LASER ASSISTED FORMING – A VALUABLE EXTENSION OF THE LIMITS OF METAL SHAPING

D. Schuöcker
Department of Non-Conventional Processing, Forming and Laser Technology, University of Technology Vienna, Austria

Abstract
During the plastic deformation of brittle materials as magnesium, titanium or high strength steels, for instance in bending of sheet metals, the local strain can exceed the ductility – the strain at rupture – and thus cracks appear that eventually lead to rupture. Hot working would be beneficial since a temperature of a few hundred centigrades leads to an increase of the ductility by more than 100%. Since during bending mentioned before the deformations take place in a narrow zone around the bending edge, selective heating for instance with a laser would be sufficient to avoid cracks. The latter concept of laser assisted bending has been successfully demonstrated and gave rise to the development of similar processes at the University of Technology in Vienna, as “Laser assisted deep drawing” and “Laser assisted wire drawing”. Other processes of laser assisted forming have been treated successfully in Aachen, Darmstadt and Erlangen.
The bulk of the actual paper work is devoted to bending, deep drawing and wire drawing with laser assistance, that have been studied theoretically and experimentally by the authors department.

Keywords: bending, drawing, brittle, ductility

1 Introduction

Production processes with lasers, either with material removal as in the case of cutting and drilling or with material addition as in joining or cladding have reached a high degree of industrial maturity and are used throughout the industry. Nevertheless manufacturing processes without a change of mass, especially forming has not experienced an important impact of laser technology up to now with some exceptions [1],[2],[3].The reason is that strong and permanent, that means plastic deformations, can only be obtained with strong forces that cannot be generated with laser radiation. Nevertheless thermal stress that has been used successfully to obtain weak plastic deformations as they are needed for the calibration of bending angles [4]. Although mechanical forces cannot be substituted by laser radiation, the stress necessary for the onset of plastic deformation, the yield strength, can be reduced by heating, for instance with a laser to a considerable amount e.g. 40% with a temperature of a few hundred centigrades for steels. Moreover heating leads to a strongly increased ductility -

the strain at rupture - where 200% can be achieved with a few hundred centigrades also in the case of steel. Thus „hot working“ allows to work with reduced forces and with a strongly reduced risk of cracks that appear if the ductility is too low compared to the strain imposed by the forming process. Heating of the whole work piece e.g. in an oven is not necessary in the case of several forming processes with sheet metals, tubes or wires since the deformation takes place only in restricted regions of the volume of the work piece and thus selective heating with high power laser beams saves energy and time compared to heating of the whole work piece. Unfortunately the latter processes of "Laser assisted forming" can not be used for bulky materials, since laser radiation is mainly absorbed close to the surface of metallic work pieces. Therefore heating of the bulk can only be carried out by heat conduction and is thus not very efficient.

Clearly laser assisted forming with its selective heating of the work piece volume can only be advantageously applied to forming processes where deformations appear only in restricted regions. A good example is bending where elongation and compression take place only close to the bending edge (see **Fig. 1**):

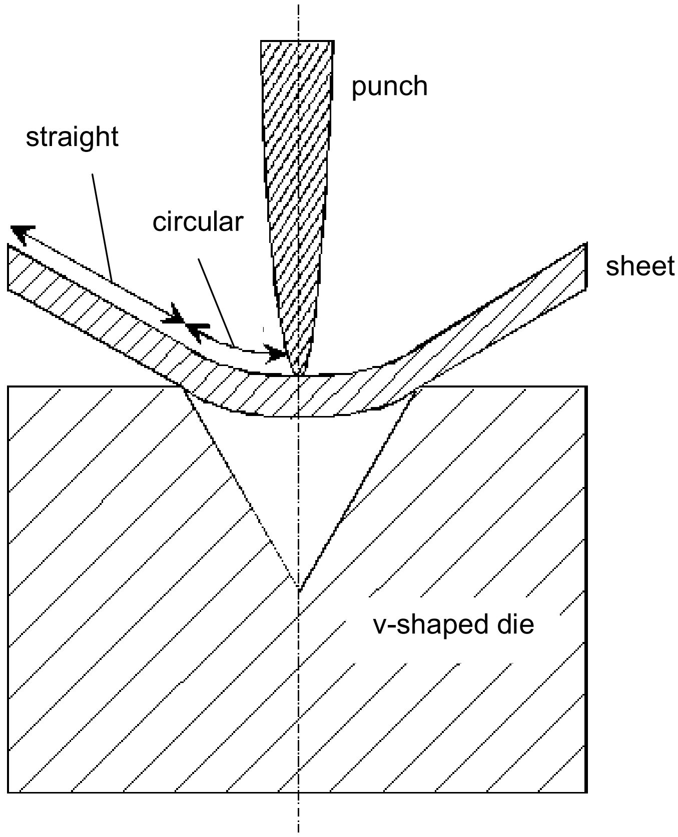

Fig. 1: *Die bending*

Related to bending is inline profiling (see **Fig. 2**) where also more or less sharp bends with a narrow deformation region must be carried out:

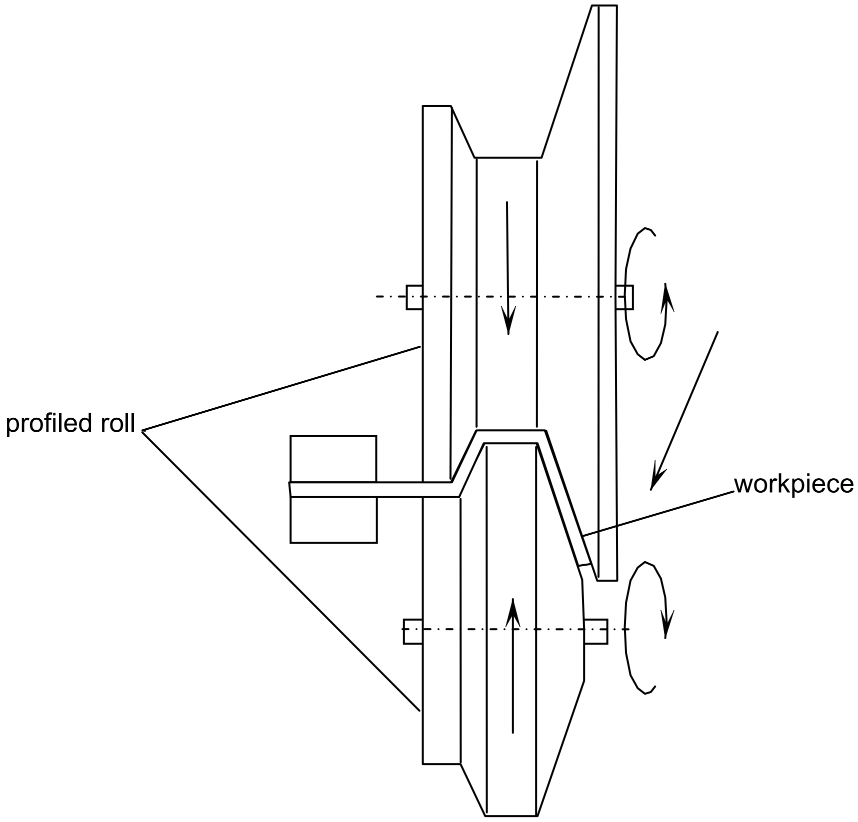

Fig. 2: *Inline profiling*

A further example is wire drawing (see **Fig. 3**) where a thicker wire is drawn trough a nozzle-like tool, that reduces the diameter, where again the deformation takes place in a restricted region of the work piece:

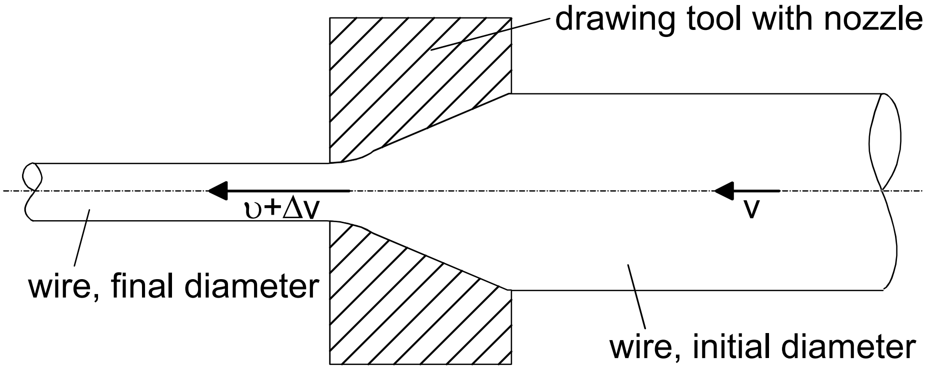

Fig. 3: *Wire drawing*

A limiting case is deep drawing (see **Fig. 4**), where main deformations take place in the flange, the remaining flat part of the work piece during the drawing process and thus a selective heating of the flange facilitates the forming process:.

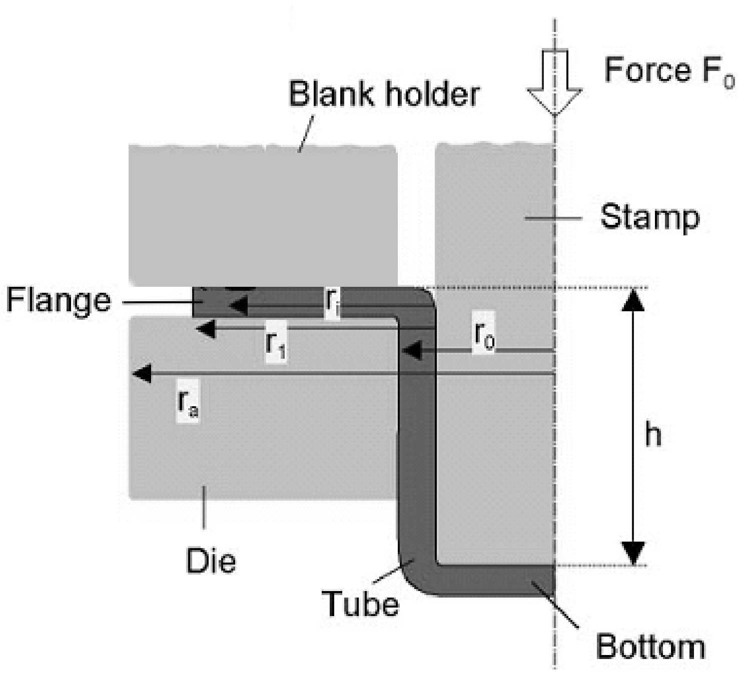

Fig. 4: *Deep drawing*

Quite similar hydro-forming is also a candidate for selective heating with lasers. With the exception of the last process for all other forming options the feasibility has already been proved by the groups mentioned above and the University of Technology in Vienna [5],[6],[7].

In the following bulk of the presentation three examples, namely laser assisted bending, laser assisted deep drawing and wire drawing without tools will be reviewed.

2 Laser assisted bending

The following chapter will contain a theoretical estimation about the process that demonstrates its advantages. Second an experimental study is presented that proves the feasibility and confirms the theoretical results. The chapter concludes with remarks about the practical implementation of the process.

It is the aim of the theoretical description of laser assisted bending to determine the effect of laser heating on the bending force and on the minimum bending radius, the latter limited by the appearance of cracks at the outer fiber, finally leading to rupture. First an energy balance relates heat gain by the irradiation of a narrow region around the bending edge by a laser beam, either with line focus or scanning along the bending line to energy consumption by heating the volume hit by the beam and heat conduction .This balance yields the temperature obtained along the bending edge, the latter strongly influencing the yield strength and ductility. Second the yield condition together with the equilibrium of forces allows to determine the strain in the outermost fiber, responsible for rupture and also the bending force [8].

The latter model has been evaluated numerically for magnesium that is hard to bend at room temperature, since even small bending angles lead to cracks and rupture. The results are shown in **Fig. 5**. where it points out that - most important - with rising laser power at constant irradiation time larger bending angels can be achieved. A little bit less important is that of course the forces necessary for bending are reduced with rising laser power.

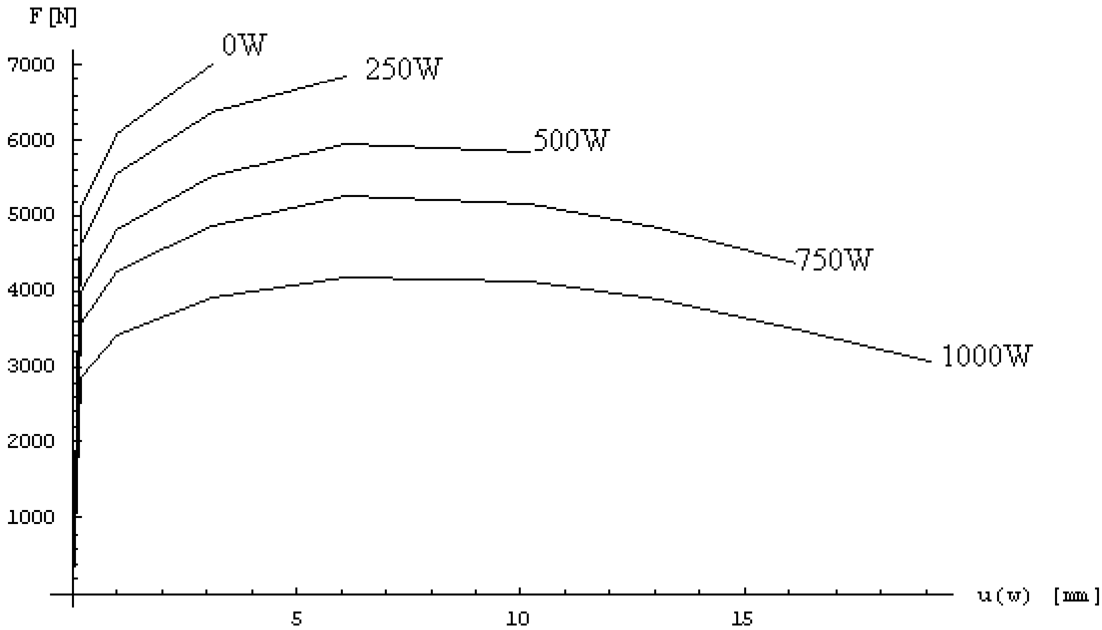

***Fig. 5:** Bending force F versus traveling way of the upper tool u for Magnesium (2 mm) for different laser powers at fixed irradiation time (end of curve indicates rupture)[8]*

From these results it can be expected that laser assisted bending is beneficial in the case of brittle materials as magnesium, but also titanium, high strength steels etc.

In order to demonstrate the feasibility of laser assisted bending an experimental set up has been constructed, that allows to heat the vicinity of the bending edge with a length of 1000 mm to a temperature of a few hundred centigrades, a temperature that should facilitate bending by a reduction of the yield strength and enhancement of the ductility without reaching the transformation point that would cause unwanted structural changes.

The experimental set up utilized a 10kW carbon dioxide laser. A ZnSe lens with a very large focal length yielded a beam with a Raleigh length of 3000 mm and a beam waist of 8 mm. The latter beam was then reflected by a mirror that moves up and down, thus moving the beam over the region to be heated along the bending line. Since the speed of the beam with respect to the work piece became zero at the begin and at the end of the bending line and showed a maximum in the middle of the latter, the laser power was controlled by a signal derived from a sensor for the position of the reflecting mirror and thus quite uniform heating has been obtained. After heating the work piece by scanning the laser beam forth and back over the bending line, what took some ten seconds and was carried out outside the bending tool, the preheated work piece was immediately shifted between the tools and finally the bending process was carried out. With the latter experimental setup for instance titanium, that cannot be bent at room temperature without cracks has been bent by 90 degrees without any problems (See **Fig. 6**) [9].

Fig.6: *Titanium Grade 2 bent without heating(left) and with laser assistance(right) [9]*

Obviously the experimental set up used for the proof of the feasibility of the process is not suited for an industrial application, where heating of the work piece must be carried out at its final position between the tools, just before or even better during the bending process, what means that all parts necessary for the generation of a line focus must be contained in one of the two bending tools. For the latter purpose for instance the bottom tool with V-form must be hollow, where nevertheless the necessary strength must not be reduced. The latter condition means that the heights of the scanning apparatus must be considerably smaller than the height of the bottom tool. Moreover the length of the scanning system must be scalable since the length of the bending tools vary from some centimeters to a few meters.

A really ideal solution was found to be the so called „Paternoster“ shown in **Fig. 7**, where two mirrors are moved by an endless belt and are driven by two rolls, where those mirrors are declined under 45° to the horizontal surface of the belt and deflect the initially horizontal laser beam in vertical direction in such a way that it hits the work piece, that rests on the bottom tool, perpendicularly.

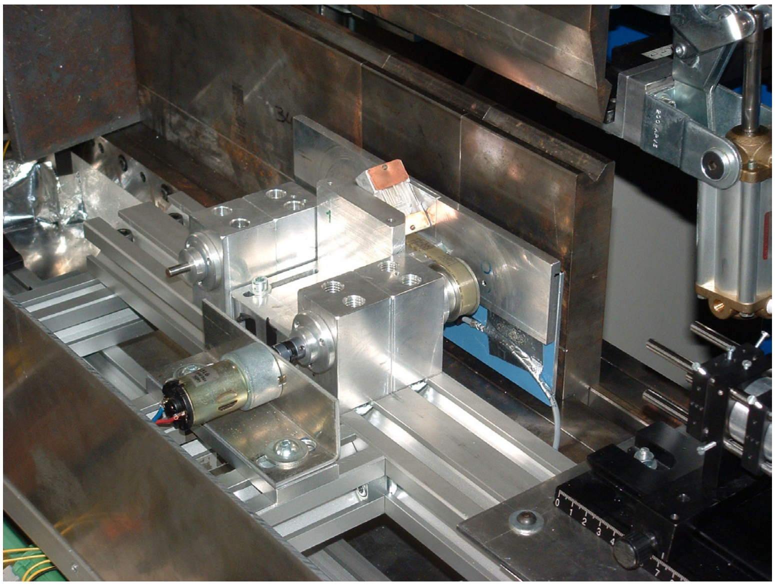

Fig.7: *Paternoster scanner [10]*

The beam is shut down shortly during the times where the mirrors are rotating around the rolls thus avoiding a reflection of the laser beam in unwanted directions. Since a constant angle of incidence and a constant speed of the beam with respect to the work piece are obtained, uniform absorption and heating along the bending line is achieved [10].

3 Laser assisted deep drawing

As in the case of laser assisted bending first of all a theoretical analysis of the process will be presented, followed by an experimental feasibility study. Finally solutions for an industrial application of the process will be discussed.

The theoretical analysis of laser assisted deep drawing has been carried out in two steps: First the temperature distribution in the work piece has been calculated under the assumption, that a narrow circular region on the “flange”, the remaining flat part of the work piece during drawing, is heated by a laser beam. Second a calculation of the necessary drawing forces based on the yield strength dependent on temperature and true strain has been carried out whereas the latter changes strongly during the forming process and along the surface of the work piece.

Fig. 8 shows the results of the latter analysis where it has been assumed that drawing without laser assistance and with three different laser power levels has been carried out. The diagram clearly shows that the maximum drawing force is essentially reduced by using laser assistance and thus it can be expected that the process is feasible.

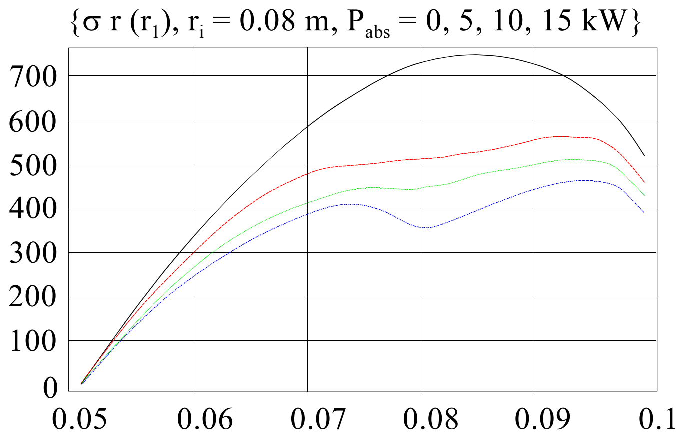

Fig. 8: *Deep drawing of a CrNi steel without heating and with laser heating of the flange at radius r_i with three different laser powers (vertical axis radial stress at the drawing edge in N/mm^2, horizontal axis flange radius during drawing in m)*

Subsequently a feasibility study was carried out with an experimental set up shown by **Fig. 9.**

Fig. 9: *Deep drawing with laser assistance: xy-table and 1,2 kW Diode laser for heating the work piece, work piece fixture and motion unit for the transport into the press, press tools in the background [11]*

As in the first studies on laser assisted bending an initially flat work piece is heated by the laser outside the tools of the deep drawing press and is then moved quickly into the tool, thus allowing the onset of the deep drawing process. The latter set up mainly consists from an

XY-table that allows to move the work piece with respect to the focused beam of a 1.2kW diode laser, a hydraulic movement unit that pushes the work piece between the drawing tools and a 60t press that carries out the deep drawing process. With this experimental set up an important problem could be identified, namely strong heat conduction from the preheated work piece to the tools, that avoids any beneficial action of laser assistance. In order to solve the latter problem the drawing die and the blank holder were covered with glass plates, each with a thickness of 10mm. The latter isolation did not only prevent the heat from being lost to the tools but also served for a certain lubrication of the drawing process. Thus the advantages of laser assistance could be proved as demonstrated by **Fig. 10**. The left picture shows a work piece drawn without laser assistance experiencing rupture at its bottom, what can also be seen from the dependence of the drawing force on time (**Fig. 11**, upper curve) that reached a maximum and jumped then abruptly to zero what indicated break of the work piece.

Fig. 10: *Drawn pot without heating (left) and with laser assistance (right) [11]*

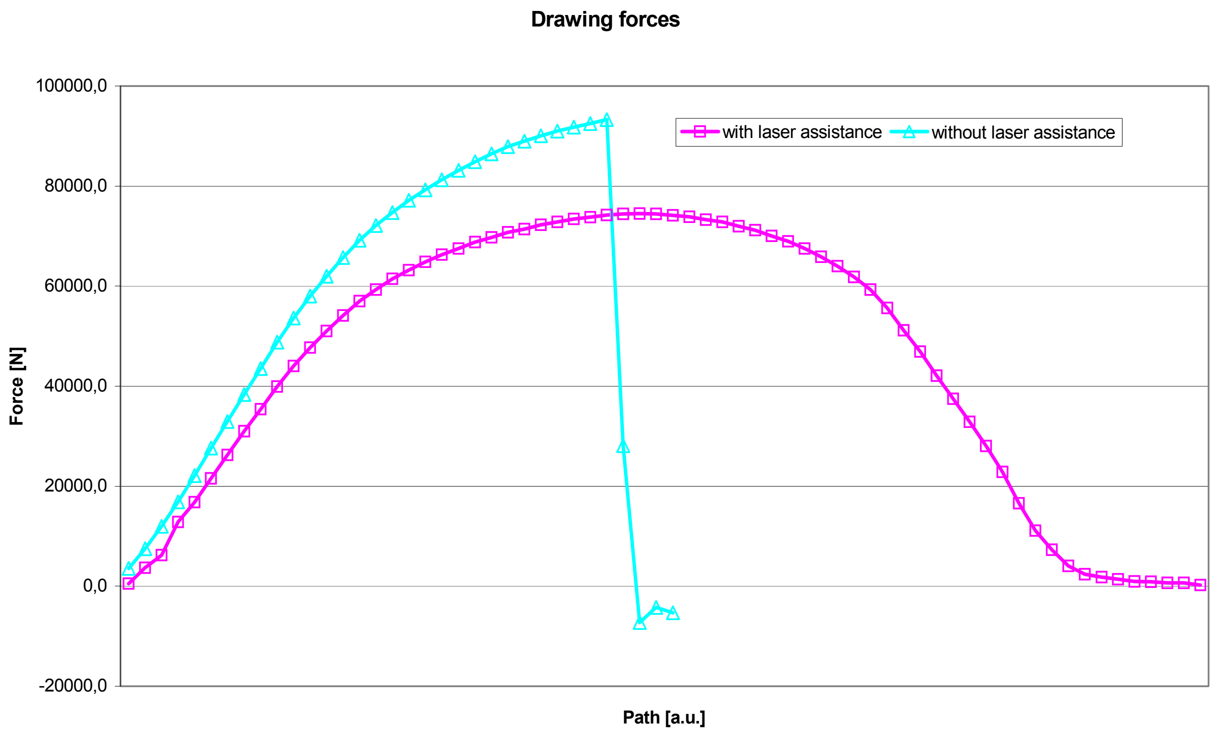

***Fig. 11:** Drawing force for cold working (red) and laser assistance (blue) [11]*

Fig. 10 (right) shows the same work piece drawn with laser assistance without any breaks, what is also illustrated by the force/time diagram (see **Fig. 11** lower curve) that shows that the force rises to a maximum that is clearly smaller than in the case of cold working and decreases then continuously to zero, thus indicating a drawing process without problems [11]. Although these experiments clearly demonstrated the feasibility of laser assisted deep drawing, it must be confessed that the reproducibility of the experiments was poor since the surface conditions of the work piece and of the tools show an important influence on the process. Although the experiments have up to now been carried out with several kinds of steels, the process might be of special benefit for the processing of brittle materials as magnesium of titanium, that can usually not be drawn at least at room temperature.

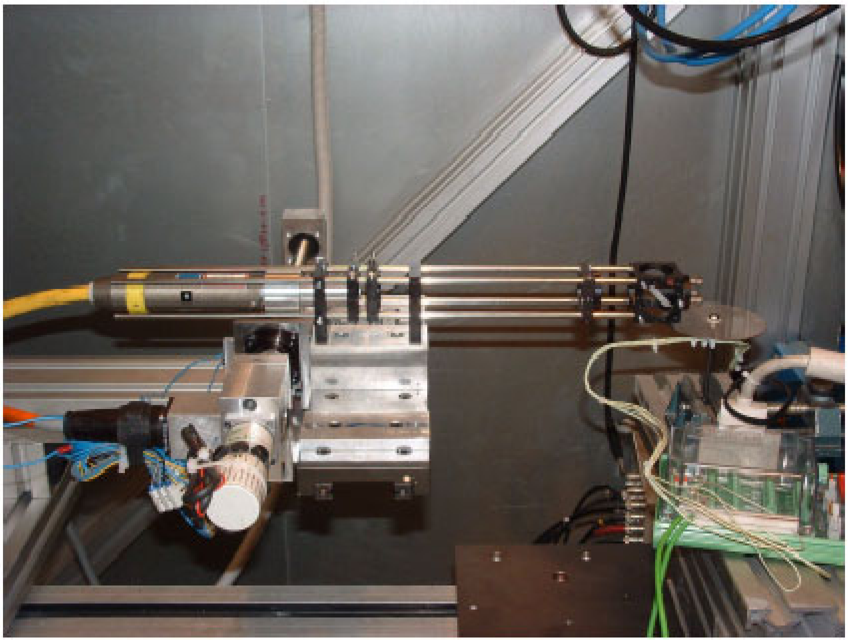

Fig. 12: *Laser finger for the heating of a work piece already situated between the drawing tools [12]*

Various attempts have been made to integrate heating of the work piece by a laser into the deep drawing press in order to reduce the two step sequence into one desired drawing step, including transport of laser radiation via fibers to openings in the tools and others. The only way that seemed to be feasible was the use of the so called “laser finger” shown in **Fig. 12** where a narrow finger is moved from outside the drawing tools by an XY-table and penetrates into the deep drawing press between the tools and the work piece already situated above the lower tool. The latter finger carries the end of a light conducting fiber and on the end of tip of the finger necessary optics that direct light stemming from a 3,6kW Nd:YAG laser onto the work piece. With this arrangement, that has most recently been investigated satisfactorily heating of the work piece and beneficial support of the drawing process have been obtained [12].

Although in the latter arrangement heating and deformations take place still one after the other, a change of the work piece fixture is not necessary and so the latter solution seems to be acceptable for industrial applications. Unfortunately the results show again a poor reproducibility, what must be the matter of further investigation.

4 Wired drawing without a forming tool

Thin wires are usually produced by drawing a thicker wire trough a nozzle-like tool that exercises strong forces on the wire. Friction is then an important problem and can only be handled by using hard materials as tungsten carbide or diamond. Nevertheless strong wear is obtained and therefore the tools must be renewed frequently, what leads to considerable costs and also time consumption. The problem can be solved if the wire is heated in a short zone for instance by a laser and is also subject to an axial force as in ordinary drawing with a tool whereas the temperature dependant yield strength in the hot region is smaller then the stress in the wire and thus in the hot region yielding takes place that leads to an elongation and to a constriction of the wire. A stable situation is reached if the decrease of the yield strength due to heating leads to a balance between stress imposed from outside and the yield strength determined by the temperature and the true strain, an equilibrium that determines the final and reduced diameter of the wire after processing with the laser and with mechanical stress.

First of all a FEM-analysis with the ANSYS code including heating by the laser and subsequent cooling as well as plastic deformation has been carried out and demonstrates the theoretical feasibility of the process. The results of this simulation are shown by **Fig. 13** and show that after passing the hot region a considerable reduction of the diameter of the wire is obtained.

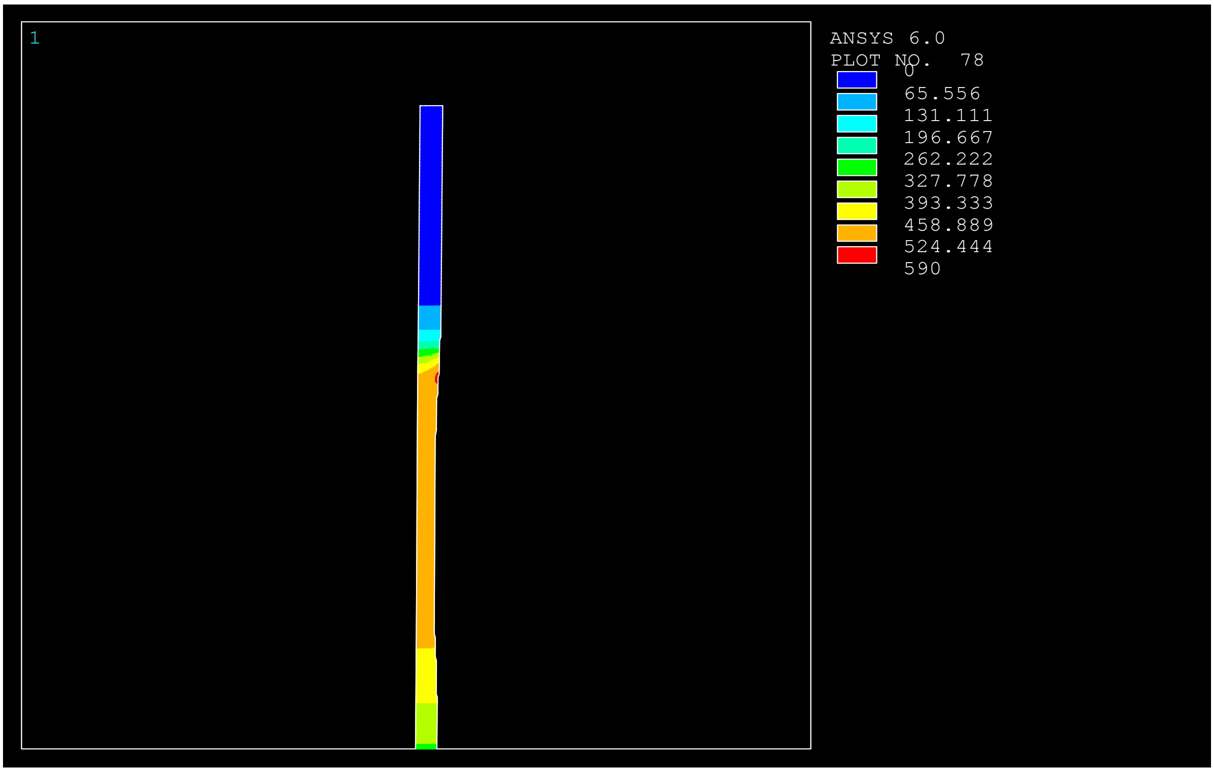

Fig. 13: *Results of the FEM simulation of laser assisted wire drawing – colourss indicate the temperature of the wire heated by a 1,2kW diode laser takes place at the upper end of the heated region (St37 initial Ø 2mm, speed of the upper end of the wire 11mm/sec, of the lower end of the wire 17mm/sec., rotational symmetry, axis of symmetry on the left side) [13]*

In order to study the experimental feasibility an experimental drawing set up has been constructed that is shown by **Fig. 14**.

Fig.14: *Wire drawing apparatus [13]*

The latter set up consists mainly from a feeding coil that carries the virgin wire with larger diameter, a brake that allows to stress the wire from above, a 1,2kW diode laser with a focusing optics that heats the wire in a small part of its length, and a cooling unit that uses a fast gas flow to carry away the heat after an equilibrium with the final diameter of the wire has been reached. Finally a second coil that rotates a little bit faster than the upper coil, collects the processed wire with its larger length and smaller diameter. Both coils are driven by motors and are controlled together with the brakes and the laser power by a professional laboratory control code (Lab-View) that uses the readings of various sensors as for the force exercised to the wire, the coil torque and the temperature as input quantities. With the latter experimental set up a short piece of wire could be processed successfully as illustrated by **Fig. 15** that shows the reduction of the wire diameter [13].

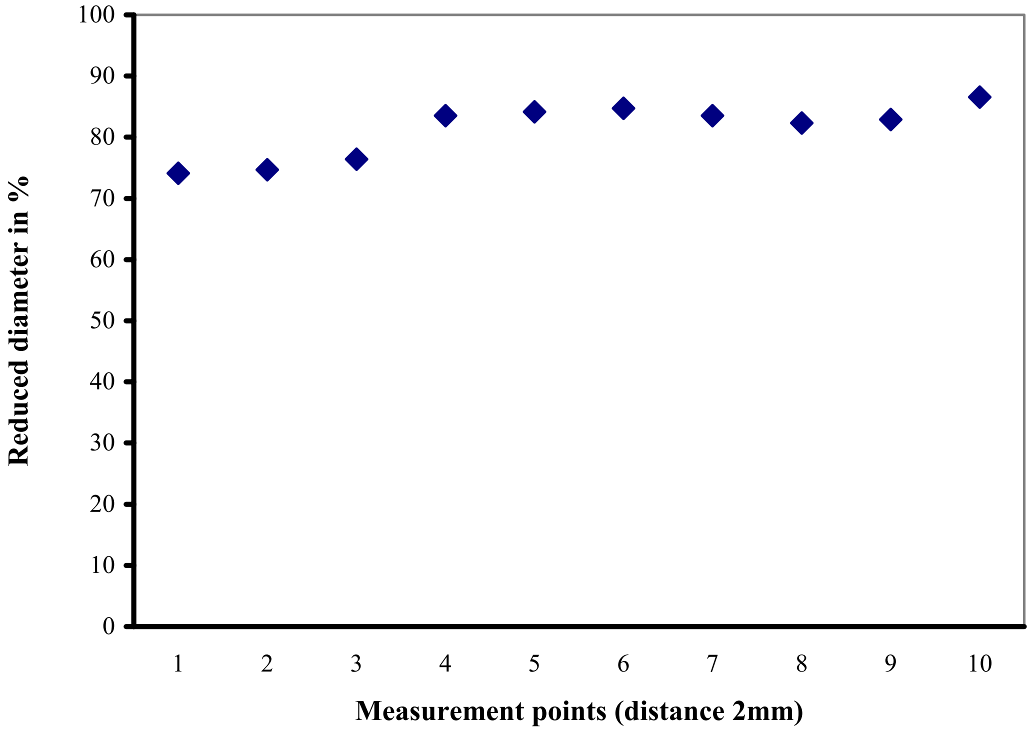

Fig. 15: *Wire diameter after laser assisted drawing dependent on main parameters (initial Ø 2 mm, speed 17mm/sec) [13]*

Several problems remain still unsolved, especially concerning the stability of the process, maximum drawing ratio, strength and the surface quality of the wire after processing what can hopefully be treated in the future.

5 Conclusions

It has been shown that laser assisted forming is an option that allows to extend the limits of forming, especially in the direction of brittle materials that can not be formed successfully at room temperature without break or rupture. Moreover laser assisted forming allows to reduce the forces necessary for forming and to avoid the use of the expensive tools.

For a few examples, namely bending, deep drawing and wire drawing, besides theoretical investigations that demonstrate the advantages of these processes the feasibility has been shown experimentally. Nevertheless to allow an industrial application of these new processes further developments and careful optimizations have to be carried out. Although only three forming processes with laser assistance have been investigated by the authors group up to now, further processes as laser assisted inline profiling or hydroforming will be investigated experimentally and theoretically in the near future, thus allowing to extend the range of application of high power lasers and as already mentioned above also the limits of forming.

Acknowledgements

The author is indept to the Federal Ministry of Transport, Innovation and Technology for financial support of the work on laser assisted deep drawing , the FFF (The Austrian Industrial Research Promotion Fund) for the supporting the work on. laser assisted bending together with TAT (Trumpf Machines Austria), the latter contributing not only by financing, but also technologically and to the FWF (Austrian Science Fund) for financing the wire drawing project.

References

[1] „Laserunterstütztes Metalldrücken schwer umformbarer Werkstoffe “Homepage des Fraunhofer IPT, Aachen 2004

[2] „Mikroumformen mit lokaler Bauteilerwärmung durch Laserstrahlung in transparenten Werkzeugen“ Homepage des Institut für Produktionstechnik und Umformmaschinen“, Darmstadt 2004, (Projektleiter R. Erhardt)

[3] „Laserunterstütztes Walzprofilieren“ Homepage – Lehrstuhl für Produktionstechnologie der Friedrich Alexander Universität Erlangen-Nürnberg, (Projektleiter M. Pitz)

[4] „Mechanismen beim räumlichen Umformen durch laserinduzierte thermische Spannungen“ – Homepage – Lehrstuhl für Produktionstechnologie der Friedrich Alexander Universität Erlangen-Nürnberg, (Projektleiter T. Hennige)

[5] D. Schuöcker, F. Killian, K. Schröder, Österr. Patent „Verfahren zum Biegen mit Laserunterstützung“
D. Schuöcker, C. Zeiner, F. Kilian „Laser Assisted Bending“, 3rd LANE 2001, Erlangen

[6] D. Schuöcker, G. Liedl, A. Kratky, ”Laser assisted shaping of metallic sheets and wires – a promising new application of high power lasers”, SPIE Conference on High power Laser Ablation IV-HPLA, Taos, New Mexico/USA, April 2002 (invited)

[7] D. Schuöcker, A. Kratky, F. Bammer, G. Liedl, B. Holzinger, ”Laser Assisted Forming”, LTLA 2003, St. Petersburg, 2003 (invited)

[8] Ferdinand Bammer, private communication

[9] Ch. Zeinar, Thesis” Laserunterstütztes Gesenkbiegen“, University of Technology, Vienna 2001

[10] Bernhard Holzinger, Thesis ”Laser assisted die bending“, University of Technology Vienna 2004, to be printed

[11] Alexander Kratky, Thesis ”Laserunterstütztes Tiefziehen – Konstruktion, Aufbau und Inbetriebnahme einer Anlage für das laserunterstützte Tiefziehen”, University of Technology, Vienna 2002
Patent „Laser unterstütztes Tiefziehen mit Halbleiterlaser und Festkörperlaser, GZ 07A 538/2001

[12] A. Kratky, G. Liedl, D. Schuöcker, ”Laserunterstütztes Tiefziehen” Report to Federal Ministry of Transport, Innovation and Technology, Vienna 2004.

[13] Martin Kaltenbrunner, Thesis ”Laserunterstütztes Drahtziehen“, University of Technology, Vienna 2004