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Forming of thin-walled elements using laser heating and mechanical load

Laserowo-mechaniczne formowanie elementów cienkościennych

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The paper presents assumptions and preliminary results of experimental investigations and numerical simulations of forming thin-walled elements using laser beam and mechanical load. An experimental stand, dedicated for bending thin-walled tubes and conical diffusers, which are used in aircraft engines, has been designed and built. The method and stand, which were tested in laboratory conditions, together with numerical analysis results show new possibilities of forming thin-walled elements.

KEYWORDS: laser forming, laser treatment, thin-walled elements, nickel alloys, finite element method

Research works on the use of a laser beam for controlled induction of permanent shape changes only due to thermal expansion - without the use of external forces - have been conducted since the 1980s. [1-3]. This technology can be termed incremental [4] or ascending [5] because total plastic deformation is usually obtained by adding up small strains caused by the local influence of the laser beam on the material being processed. In the case of laser forming, there is no mechanical contact between the shaping tool and the workpiece. This technique also gives the possibility of remote forming of elements.

The discussed method, developed as part of the NCBR research grant No. PBS3/A5/47/2015, consists in hybrid thermal-mechanical profiling by simultaneous operation of a laser source of heat and external forces. The aim of this project is to add the effect of external forces to the laser beam on the material, and in particular to develop a method of shaping thin-walled elements, including for the aviation industry (fig. 1), produced from high-temperature alloys, such as: Inconel 625 and Inconel 718 nickel superalloys and AISI 410 and AISI 325 high-alloy martensitic steels. Successful trials of hybrid forming of flat bars made of these materials using gravitational load are presented at work [6].

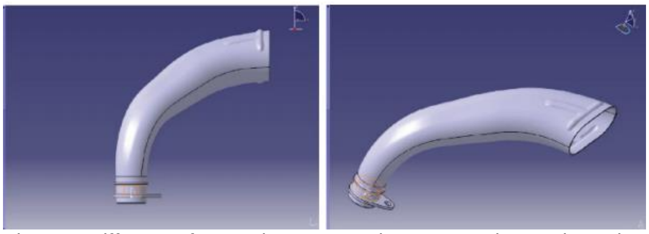

Fig. 1. Diffuser of a turboprop engine, currently made using traditional methods: stamping of two halves and their welding

In order to accomplish this task, a scientific consortium was established consisting of scientific centers, selected according to their experience and competence in relevant research areas. The consortium members were: Kielce University of Technology (project leader), Institute of Fundamental Technological Research PAS, Metal Forming Institute and Rzeszów University of Technology.

Assumptions

Bending of the straight section of the tube for the given bending angle *α* and the bending radius R were considered. In the case of mechanical bending, external forces usually induce a high value stress and plastic deformation over a large area of the shaped element. However, in the case of laser bending, the deformation is located near the trajectory of the laser beam on the formed element. The hybrid approach (i.e. forming with the participation of external forces and laser heating) gives the possibility of incremental induction of plastic deformation locally, in selected and well-defined zones of shaped elements.

The concept of the laser-mechanical forming process is based on the assumption that only the part of the element subjected to the laser beam is subjected to bending. The laser beam heats the selected area of the element to the set temperature, which improves the plastic properties in this area. Due to the application of the external force *F*, the area at the right temperature becomes plasticized and deformed.

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The remaining part of the formed element, which has a lower temperature, does not undergo any deformation, and only a thin strip of the element undergoes the plastic deformation at the current process phase. The width of this bar depends on the diameter, power and speed of movement of the laser beam falling on the surface of the element. The scheme of shaping concept according to these assumptions is presented in fig. 2.

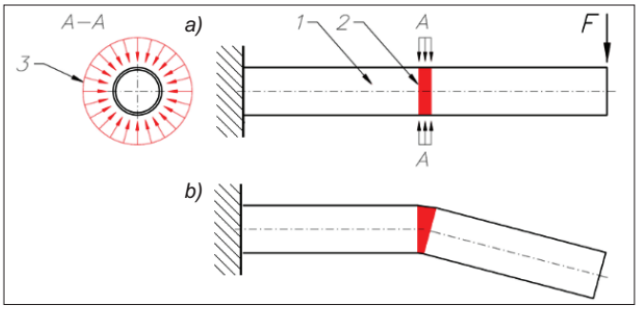

Fig. 2. Diagram of laser-mechanical shaping: a) element during heating, b) element after bending. Markings: 1 - tubular element subject to bending, 2 - laser heated to a given temperature area around section *A* - *A* of the element, 3 - example of uniform heating of the tubular element on its circumference, *F* - applied external force

Concept

During the work, several concepts of the process were created. For further work, the concept of the so-called free bending arm (fig. 3). According to this concept, an element 1 to be machined is installed between the pushing actuator 2 and the free bending arm 3. The laser head 4 heats the element circumferentially in a bending plane comprising the laser beam trajectory and the pivot point of the bending arm.

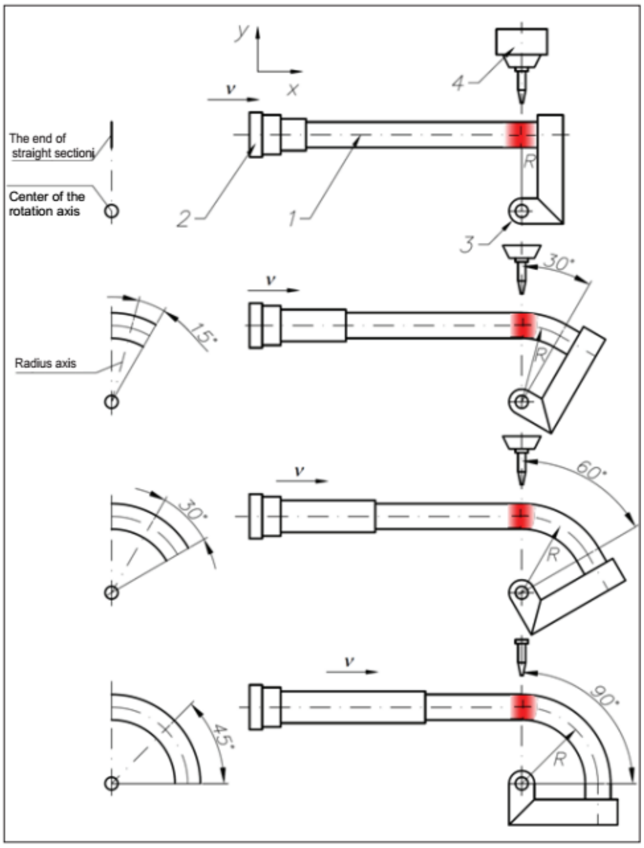

Fig. 3. Individual stages of shaping the element according to the concept with a free bending arm (diagram): 1 - tube element subject to bending, 2 – pushing actuator, 3 - free bending arm, 4 - laser head

At the same time, the actuator 2 pushes on the element 1 with a force *F*. As a result of plasticizing, the tubular element bends with the radius *R*, defined by the distance of the tube axis from the axis of rotation of the arm 3. This concept assumes that only the actuator 2 will be driven and the movement of the bending arm 3 will be the resultant one (free bending arm).

Design

Based on the chosen concept, the technical design of the device was made. Taking into account technical possibilities and research needs, the concept in the form presented in fig. 4 was first developed.

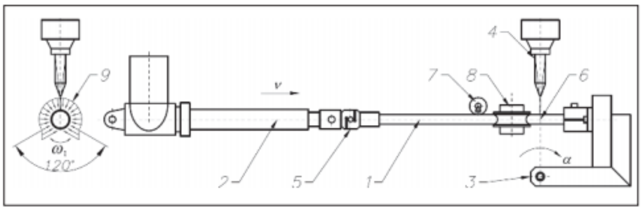

Fig. 4. Diagram of the main components of the device: 1 - workpiece, 2 - pushing actuator, 3 - free bending arm, 4 - laser head, 5 - force sensor, 6 - bending plane, 7 - roll of reaction, 8 - guide roll, 9 - heating trajectory in the bending plane

Technical data of the designed device:
- pushing actuator DSV5030-200-03 and force sensor with measuring range 0÷1000 N,
- maximum pushing force 5000 N,
- minimum diameter of the bent element - without restrictions,
- maximum diameter of the bent element 50 mm,
- maximum bending angle of 90°,
- minimum bending radius of 50 mm,
- maximum bending radius of 127 mm (at a maximum angle of 90°),
- maximum bending radius of 229 mm (at a maximum angle of 50°).

The conceptual design of the device is presented in fig. 5.

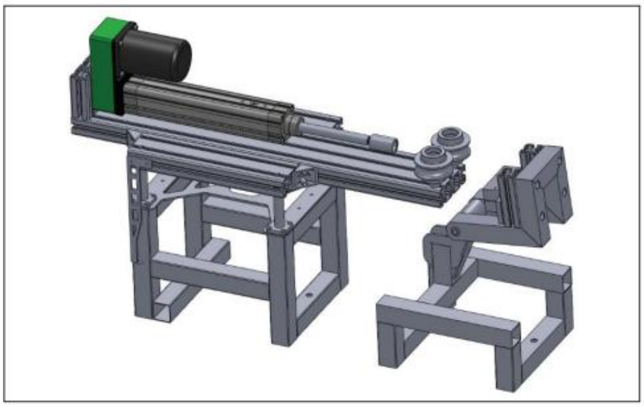

Fig. 5. Conceptual design of the device - main elements

Based on the technical design, the device was built and the test stand was assembled.

Research

Experimental tests were carried out regarding the bending process of a 20 mm diameter tube and 1 mm wall thickness made of X5CrNi18-10 stainless steel. The bending radius R was 215 mm. The beginning of the tubular element was rigidly fixed in the handle of the bending arm.

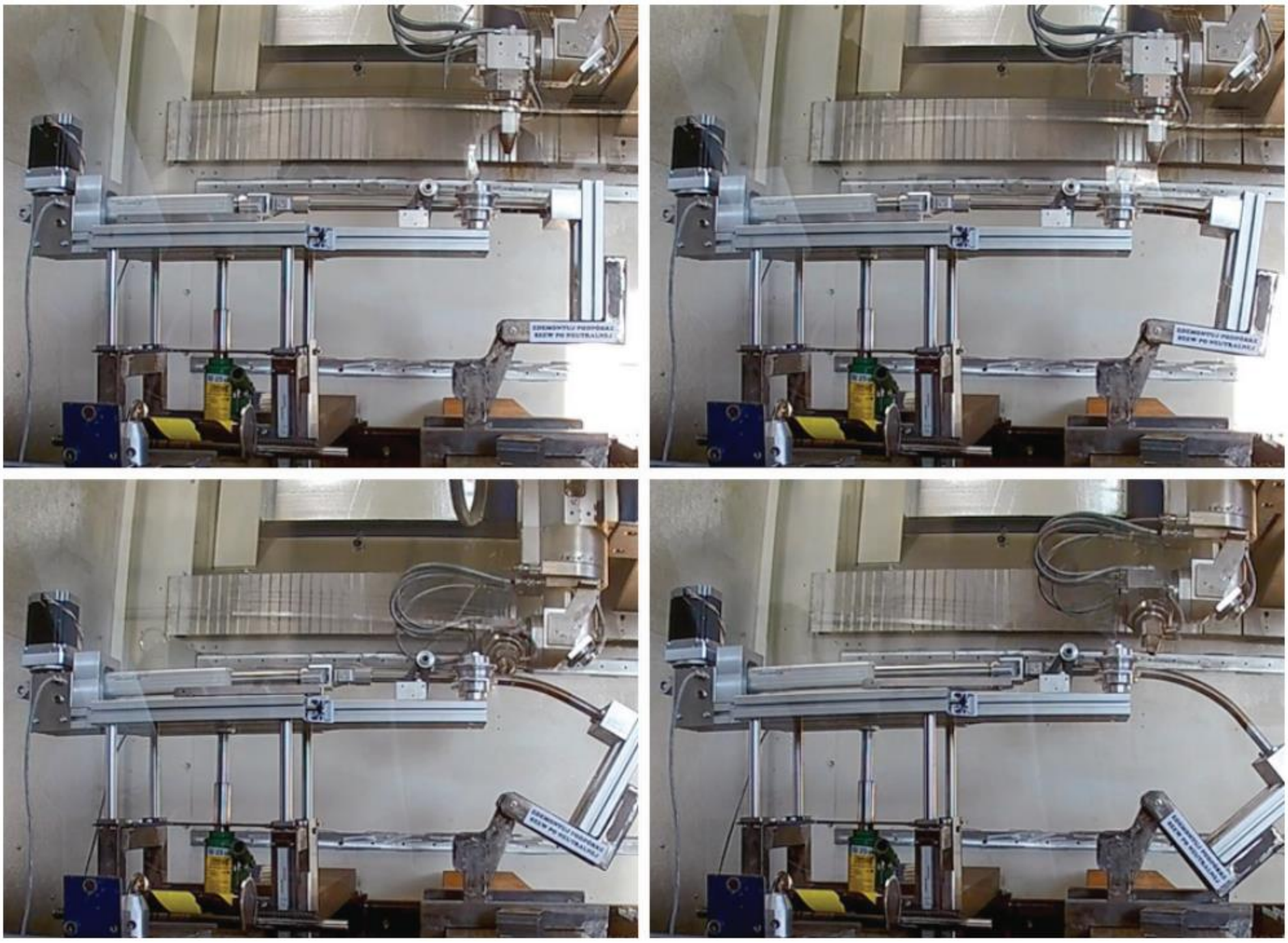

Fig. 6. Individual stages of the bending process

The attached tube was heated with a laser beam, moving in an oscillatory way in the plane of bending. The set trajectory of the beam on the surface of the material was determined by the possible range of motion of the laser head on the TRUMPF LaserCell 1005 five-axis laser machining center. The operating parameters of the CO_2 laser used were: power P = 400 W, linear velocity of the laser spot on the surface ω_l = 4000 mm/min (66.7 mm/s). Concurrent with heating, the force from the pushing actuator acted upon the shaped tubular element. The actuator feed speed was set to v = 20 mm/min (0.33 mm/s). At the maximum permissible extension of the actuator l = 195 mm, a bending angle α = 50° was obtained. Fig. 6 shows the individual phases of bending the discussed tubular element. The finished elements and diagrams of bending forces are shown in fig. 7 and fig. 8.

Fig. 7. Finished elements

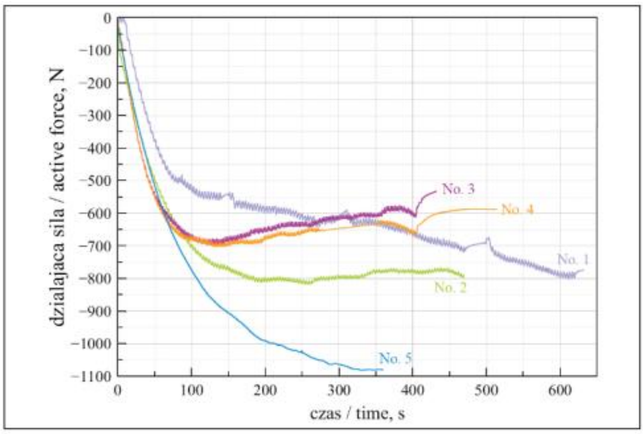

Fig. 8. Graph of the recorded actuator thrust force

Numerical simulations

Based on the assumptions, the concept realized and the experiments carried out, numerical simulation of the process was carried out. The fields of temperature, stress and strain during thermo-mechanical loading of tubes were determined as part of the thermo-mechanical, sequentially-coupled analysis. First, the temperature field generated by the moving laser beam, assumed as a surface heat source, was determined. Then, this temperature field was used as a thermal load in quasi-static mechanical analysis taking into account external mechanical load. Details of the numerical model are described in [7].

Fig. 9 shows an example of the temperature distribution on the surface of the tube being bent, determined in the simulation. Corresponding distribution of the equivalent

HMH stress is presented in fig. 10. The results of numerical simulations show the localized thermal impact of the laser beam on the shaped element. The distribution of equivalent stress shows the effect of local reduction of the yield point of the material in the area of the laser path, which induces the desired plastic deformation in a limited area of the element at a given time.

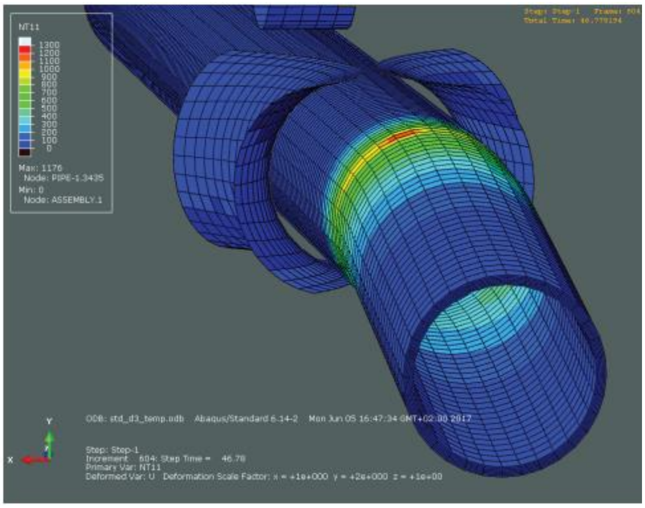

Fig. 9. Temperature distribution during hybrid tube bending

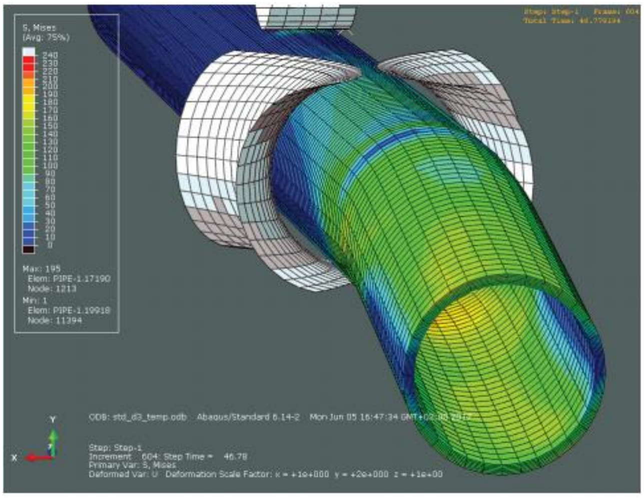

Fig. 10. Distribution of equivalent stress (according to the HMH hypothesis) during the hybrid bending of the tube

Conclusions

Developed laser-mechanical shaping concept was tested on a specially designed and built workstation. The bending effect of the tubes was obtained at the relatively low power of the laser beam. Further reduction of the required beam power can be obtained by using a laser emitting a beam of a shorter wavelength than the CO_2 laser beam (wavelength 10.6 μm). The energy of a diode, Nd:YAG or fiber laser beam, with a wavelength of approx. 1 μm, is much better absorbed by metallic materials. Further research will allow the determination of technical parameters and the possibility of the proposed shaping the elements with a different initial shape.

The developed method and device for the hybrid shaping of thin-walled profiles were filed to the Patent Office of the Republic of Poland (application dated May 10, 2017, application number PL421537).

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