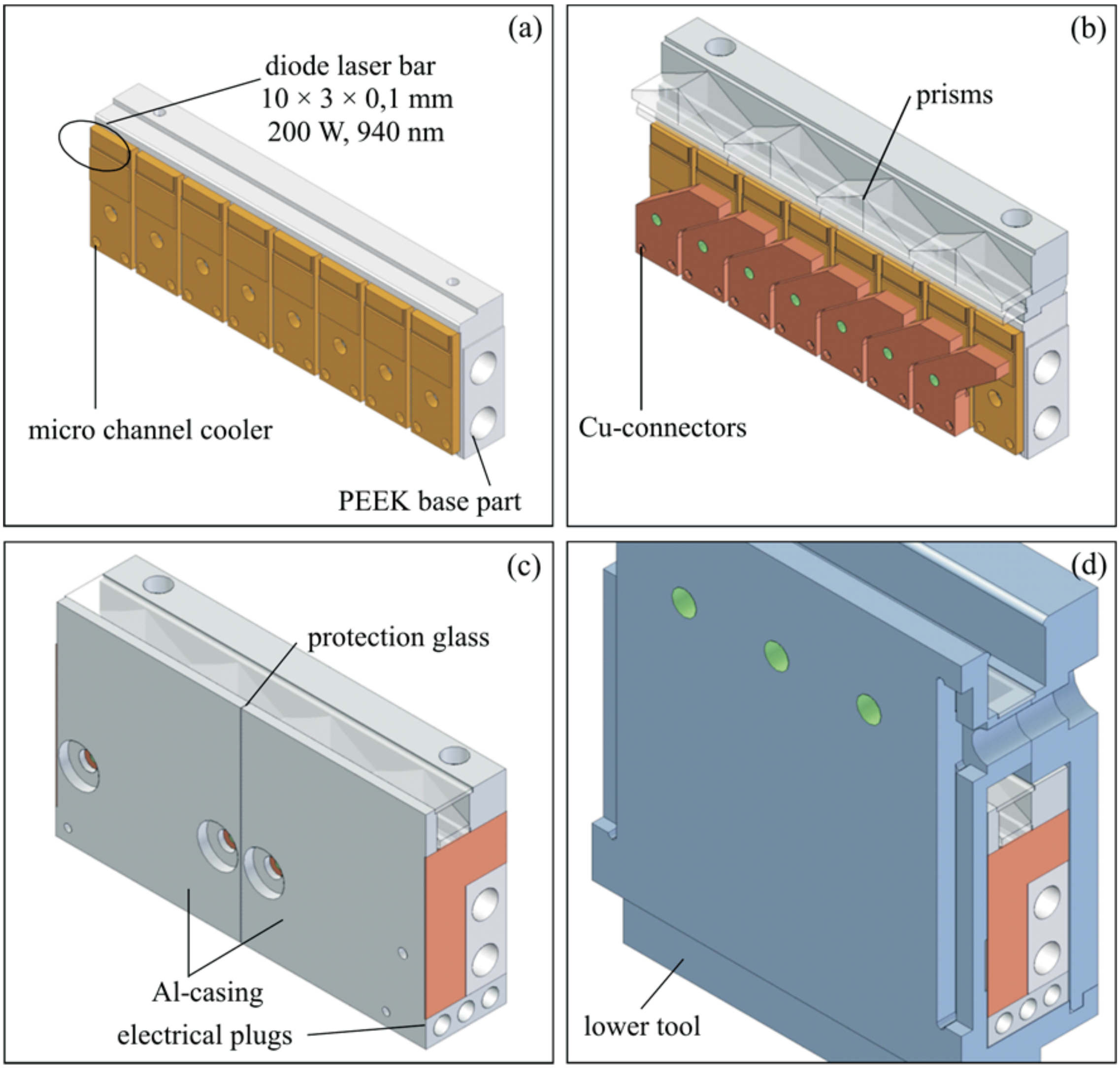

Figure 4 Building up of the diode laser for 100 mm bending length [3]

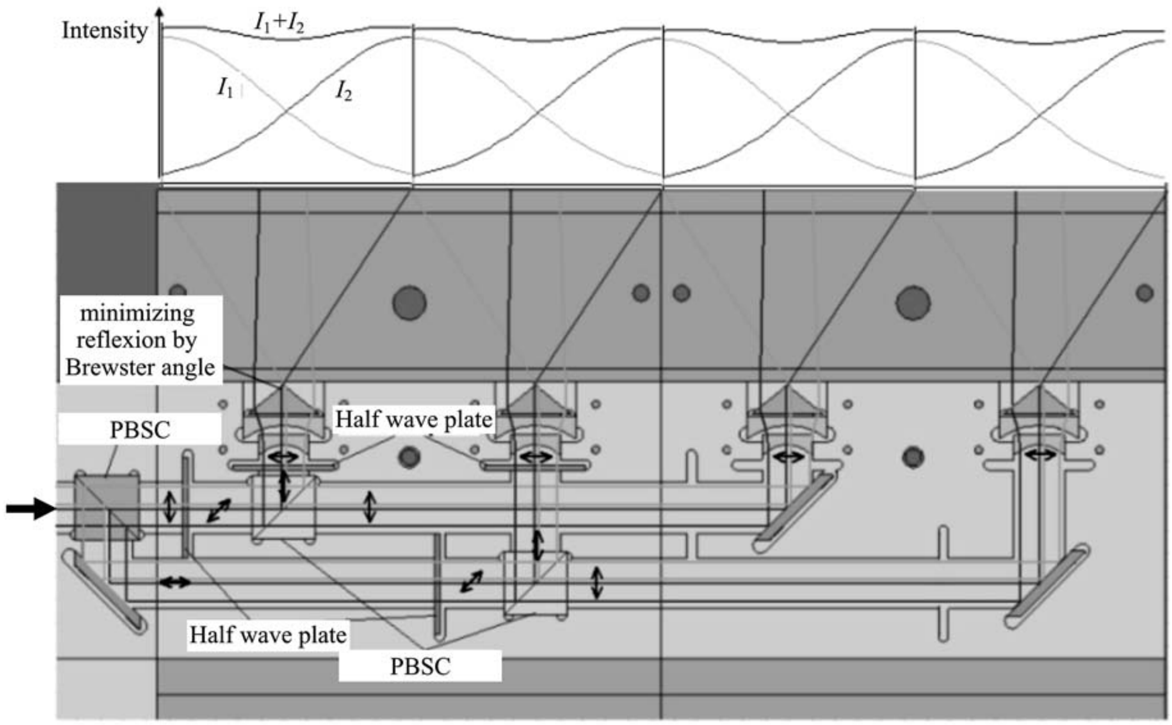

Figure 5 Principle of the beam splitter (Here for 200 mm bending length). The arrows indicate the polarization in direction of beam propagation. [4]

bending length, which yields an optical power of 16 kW/m. The diode laser rests on the bottom of the lower tool, which consists of two parts. The screws, that fix them, are located above the diode lasers. To avoid shadowing of the work piece by these screws, 4 prisms, shown in Fig. 4b cross the 2 neighbored beams so that between the crossing points the screws can be located.

Fig. 4a shows the mounting of 8 micro channel coolers on the base part (made of the plastic PEEK), which contains the channels for cooling water supply. Cu-connectors fix the lasers and provide a serial connection as shown in Fig. 4b together with the Fast-Axis-Collimation-lenses (cylinder lenses to collimate the beam, which leaves the laser diode bar with strong divergence) and the prisms. To enable a compact design the casing is made of two parts, each of which has a contact to the first and the last diode laser bar respectively, and contains the connectors to the neighbor-lasers or to the power supply (Fig. 4c). Casing parts of neighbored diode lasers are electrically connected via three plugs (Fig. 4c and Fig. 2). To protect the optics from dirt falling down from the work piece a protection glass is inserted. (This is kept clean during the bending process with pressured air.) Thin side covers finish the diode laser that can now be inserted into the lower tool (Fig. 4d, view from the machine side), which consists of two parts and contains a cavity for the diode laser, which can be inserted from the side or from the front.

Fig. 2 shows a finished laser for 100 mm bending length from the front side, showing the electrical connectors. Similar devices were built for 50 mm bending length and such for 25 mm are planned so that some flexibility is possible. Many bending applications, e.g. for casings, demand an accurate setup of certain bending lengths.

The in- and outlets for the cooling water must be sealed with O-rings. This requires that the lasers are pressed together by plates that are mounted on the ends of the array of lower tools.

Fig. 1 shows a complete bending tool for 400 mm bending length with a laser power of 6,4 kW. For work pieces shorter than 400 mm the lasers below non-covered tools would emit into free space. To prohibit that, a glider, made of aluminum, is installed on the left hand side of the setup. During every bending operation this glider is shifted via pneumatics until it touches the work piece. Then the laser operation starts.

3 The solid state laser solution

To achieve a homogeneous intensity distribution on bending lengths up to several meters an adjustable design based on polarization optics was chosen. First a polarizing beam splitter cube (PBSC) divides the unpolarized laser beam into one horizontally and one vertically polarized beam propagating on two horizontal parallel paths through the lower tool (Fig. 5, [4]). To ensure that both beams have the same power a depolarizer should be used in front of this first PBSC.

Every 50 mm a combination of a $\lambda/2$-wave plate and a PBSC reflects a part of one of the two beams up to the work piece. By rotating the wave plate around the axis of light propagation the amount of reflection can be adjusted. To ensure the same power for all reflected beams the stage with the number i (counted from the last stage) has to have a reflection $R = 1/i$. Hence the last stage with $i = 1$ is fully reflecting, the second must reflect 50 %, the third 33 % and so on. Here each stage (also referred to with "tool") has a length of 100 mm. The system for 200 mm bending length, as shown in Fig. 5, has two stages, i.e. $i = 2$.

Each reflected beam is distributed with a combination of two lenses and one prism on a length of 50 mm [4].

4 Effect on production and products

The main impact of laser assisted bending can be seen in the possibility of an easy production of bending parts. Consider for example the casing shown in Fig. 7. It

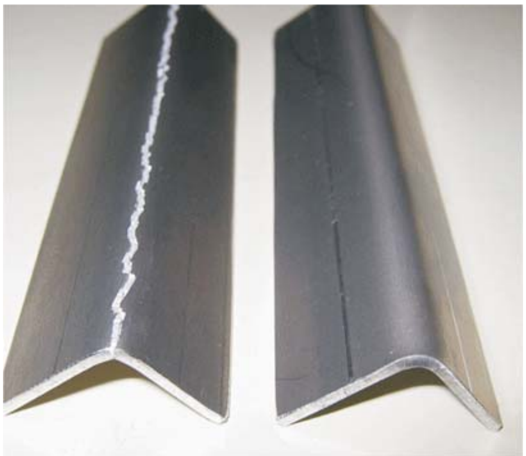

Figure 6 Comparison of cold (crack) and laser assisted bending of the Mg-alloy AZ31

is made with laser-assisted bending (the setup in Fig. 1) out of the Mg-alloy AZ31, which breaks during cold-bending (Fig. 6). 6 bends are involved and since the part cools rather fast due to radiation and heat conduction oven heating would be very cumbersome.

It is further "sustainable" in terms of energy saving during production as discussed in the next chapter. No "over-heating" and no heating of undeformed parts is needed due to the precise heat input. This reduces negative impacts of the heating on the material. We mention now some very different applications of laser assisted bending for four different materials groups, to give an idea about the huge range of possible applications in general:

1 Mg-Alloys are interesting for casings for electronic devices (Fig. 7)
2 High-strength Al-alloys will be needed to reach the weight-specifications for future transport-electro-vehicles e.g. in urban car-free zones.
3 Cranes need high strength steels which very often show cracks during bending.
4 Titanium-alloys are widely used in aerospace-industry, e.g. as connectors to connect in the fuselage the outer skin with the inner construction. These connectors are bending parts.

Figure 7 Bending part made of AZ31 with 6 bends with ~250 mm length

5 Temperature and energy considerations

Fig. 8 shows the scheme used for the analytic calculation of the 2-dimensional temperature course in the

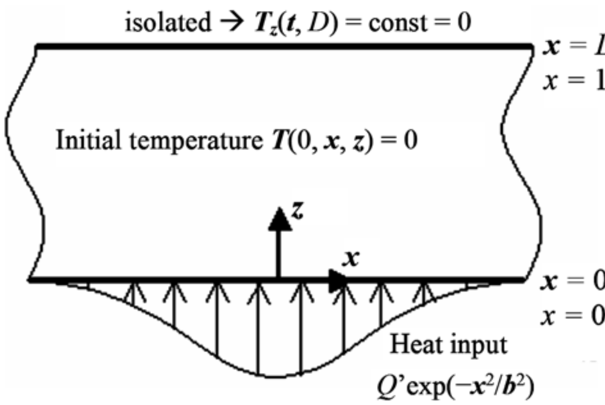

Figure 8 2-dimensional heat-conduction with Gaussian heat input on lower surface and isolated upper surface

work-piece with thickness D. The upper surface is assumed to be isolated and on the lower surface a Gaussian heat input with full width 2$\boldsymbol{b}$. We define here the normalized width $b = \boldsymbol{b}/D$.

Note that instead of the real coordinates $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$ normalized coordinates x, y, z are used, i.e. $(x, y, z) = (\boldsymbol{x}/D, \boldsymbol{y}/D, \boldsymbol{z}/D)$. With the absorbed power per length P_{abs} (W/m) the normalized heat input Q', a reference temperature T_{ref}, and a reference time t_{ref} are defined:

$$Q' = \frac{P_{\text{abs}}}{\sqrt{\pi}\,\boldsymbol{b}}, \quad T_{\text{ref}} = \frac{1}{\sqrt{\pi}} \frac{D}{\boldsymbol{b}} \frac{P_{\text{abs}}}{\lambda_{\text{W}}}, \quad t_{\text{ref}} = \frac{D^2}{\alpha}. \tag{1}$$

This allows the definition of a normalized temperature $T = \boldsymbol{T}/T_{\text{ref}}$ ($\boldsymbol{T}$ real temperature increase in K). The solution of the corresponding partial differential equation with boundary and initial conditions as given in Fig. 8 is given by the formula (which can be derived by a Laplace-transformation of the problem)

$$T(t,x,z) = \frac{b}{\sqrt{\pi}} \int_0^{\infty} \exp\left(-\frac{b^2\kappa^2}{4}\right) T_{\kappa}(t,x,z)\,\mathrm{d}\kappa, \tag{2}$$

with

$$\frac{T_{\kappa}(t,x,z)}{\cos(\kappa x)} = \\ = \frac{\cosh(\kappa z)\coth(\kappa) - \sinh(\kappa)}{\kappa} - \frac{\exp(-t\kappa^2)}{\kappa^2} - \\ - \sum_{k=1}^{\infty} \frac{2\exp\left(-t(\kappa^2 + k^2\pi^2)\right)\cos(k\pi z)}{\kappa^2 + k^2\pi^2}. \tag{3}$$

Fig. 9 shows plots of Eqs. (2) and (3) at $x = 0$ for two materials (AZ31…Mg-Alloy and Titan Grade II) with thickness $D = 2$ mm at the upper and lower side of the work-piece, i.e. at $z = 0$ and $z = 1$ ($\boldsymbol{z} = D$) for a heating power of P = 13 W/mm, which corresponds to the diode laser solution with a current of 190 A. The absorbed power is $P_{\text{abs}} = \eta_{\text{abs}} P$, where in case of AZ31 the absorption factor η_{abs} = 37 % and in case of Titanium η_{abs} = 44 %.

Note that the significantly higher temperature for Titanium is not only due to the higher absorption but even more to its low heat conductivity; such that less power is lost due to heat conduction.

The heating time t_{h} to reach the desired forming temperature T_{f} can now be approximated by

Table 1 Energy comparison between oven and laser heating of a 100 mm wide stripe for different materials

	Forming-temp.	thermal diffusivity	thermal conduct.	abs-orption	heating time	absorbed energy	diode las plug energy	casing plug diod energy	casing oven energy	energy relation
	°C	mm²/s	W/(m·K)	%	s	kJ/m	kJ/m	kJ	kJ	%
Duralumin graphite coated	300	94	237	80	4,4	46,1	115,3	173	624	28
Mg (AZ31)	300	45	84	37	7,8	37,7	101,8	153	462	33
Titan Grade II	600	6,7	16	44	5,5	31,2	142,1	213	1182	18
Steel	600	13	48	50	19,4	126,1	504,5	757	1828	41

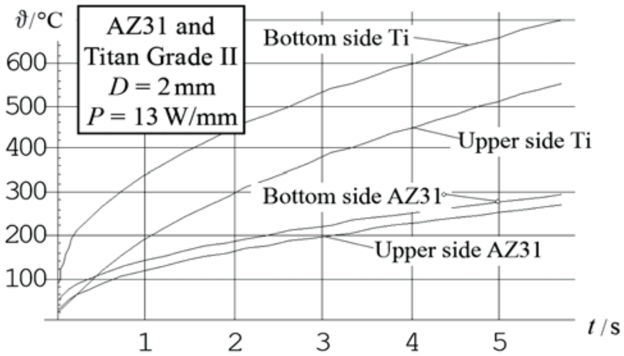

Figure 9 Simulation of heating curves at the bottom and upper side for Mg- and Ti- sheet metals

$$t_{\mathrm{h}} = t_{\mathrm{ref}} \frac{\left(\frac{T_{\mathrm{f}}}{T_{\mathrm{ref}}}\right)^2 + \left(\frac{T_{\mathrm{f}}}{T_{\mathrm{ref}}}\right)\sqrt{\left(\frac{T_{\mathrm{f}}}{T_{\mathrm{ref}}}\right)^2 + 2b^4}}{2b^2}, \tag{4}$$

which can be deviated from the formulas (2-3). Here $b = \boldsymbol{b}/D$ should fulfil $0{,}5 < b < 1$.

The absorbed energy E_{abs} per m is calculated with $E_{\mathrm{abs}} = t_{\mathrm{h}}\,P_{\mathrm{abs}}$, while $E_{\mathrm{laser}} = t_{\mathrm{h}}\,P$ holds for the invested laser energy per m. The plug energy depends on the efficiency η_{laser} of the laser source, which is ~50 % for the diode laser solution and ~25 % for the solid state laser solution, if a modern fibre- or disk-laser is used. Tab. 1 calculates the plug energy per m for the diode laser solution with $E_{\mathrm{plug}} = E_{\mathrm{laser}}/\eta_{\mathrm{laser}} \sim 2E_{\mathrm{laser}}$.

We try now to compare the energy input for laser assisted bending of the casing in Fig. 7 with the energy input for the same casing but heated with an oven. The part needs 6 bends of 250 mm length each, yielding 1,5 m bending line for one part. The energy needed for laser-assisted production of one part is therefore $1{,}5E_{\mathrm{plug}}$. In case of oven heating we assume a series production where e.g. 100 parts are heated to make one bending. Then the parts must be heated again for the next bending. We assume that in the mean time the part cools out completely. Therefore each part must be heated 6 times. Further for the calculation of the oven energy it is assumed that approximately 10 % more temperature is needed to overcome the energy loss during the handling time between oven and bending press. We calculate therefore for one part $E_{\mathrm{oven}} = 6\rho\, c_p\, D\, A\, T_{\mathrm{oven}}$ ($T_{\mathrm{oven}} = 1{,}1T_{\mathrm{form}}$, A ~0,0625 m² … area of the part, D … thickness, $\rho\, c_p = \lambda_{\mathrm{W}}/\alpha$ ... density $\rho \times$ specific heat capacity c_p).

Tab. 1 shows based on the above formulas for 4 different materials (Duraluminium, Mg-alloy AZ31, Titan Grade II, steel e.g. MSW-1200) the calculated energy inputs. We assume a diode laser line power P = 13 W/mm, a sheet thickness D = 2 mm, and laser line width $2\boldsymbol{b}$ = 2 mm.

The last three columns of Tab. 1 (energy per part with diode laser assisted bending, energy per part with oven heating, relation between both in %) show that laser assisted bending is clearly an energy effective method when compared to classical oven-heating. The biggest gain is found in case of Titan, due to its high absorption and low heat conductivity. Note that the absorption values strongly depend on the condition of the surface and the used values here are estimations based on measurements.

6 Conclusion

The use of laser assisted bending for production with brittle ultra-light and/or high strength materials was discussed, first regarding different engineering fields, second regarding energy, where significant saving is possible when compared to classical oven heating.

Experiments show that laser assisted bending of Al-parts needs the use of an absorption layer like graphite. In case of high strength steels an accurate temperature control is necessary and some steel-alloys lose strength due to this process. Mg- and Ti-alloys can be bent with this new method usually without complications. Further this new production method is an energy saving method for the bending of brittle metals and the ease of operation, which can be compared with simple cold-bending, and it allows going new ways in construction and production of light weight parts.

We see applications for building machines, container systems, shelf logistic, chair-lifts, fire-fighter systems, waste management systems and so on. The ease of production and the saving of weight in the final product will allow further steps towards sustainable engineering.

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Symbols

D – metal sheet thickness, mm
b – half width of laser line, mm
x, y, z – real coordinates, mm
$\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$ – normalized coordinates, –
P_{abs} – absorbed power, W/m
Q' – normalized heat input, –
$\boldsymbol{T}$ – thermodynamic temperature, K
T_{ref} – reference temperature, K
T – normalized temperature, –
t_{ref} – reference time, s
λ_W – thermal conductivity, W/(m·K)
ρ – density, kg/m^3
α – thermal diffusivity, m^2/s
c_p – specific heat capacity at constant pressure, J/kg
η_{abs} – absorption factor, –
κ – integration variable in the Laplace space, –
k – counting variable in the sum of Eq. 3, –

Authors' addresses:

Bammer Ferdinand
Vienna University of Technology
Institute for Production Engineering and Laser Technology
Gußhaus-Street 30, A-1040, Vienna, Austria
+43 1 58801 311616, f.bammer@tuwien.ac.at

Schumi Thomas
Vienna University of Technology
Institute for Production Engineering and Laser Technology
Gußhaus-Street 30, A-1040, Vienna, Austria

Otto Andreas
Vienna University of Technology
Institute for Production Engineering and Laser Technology
Gußhaus-Street 30, A-1040, Vienna, Austria

Schuöcker Dieter
Oberösterreichisches Laserzentrum
Gaswerkgasse 4, A-4810, Gmunden, Austria
+43 (0) 7612/65679, dschuoecker@ooelz.at