Lasers in Manufacturing Conference 2023

Design of freeform optic module creating a ring-shaped laser beam profile for localized heating of sheet metals

Teng Chen[a,*], Tobias Schmid[a], Florian Hüsing[a], Henning Janssen[a], Christian Brecher[a,b]

[a]Fraunhofer Institute for Production Technology IPT, Steinbachstraße 17, 52074 Aachen, Germany;
[b] Laboratory for Machine Tools and Production Engineering WZL of the RWTH Aachen University,
Campus-Boulevard 30, 52074 Aachen, Germany

Abstract

Laser-based preheating is an energy-efficient method to locally enhance the formability of a metal sheet. A ring-shaped beam can be used for preheating in the flange forming process. According to the tailored heat principle, only the area to be formed is heated. In this paper, a method is presented to design modules with reflective freeform optics (FFO) that converts a collimated Super-Gaussian beam into a ring-shaped beam at a working distance of e.g. 170 mm and deflects the laser beam by 90° simultaneously. The FFO design is based on a 2D geometric model of the optical system and is iteratively optimized according to the process requirements. The FFO was manufactured by fast tool diamond turning and placed into an integration model within a progressive die tool. The design was verified by beam profile measurement as well as by analyzing the formed part quality.

Keywords: Flange forming; sheet metal working; Tailored Heat; freeform optics design; ring-shaped intensity profile

1. Introduction

Preheating of metal sheet is a widely used method to enhance the formability of metal sheets and avoid defects in forming processes (Storms, 2021). Using laser radiation as the heat source for preheating has multiple advantages like high geometric flexibility, fast controllability, precision of heated area, as well as short heating time (Janssen, 2022). In the research project Simulation Flange Forming, a process model for

---

* Corresponding author. Tel.: +49 241 8904-473; fax: +49 241 8904-6473.
E-mail address: teng.chen@ipt.fraunhofer.de

laser-based heating has been developed and the feasibility of the laser preheating in sheet meal processing has been proven. In the research project FESt, Fraunhofer IPT aims at integrating a laser system into fine blanking processes and progressive die tools in order to realize the localized preheating. Since the interesting area in this fine blanking process and in the flange forming with a previously punched pre-hole in the center area is ring-shaped, a laser spot with typical Gaussian intensity distribution is not suitable, as most of laser energy propagates through the pre-hole. Until now, a scanner has been applied to achieve defined heating profiles (Brecher et al., 2014). In this paper, a preheating module equipped with a reflective freeform optic (FFO) has been designed to convert a Gaussian laser spot into a ring-shaped spot with required geometric features. The module has been then constructed and integrated into a progressive die tool. To validate the module design, the intensity distribution of the laser beam at the working plane has been measured and compared with the targeted profile. Finally, a flange forming tests have been conducted with localized preheating using the FFO optic module.

2. State of the Art

2.1. Thermal-assisted sheet metal processing

In sheet metal processing, local thermal assistance during machining offers advantages in various ways for the process and the component: thermal softening that enhances metal sheet formability and thus forming qualities, surface hardening that enhances strength, as well as semi-hot or hot processing that modifies workpiece’s mechanical properties in e.g. forging technology. (Storms, 2021; Janssen, 2022) Both shearing and, as a separate field, fine blanking (project: FESt), as well as forming flanges (project: Simulation Flange Forming) are suitable processes in sheet metal working and provide input for the paper.

As a representative example of various forming operations, flange forming is used in in this paper. The process sequence is divided into three stages for this purpose, with a pre-hole being punched first. This creates a work hardening at the cut edge. Subsequently, local heating is applied around the pre-hole to release the strain hardening and/or to subsequently form the flange in a third (hot) process. Based on the concept of “Tailored Heat”, an optimized local heating process is realized by applying a ring-shaped laser radiation at the working area, i.e. around the pre-hole on the metal sheet (EFB e.V., 2019).

2.2. Beam shaping and forming ring-shaped laser profiles

Beam shaping is a process that redistributes the irradiance and the phase of a laser beam. Based on different principles applied in realizing irradiance and phase redistribution, beam shaping techniques can be categorized into three classes: reflective, refractive, and diffractive beam shaping (Dickey and Holswade, 2000). In diffractive beam shaping, diffractive optical elements (DOE) with microstructure patterns on the optical surface will be used to locally modify the phase of the passing laser beam and thus shape the light using diffractive effects. Although DOEs have technical advantages like smaller optical size and higher shaping accuracy, their high sensitivities to laser wavelength limits its applications where the laser source has a relatively wide spectrum (e.g. diode lasers), and their high requirements on alignment makes the system less robust (Dickey and Holswade, 2000). Compared to refractive and diffractive beam shaping, where optic elements are made of transmissive material and require a beam propagation through the optical element, reflective beam shaping uses beam shapers consisting of highly reflective optical elements, which allows water cooling on the back side and thus is more suitable for applications with high-power laser radiation.

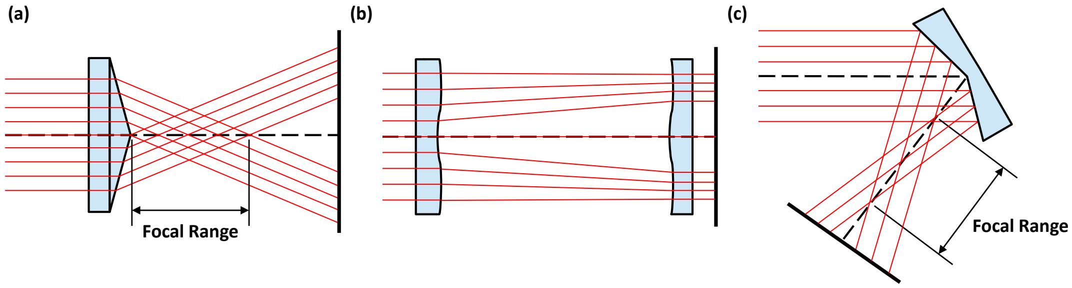


Fig. 1. Existing methods to convert Gaussian or top-hat laser beam into ring-shaped laser beam via (a) axicon, (b) πShaper and (c) reflective axicon.

Ring-shaped laser beams, also known as doughnut-shaped laser beams, are of increasing significance in laser-based processes. They have been studied and applied in various laser-based processes, such as laser welding (Brown et al., 2010), additive manufacturing (Grigoriev et al., 2022), and optical trapping (Nossir et al., 2021). The most widely applied method to generate ring-shaped laser beam is to use an axicon, a conical lens, to realize refractive beam shaping (see Fig. 1 (a)). However, this method faces problems like generating internal focal range during the laser propagation and thermal lensing effect due to difficulties in cooling down the axicon element, which limits its application in high-power laser applications. Laskin et al., 2015 have developed and commercialized a refractive-based optical module called πShaper, which can shape a laser beam into ring shape with an output power up to 500W (see Fig. 1 (b)). However, this module is not able to generate laser beams with nearly zero irradiance at the beam center and still has application limitations for multi-kW lasers. Another possibility is to use a customized optical element called "reflective axicon" (see Fig. 1 (c)) that applies reflective beam shaping on the incident beam (Edmund Optics, 2020). This element can handle multi-kW laser radiation but also generate internal focal range. To sum up, there is no method found that can do beam shaping for multi-kW laser beams without generating internal focal point or range within the working distance.

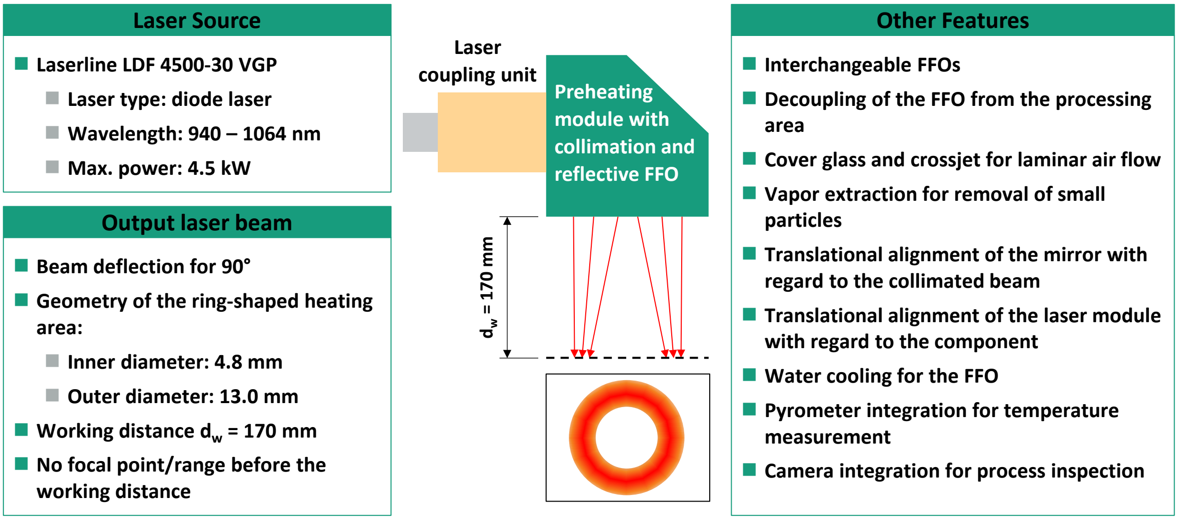
2.3. Freeform optics

The concept FFO refers to reflective or transmissive optics with at least one freeform surface that is not rotationally symmetric. Due to the localized features on the freeform surface, these optics can realize complicated beam shaping and thus have wide range of applications, e.g. in measurement, lighting and illumination, as well as laser material processing (Rolland et al., 2021). Common FFO design methods require the calculation of a nonlinear partial differential equation of the Monge-Ampère (MA) type (ten Thije Boonkkamp et al., 2015). On the other hand, several iterative design methods have been developed based on ray-mapping techniques that avoid the complicated mathematical calculation (Chang et al., 2016; Feng et al., 2017). However, forming an integrable and continuous freeform surface is the challenging step of these methods. There is a need for simplified and efficient FFO design methods especially for generating commonly used (e.g. ring-shaped) laser beams.

3. Design of the preheating module

This paper aims at designing a cost-effective and robust preheating module that can be integrated into the progressive die on a forming press at Fraunhofer IPT and generate ring-shaped laser beam for preheating a continuous S700MC steel sheet. As a boundary condition for FFO design, compatibility with a diode laser available at the Fraunhofer IPT (Laserline LDF 4500-30; λ = 940 – 1064 nm; optical power up to 4.5 kW) is assumed. The requirements for the preheating module can be seen in Fig. 2.

To realize the beam deflection as well as the generation of ring-shaped beam, two optical elements, i.e. a collimation and a reflective FFO, are used as core components in the preheating module. In order to specify the incident beam of the reflective FFO, the laser beam profile after collimation has been measured and fitted by standard Gaussian distribution (see Fig. 3). For the simplicity and the generality of the reflective FFO design, the incident laser beam is assumed to be an ideally collimated Gaussian beam with a beam radius of 15 mm. As described in Fig. 2, the reflective FFO is expected to deflect the laser beam for 90° and generate a ring-shaped laser beam at the working plane that is 170mm after the deflection and is vertical to the beam propagation direction. At the working plane, the ring-shaped beam should have an inner and outer diameter of 4.8 mm and 13.0 mm, respectively. The laser power enclosed by the inner and outer diameters should account for at least 80% of the total laser power, and the local intensity should stay as stable as possible in circumferential direction.



Laser Source

- **Laserline LDF 4500-30 VGP**
  - **Laser type: diode laser**
  - **Wavelength: 940 – 1064 nm**
  - **Max. power: 4.5 kW**

Output laser beam

- **Beam deflection for 90°**
- **Geometry of the ring-shaped heating area:**
  - **Inner diameter: 4.8 mm**
  - **Outer diameter: 13.0 mm**
- **Working distance d_w = 170 mm**
- **No focal point/range before the working distance**

Other Features

- **Interchangeable FFOs**
- **Decoupling of the FFO from the processing area**
- **Cover glass and crossjet for laminar air flow**
- **Vapor extraction for removal of small particles**
- **Translational alignment of the mirror with regard to the collimated beam**
- **Translational alignment of the laser module with regard to the component**
- **Water cooling for the FFO**
- **Pyrometer integration for temperature measurement**
- **Camera integration for process inspection**

Fig. 2. Requirements profile and general working conditions for the development of the preheating module.

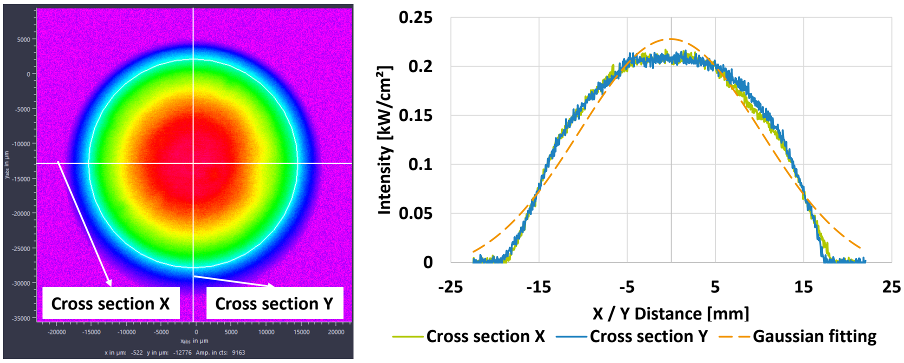


Fig. 3 Measured intensity profile of the incident beam of the reflective freeform optic in the designed preheating module.

3.1. Reflective freeform optic design

In order to avoid complicated calculation of MA equations during the FFO surface design, a simplified design method specifically for generating ring-shaped beam has been developed by Fraunhofer IPT. Instead of inverse calculating the FFO surface from the desired outcome, this method starts from the standard mathematical equation of a conic curve, and iteratively optimize the surface by locally adjusting the geometric parameters in the equation. This section introduces the design procedure proposed in this paper.

As shown in Fig. 4, the simplified FFO design procedure starts with rotating a parabola segment around an off-centered axis. The parabola segment can be described by the mathematical equation as follows:

$$z(r) = \frac{c(r-R)^2}{1+\sqrt{1-c^2(r-R)^2}} \tag{1}$$

where r and z indicate the radial distance and the corresponding sag of the parabola curve, respectively; c and R correspond to the radial offset as well as the curvature of the curve respectively.

The off-centered rotation of such a curve generates a surface that converts the incident Gaussian beam into a coaxial ring-shaped beam by reflective beam shaping. This surface is then combined with a 45° tilted plane mirror to form a reflective FFO surface that can generate a ring-shaped beam while deflecting the beam for 90°. However, with this combined surface a rotationally symmetric intensity distribution can only be generated at the focal plane due to the asymmetrically distorted wavefront. In the work of this paper, an optimization algorithm has been developed for the localized adjustment of geometric parameters for the rotated parabola segment. Consequently, the focal plane is tilted, and a ring-shaped laser intensity distribution is generated at the horizontal working plane that lies between the reflective FFO and the focal plane.

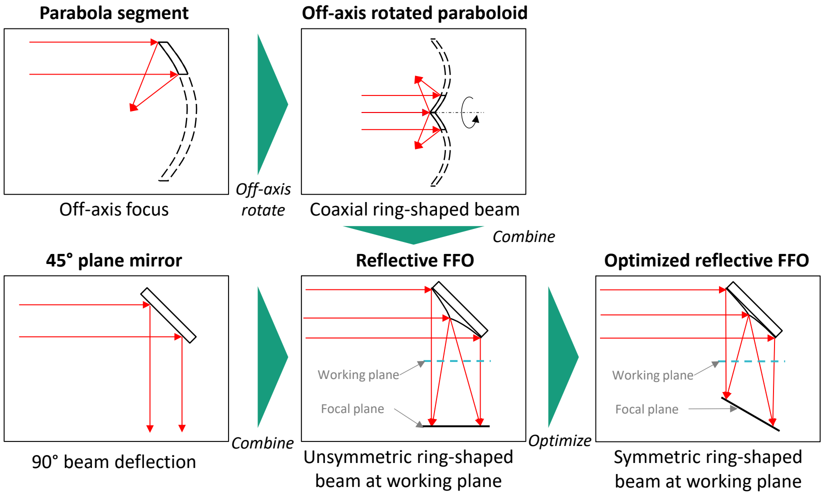


Fig. 4. Illustration of the design procedure for a reflective freeform optic.

After the optimization process, a point cloud representing the sag value of local points on the FFO surface was generated. A spline surface was then generated based on the sag point cloud using the software ZEISS Reverse Engineering, and a reflective FFO model with a solid body was generated using the CAD software SOLIDWORKS. The designed FFO element was manufactured by ultra-precise diamond turning process on a

INNOLITE IL300 fast-tool turning machine. To guarantee high reflectivity in the laser wavelengths and high cooling performance at high laser powers, oxygen free copper (OFHC) has been selected as the raw material of the FFO, and a high-reflective Enhanced Gold coating from Pleiger has been applied on the FFO surface.

3.2. Mechanical design and system integration

Based on the feature requirements in Fig. 2 and the FFO design from Section 3.1, components of the preheating module have been designed. Fig. 5 shows the CAD model of the preheating module with features specified in project FESt. The upper part of the heating module has a completely encapsulated space with a collimation, a FFO holder and a FFO adjustment unit. The FFO can be exchanged within the module for different heating area geometries. A camera is installed for visual process inspection. A pyrometer is installed in the lower section to measure the temperature above the sheet for closed-loop temperature control. The cross-jet provides laminar airflow to protect the optics and the pyrometer. The exhaust removes particles. A beam trap is installed under the sheet to act as a guard at the end of the sheet. The module is designed to be as compact as possible so that it can be integrated into the progressive die within an idle stage between two tool modules.

In order to conduct a feasibility study about laser-based preheating for flange forming process, the module has been mounted with the designed FFO with an integrated into the progressive die (see Fig. 6 (a)).

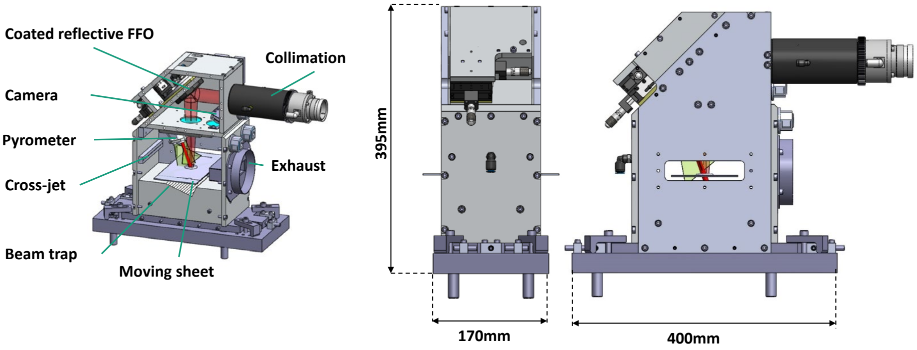


Fig. 5. CAD model of the preheating module.

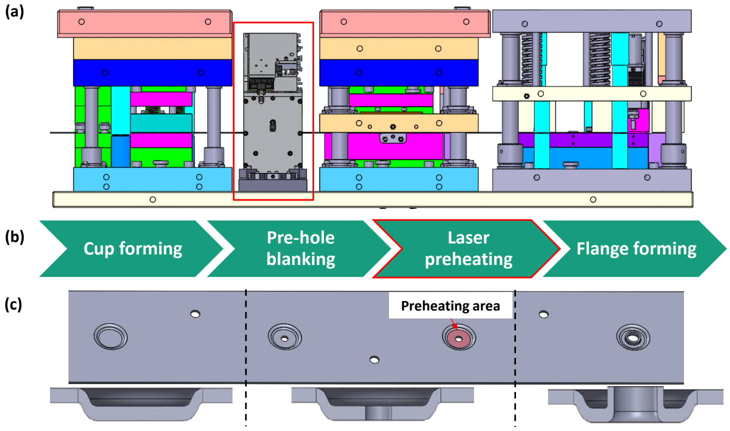


Fig. 6. (a) Progressive die design. The preheating module is highlighted. (b) Process steps of the progressive die. The highlighted stage indicates the function of the integrated preheating module. (c) The metal sheet layouts at each stage in top view and in cross section.

The progressive die has four main stages at its core (see Fig. 6 (b)): 1. Forming of a cup; 2. Shearing of the pre-hole; 3. Local laser preheating; 4. Flange forming. The first two steps are conducted at room temperature by the first tool module, which generates work hardening at the formed areas as well as the shearing zone. The preheating module is integrated within an idle stage after the first tool module, enabling the local preheating that reduces the local strain hardening and thus enhances the formability of the workpiece before the flange forming process. Finally, the preheated workpiece is formed in flanges at the second tool module.

As an exemplary process, a flange forming process with laser preheating has been selected within the scope of the research project Simulation Flange Forming. Detailed results of the laser-assisted flange forming are shown in Section 4.2.

4. Simulation and Experimental validation

4.1. Simulation and measurement of output laser beam profile

To validate the FFO generated by the design method described in Section 3.1, a raytracing simulation has been conducted using the CAD model of the FFO surface, and the output laser beam profile generated by the manufactured FFO has been measured. The simulated intensity profile has been analyzed and compared with the measurement result. Finally, a comparison between the ring-shaped beam generated by the reflective FFO in this paper and the one generated by commercial axicon has been conducted.

In raytracing simulation, the CAD model of the FFO surface generated in Section 3.1 had been imported into an optical model constructed in the non-sequential mode of Zemax® OpticStudio software. The intensity profiles had been simulated at varying working distances from 120 mm to 220 mm after the beam deflection at the FFO element. A collimated Gaussian beam with the parameters given in Section 3.1. was modelled in the software as the laser source. Fig. 7 (a~c) shows the raytracing simulation results, where the results at the baseline working distance of 170 mm are highlighted.

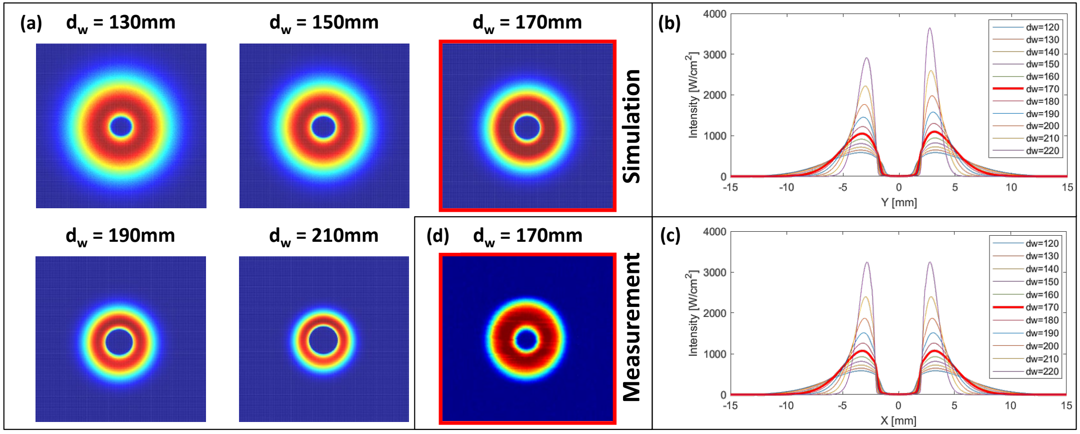


Fig. 7. (a) Simulated 2D-intensity profiles of the laser beam at varying working distances d_w = 130 – 210mm. (b,c) Simulated 1D-intensity profiles at varying working distances d_w = 120 – 220 mm in cross sections X=0 (b) and Y=0 (c). (d) Measurement of the laser beam intensity distribution at the baseline working distance d_w = 170 mm.

At the baseline working distance of 170 mm, 82.6% of laser power lies within the area enclosed by the inner and outer ring diameters. The peak intensity is detected at a radial distance of 3.2 mm, and the peak-valley difference of local intensities at this radial distance along the circumference direction is 4.5%. No intermediate focus is occurring along the laser beam propagation before reaching the working distance.

After manufacturing the FFO, the optical module is assembled and integrated into the progressive die. A beam profile measurement has been conducted using a PRIMES® BeamMonitor BM100+ device (see Fig. 7(d)). At the working distance of 170 mm, 80.3% of total power lies within the enclosed ring area. The peak intensity was measured at the radial distance of 3.7 mm, where the peak-valley intensity difference along the circumference direction accounts for 11.5%. A significant agreement between the simulation and measurement results is observed.

A comparison has been performed with conventional beam shaping solution using refractive axicon. Fig. 8 shows the comparison of both solution in hardware, generated beam profile, as well as the heating results on the metal sheet.

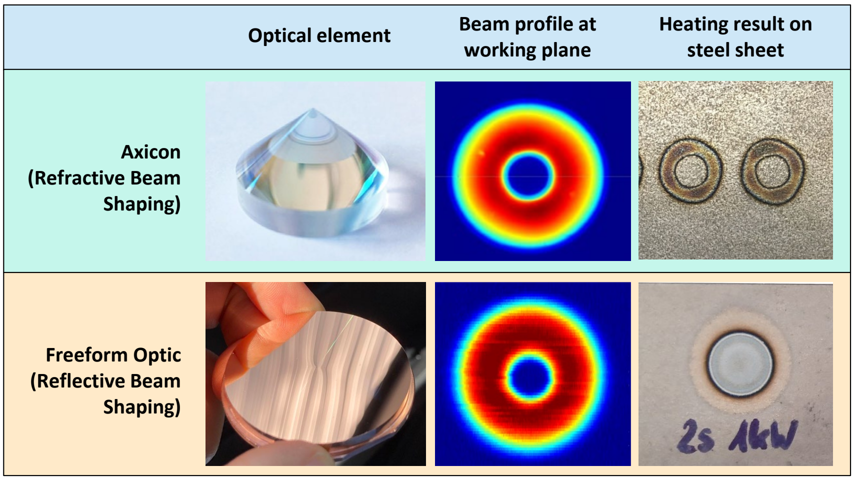


Fig. 8. Comparison between state-of-the-art refractive beam shaping and the reflective beam shaping solution proposed in this paper.

Compared with the state-of-the-art refractive beam shaping solution, the reflective beam shaping solution with FFO proposed in this paper has following technical advantages in the sheet metal heating context:

- Superior circularity of beam profile can be realized by reflective FFO
- No additional mirror for 90° beam deflection required
- Direct cooling of FFO for minimized thermal lensing effect
- No focal range is formed before the working distance, protecting cover glasses and avoiding excessive absorption or scattering in challenging process environments

4.2. First time test of laser-assisted flange forming

As shown in Fig. 9, the preheating module has been integrated into the progressive die, and the first tests of flange forming process have been carried out with and without the laser preheating respectively. By applying 2 kW laser power for one second, the temperature of the S700MC steel sheet surface can reach up to 1242 °C, and the work hardening within the sheet material is significantly reduced. At a stroke rate of 30 strokes/min, a preheated steel sheet can be formed without crack generation, while a cold forming process with the same parameters results in severe crack defects on the workpiece.

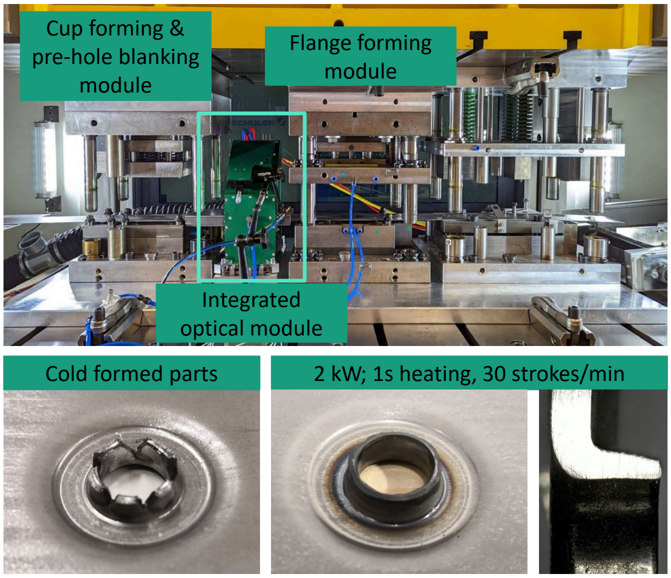


Fig. 9. Integration of the optical module into a progressive die (top); Comparison of flange forming results without and with laser preheating (bottom).

In summary, the integrated optical module has successfully realized the preheating in a progressive forming process and effectively improved the formability of the metal sheet.

5. Conclusion and Outlook

In this paper, a new method for designing reflective FFO converting a Gaussian input beam into a ring-shaped intensity distribution has been presented. This method has been applied to design a FFO used in a laser-based preheating module for flange forming process.

The design method is based on localized parameterization of mathematical expression instead of solving non-linear MA-type equations or applying ray-mapping techniques, which leads to significantly simplified calculation process. Simulation and experiment have shown that the reflective FFO designed in this paper is able to deflect the beam at 90° and generate a ring-shaped intensity distribution at the working plane. Compared to the state-of-the-art solution for generating ring-shaped beams, the solution based on reflective FFO is advantageous for the application in sheet metal processing due to its higher robustness, geometrical suitability of the beam path and especially due to the higher circularity of the generated beam profile as well as lower thermal lensing effect.

The current FFO design method is developed specifically for generating ring-shaped laser beams. Further research should expand the feasibility of this FFO design methods of other types of output beams.

Acknowledgements

The results presented in the paper have been generated in the context of the research project “FESt” and “Simulation Flange Forming”.

The research and development project “FESt” is funded within the program “Technology Transfer Lightweight Construction” of the Federal Ministry of Economics and Climate Protection (BMWK) and is supervised by the Project Management Jülich (PTJ). Funding code: 03LB3016B.

The IGF project "Simulation Flange Forming" is funded within the framework of the program for the promotion of industrial community research (IGF) based on a resolution of the German Bundestag by the German Federal Ministry of Economics and Climate Protection (BMWK) through the German Federation of Industrial Research Associations (AiF) with the supervision of the European Research Association for Sheet Metal Processing EFB e.V. Funding code: 21257N.

References

Brecher, C., Emonts, M., Eckert, M., Weinbach, M., 2014. Double sided irradiation for laser-assisted shearing of ultra high strength steels with process integrated hardening. Physics Procedia, 56, 1427-1435.

Brown, M. S., Arnold, C. B., 2010. Laser precision microfabrication. Springer Ser. Mater. Sci, 135(0933-03391), 120.

Chang, S., Wu, R., An, L., Zheng, Z., 2016. Design beam shapers with double freeform surfaces to form a desired wavefront with prescribed illumination pattern by solving a Monge-Ampère type equation. Journal of Optics, 18(12), 125602.

Dickey, F. M., Holswade, S. C., 2000. Laser beam shaping: theory and techniques. Marcel Dekker, New York.

Edmund Optics, 2020. Reflective laser beam shaping (Website). https://www.edmundoptics.eu/knowledge-center/trending-in-optics/reflective-laser-beam-shaping/ (Date: 27th May 2023)

EFB e.V., 2019. Laserunterstütztes Kragenziehen hochfester Stähle. Merkblatt EFB 5130.

Feng, Z., Froese, B. D., Liang, R., Cheng, D., Wang, Y., 2017. Simplified freeform optics design for complicated laser beam shaping. Applied Optics, 56(33), p9308-9314.

Grigoriev, S. N., Gusarov, A. V., Metel, A. S., Tarasova, T. V., Volosova, M. A., Okunkova, A. A., Gusev, A. S., 2022. Beam shaping in laser powder bed fusion: Péclet number and dynamic simulation. Metals, 12(5), 722.

Janssen, H., Schmidt, F., Schmid, T., 2022. Optimierte Prozesse mithilfe lokaler Erwärmung und KI. Maschinenbau. Die Deutschland-Ausgabe des Schweizer Industriemagazins. https://doi.org/10.24406/h-427830.

Laskin, A, Laskin, V, Ostrun, A., 2015. Generation of doughnut spot for high-power laser technologies using refractive beam shaping, High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications IV. SPIE, 9356: p. 41-48.

Nossir, N., Dalil-Essakali, L., Belafhal, A., 2021. Optical trapping of particles by radiation forces of doughnut laser beams in the Rayleigh regime. Optical and Quantum Electronics, 53, 1-13.

Rolland, J. P., Davies, M. A., Suleski, T. J., Evans, C., Bauer, A., Lambropoulos, J. C., Falaggis, K., 2021. Freeform optics for imaging. Optica, 8(2), p161-176.

Storms, T., 2021. Laserunterstütztes Kragenziehen. Dissertation. RWTH Aachen

ten Thije Boonkkamp, J. H., Prins, C. R., IJzerman, W. L., Tukker, T. W., 2015. The Monge-Ampere equation for freeform optics. In Freeform Optics (pp. FTh3B-4). Optica Publishing Group.