



New Optical Element “Adjust-Shaper” for Achieving Dual Beam Generation to Improve Laser Welding Quality

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Laser welding is increasingly used across various industries, especially in the automotive sector, due to rising demands for vehicle weight reduction and electrification. It is known that improvements in processing quality, such as reduced spatter, can be achieved by irradiating metal materials with a dual beam consisting of a center beam and a ring beam. While one method to achieve this involves introducing an oscillator capable of outputting dual beams, another method uses a beam-splitting diffractive optical element (DOE^{*}). The first approach faces the challenge of high implementation costs, while the second approach faces the challenge of the inability to adjust the intensity ratio of the dual beams, respectively. To address these challenges, Sumitomo Electric Hardmetal Corp. developed the Adjust-Shaper, which retrofits existing single beam systems to enable dual beam output and allows for flexible adjustment of the intensity ratio. This paper presents the product features and evaluation results from its implementation in a laser processing head.

Keywords: laser welding, reduced spatter, beam shaping, ring beam, DOE

1. Introduction

Since the 1990s, laser welding has seen increasing industrial applications, particularly in the automotive sector. Especially in recent years, as the demand for lighter car bodies, electrification, and smart factories has increased, it has found applications in a variety of situations, such as welding car bodies and motor magnet wires, sealing of lithium-ion batteries, and welding busbars. To join these diverse materials and components with high quality, beam shaping technology that optimizes beam shape and intensity distribution is essential.⁽¹⁾

Figure 1 shows a schematic of the optical system for laser welding using a fiber laser or disk laser. The laser beam output from the laser oscillator, transmitted through the delivery fiber, is collimated by a collimating lens and then focused by a focusing lens to a single point at the processing point. Without beam shaping, the laser beam has an extremely high energy density in the vicinity of the focal point, causing the metallic material to form plasma and create keyholes (Fig. 2 (a)). In the vicinity, the metal liquefies and forms a molten pool, while the metal vapor from the keyhole causes spatter, rough weld beads, and damage to the appearance of the weld joint, which can result in the formation of internal blowholes and a decrease in the strength of the joint. Therefore, in recent years, dual beam welding, a type of beam shaping, has become the de facto standard in laser welding. As shown in Fig. 2 (b), when the intensity distribution is configured with the center beam surrounded by ring beams, it is known that the width of the keyhole and the molten pool expands, which suppresses the eruption of metal vapor and improves the quality by reducing spatter.

There are primarily two methods to achieve such dual beams, as shown below. The first method involves using a double-core fiber,^{(2),(3)} but this has the drawback of high initial costs because the oscillator must also be changed to one compatible with the double-core fiber. The second

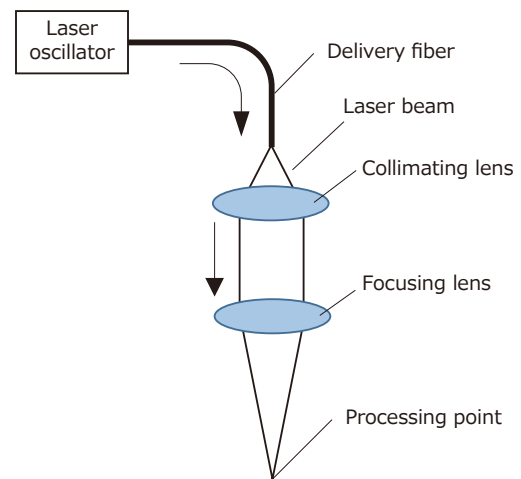


Fig. 1. Optical system for laser welding

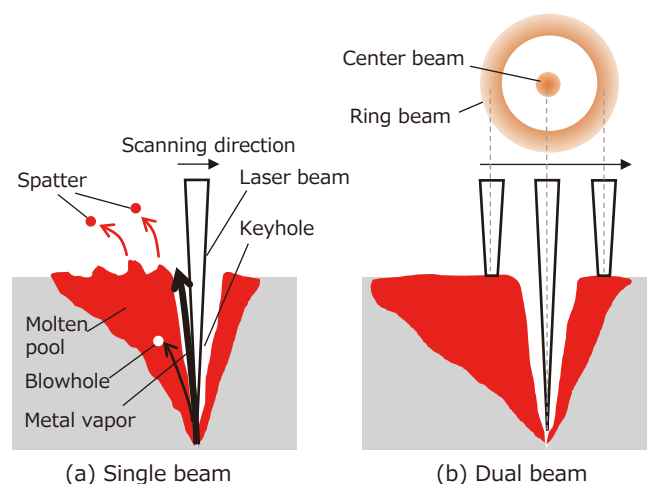


Fig. 2. Appearance during laser welding

method is to use a beam-splitting diffractive optical element (DOE) to create a simulated ring-shaped beam split. This method has lower initial costs since it only requires adding a DOE to existing laser welding machines; however, the intensity ratio between the center beam and the simulated ring beam is determined by the design of the DOE, which means it cannot be adjusted or optimized as needed.

Therefore, Sumitomo Electric Hardmetal Corp. has developed an adjustable shaper (hereinafter referred to as “Adjust-Shaper”) that can be added to existing laser welding machines and allows for the adjustment of the intensity ratio between the center beam and the ring beam.

2. Features of Adjust-Shaper

2-1 Operating principle

Typically, the Adjust-Shaper is used in front of the focusing lens (Fig. 3). It consists of two DOEs with spiral surface microstructure, and by rotating one of them along the optical axis, the intensity ratio between the center beam and the ring beam can be varied.

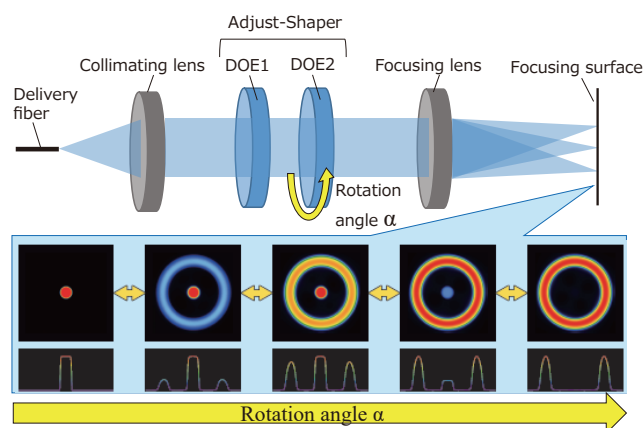


Fig. 3. Configuration of Adjust-Shaper

Before explaining the principle that allows for variable intensity ratios with two DOEs, we first describe how a ring beam is generated using a single DOE with a simple two-step spiral surface microstructure and a focusing lens (Fig. 4 (a)). The surface microstructure of the DOE is designed to provide the desired phase change to the laser beam passing through it, according to its step height. For example, to impart a change of one wavelength λ (i.e., a phase shift of 2π) to the laser beam, considering the propagation in air (with a refractive index of 1) and a material refractive index of n , the required step height is $\lambda/(n-1)$. Similarly, to achieve a phase shift of π (i.e., half a wavelength), the step height would be $\lambda/2(n-1)$. The cross-section of the spiral surface microstructure (hereafter referred to as the phase distribution) cut radially at any azimuthal angle θ results in a rectangular diffractive grating with a step height of $\lambda/2(n-1)$ corresponding to a phase shift of π and a period T , as shown in Fig. 4 (b). The relationship between the phase distribution $\phi(x,y)$ of the DOE and the

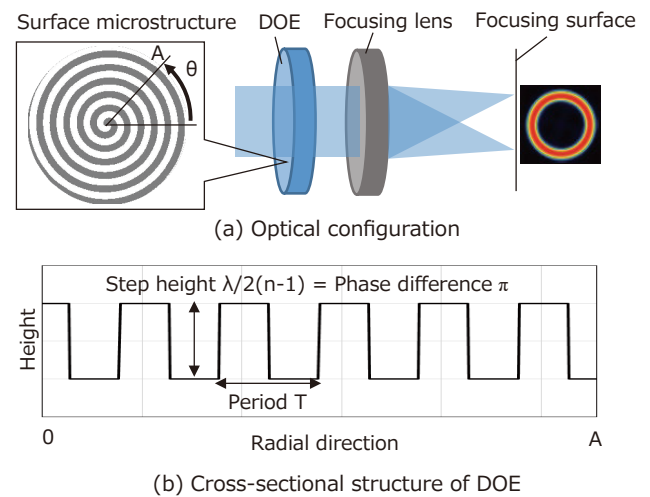


Fig. 4. Generation of ring beam with one DOE and focusing lens

intensity distribution $I(x',y')$ of the laser beam at the focusing surface of a lens with focal length f is given by the complex amplitude distribution $\exp\{i\phi(x,y)\}$ as shown in Eq. (1).⁽⁴⁾

$$I(x',y') \propto |\mathcal{F}[\exp\{i\phi(x,y)\}]|^2 \quad \dots\dots\dots (1)$$

($\mathcal{F}$ is the Fourier transform operator)

In the case of the phase distribution of the one-dimensional diffraction grating described above, diffracted light occurs at positions located at a distance of $s\lambda f/T$ (order $s = \pm 1, \pm 3, \pm 5, \dots$) from the center. The energy ratio of each diffracted light is 40.5% for $s = \pm 1$, 4.5% for $s = \pm 3$, and 1.6% for $s = \pm 5$ when the incident beam is 100% (Fig. 5 (a)). Therefore, the entire spiral phase distribution corresponds to rotating the intensity distribution in Fig. 5 (a) around the origin, resulting in a ring-shaped intensity distribution shown in Fig. 5 (b). The intensity ratio of each ring beam becomes smaller than the above energy ratio, as the intensity is inversely proportional to the circumference length of the rings. The innermost ring corresponds to the order of $s = \pm 1$, and the ring diameter D is given by Eq. (2).

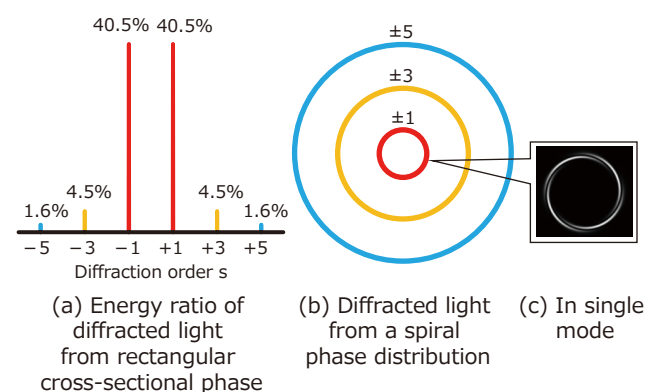


Fig. 5. Diffracted light under various conditions

$$D = \frac{2\lambda f}{T} \dots\dots\dots (2)$$

When a single-mode laser with high coherence is used as the incident beam, tailing and splitting occur in part of the ring as shown in Fig. 5 (c). This phenomenon is caused by the interference between the +1st-order light and the -1st-order light.⁽⁵⁾ In contrast, high-power multimode lasers commonly used in laser welding do not cause such tailing and splitting.

Following that, we explain the principle of varying the intensity distribution using two DOEs. We assume that the phase distribution does not change during the beam propagation between the two DOEs, meaning that the two DOEs are located very close to each other. The step height and radial period of the DOEs are the same as in the case of a single DOE. Initially, when the rotation angle is 0 degrees, the phase distributions of the two DOEs are perfectly matched (Fig. 6). In this case, by passing through the step height corresponding to a phase difference of π for both DOEs, the resulting phase difference becomes 2π , which is equivalent to 0.

The combined phase of the two DOEs forms an equi-phase surface, which is equivalent to having no DOEs at all. Therefore, the intensity distribution at this point at the focusing surface consists only of the center spot.

Next, when one DOE is rotated by 90 degrees, the radial cross-sectional phase distribution at any azimuthal angle θ becomes as shown in Fig. 7. The phase distributions of the first and second DOEs are shifted radially by

90 degrees, or one-quarter of a period. Then the combined phase of the two DOEs forms a spiral phase with a period of $T' = T/2$, resulting in a ring diameter that is twice that of a single DOE, according to Eq. (2). Consequently, the intensity distribution at the focusing surface is only for the ring. As the rotation angle varies continuously between 0 and 90 degrees, the intensity ratio between the center beam and the ring beam can be made variable.

In addition, when the spiral phase distribution φ is generalized in polar coordinates, it can be expressed as shown in Eq. (3).

$$\varphi(r, \theta) = g\left(\frac{2\pi}{T}r + m\theta\right) \dots\dots\dots (3)$$

g is a periodic function, and in the case of a single DOE with a two-step phase, it results in a rectangular distribution with a phase difference π and a radial period T . m is a value referred to as the topological charge, representing the inverse of the rotation period of the spiral. While we have previously shown the DOE phase for the case of $m = 1$, if $m = 3$, the phase distribution becomes as shown in Fig. 8, resulting in a rotation period of $1/3$. In this case, the range of rotation angles that can vary the intensity of the center beam and the ring beam is from 0 to 30 degrees, which is one-third of that in the case of $m = 1$. This is an effective design parameter when aiming to operate within the desired range of rotation angles.

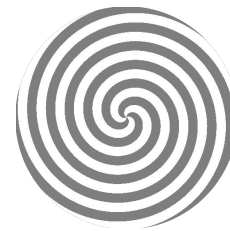


Fig. 8. DOE phase distribution ($m = 3$)

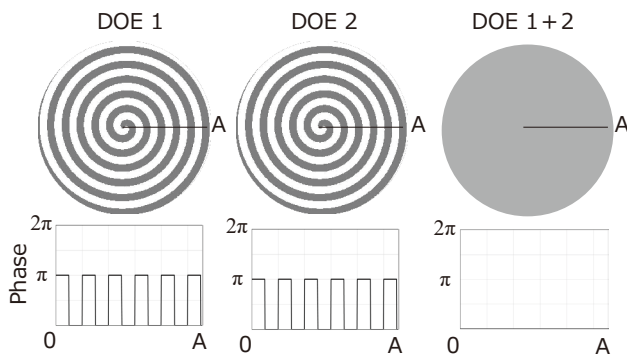


Fig. 6. Phase distribution at a rotation angle of 0 degrees for DOE 2

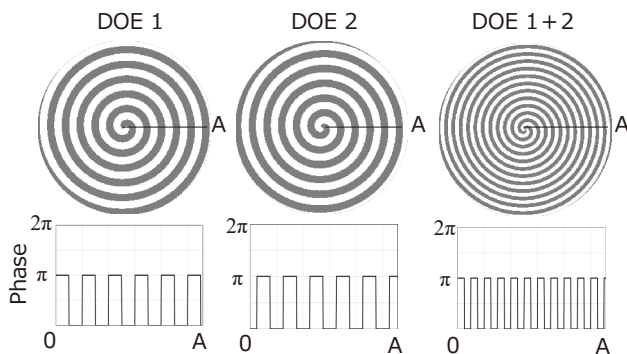


Fig. 7. Phase distribution at a rotation angle of 90 degrees for DOE 2

2-2 Manufacturing method

The manufacturing of the DOE is conducted using photolithography, similar to the microfabrication processes used in semiconductors. Our company has a microfabrication process line for optical materials such as quartz glass and zinc selenide (ZnSe), and we have experience in producing DOEs over a wide range of wavelengths from short to long wavelengths (266 nm to 10.6 μm). The basic manufacturing method for the Adjust-Shaper is the same, allowing compatibility with various wavelengths.

Additionally, to ensure the Adjust-Shaper functions correctly, the alignment between the two DOEs needs to be precisely matched to the order of micrometers. Our company has established a high-precision assembly method for lenses, exemplified by F θ lenses, and by extending this know-how to the Adjust-Shaper, we have achieved the assembly with stringent alignment accuracy. The next chapter will present the results of the characteristic evaluation of the manufactured Adjust-Shaper.

3. Characteristic Evaluation

3-1 Measurement of intensity distribution

Table 1 shows the specifications of the prototype Adjust-Shaper. The mount shape is compact enough to be easily attached to the laser processing head while having a rotation mechanism for one of the DOEs. Figure 9 shows the optical system of the laser welder used in this experiment. A multimode fiber laser with a center wavelength of 1,070 nm and an output of 2 kW was used as the oscillator. The center spot diameter and ring diameter calculated from various conditions are $\phi 200 \mu\text{m}$ and $\phi 625 \mu\text{m}$, respectively. Figures 10 (a) to (d) show the results of intensity distribution measurements with a beam profiler placed on the focusing surface for rotation angles of 0, 65, 75, and 90 degrees, respectively. As described in Section 2-1, it can be confirmed that only the center beam is present at 0 degrees, only the ring beam at 90 degrees, and that the intensity

Table 1. Specifications of the prototype Adjust-Shaper

Outline	66 × 66 × t35 mm
Design wavelength	1064 nm
DOE material	Synthetic quartz
DOE element size (effective diameter)	$\phi 50 \text{ mm}$ ($\phi 45 \text{ mm}$)
Number of phase levels	2 levels
Radial period T of DOEs	1.7 mm
Topological charge m	1
Range of rotation angles for the DOE 2	0–90 degrees
Variable range of intensity ratio (Center : Ring)	1:0–0:1
DOE coating	Low-absorption AR coating

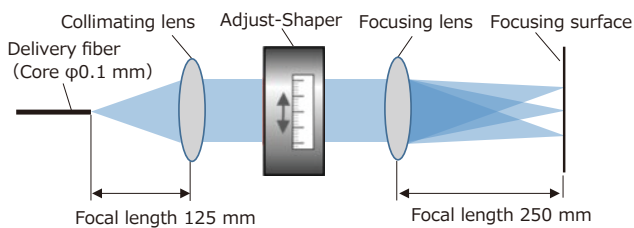


Fig. 9. Optical system for evaluation

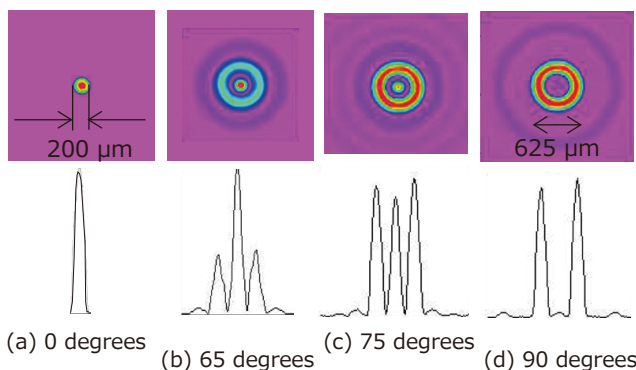


Fig. 10. Intensity distribution on the focusing surface

ratio between the center beam and the ring beam changes according to the rotation angle. It can also be verified that the center spot diameter and the ring diameter are consistent with the calculated values mentioned above.

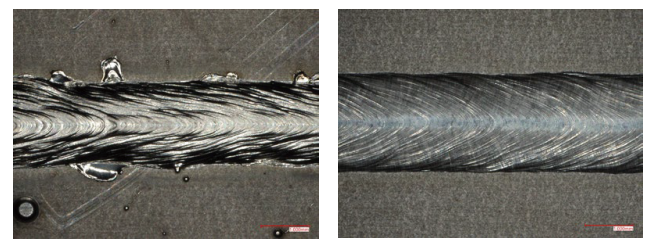
3-2 Implementation Evaluation

Next, we present the results of a melt-run test in which the laser irradiates stainless steel plates while being scanned in one direction at a constant speed as a basic evaluation of laser welding. The optical system is the same as that described in Section 3-1, and other test conditions are shown in Table 2.

Table 2. Laser welding conditions

Workpiece	SUS304, 5 mm thick
Oscillator output	2 kW
Scanning speed	2 m/min
Assist gas	Nitrogen

Figure 11 (a) shows a photograph of the weld appearance after irradiating the workpiece with the center beam only at a rotation angle of 0 degrees, which can be considered as the state without the Adjust-Shaper (refer to Section 2-1). Figure 11 (b) presents the results at a rotation angle of 65 degrees, where a dual beam combining the center beam and the ring beam was used. It is evident that the latter results in a smaller undulation of the weld bead and fewer spatter from the molten metal, indicating a higher quality weld. Additionally, during laser irradiation, it was confirmed that many spatters occurred under the former condition, while almost no spatter was generated under the latter condition, demonstrating that the Adjust-Shaper suppresses spatter during laser welding and improves weld quality.



(a) Rotation angle 0 degrees (Center beam only) (b) Rotation angle 65 degrees (Center + ring beam)

Fig. 11. Photograph of the weld appearance

4. New Design to Enhance Diffraction Efficiency

In the Adjust-Shaper with the two-step spiral phase introduced so far, the diffraction efficiency for the state with only the ring beam is 81% for the ± 1 st-order light (innermost) and even 90% when including the ± 3 rd-order ring beam. The remaining 10% consists of the ± 4 th-order and higher diffracted light generated further outward, leading to energy loss (refer to Section 2-1). The reason that such higher-order diffracted light is relatively preva-

lent is that the phase distribution of the DOE has steep rectangular change points. This can be intuitively understood by technicians with knowledge of image processing, based on the Fourier transform relationship shown in Eq. (1).

Therefore, we devised a new design that can suppress higher-order diffracted light by using a phase distribution that is different from a rectangular function. Figure 12 (a) shows the phase distribution with a radial cross-section of the two DOEs set to a sine wave. Unlike the two-step case, at a rotation angle of 0 degrees, only the ring beam is present (Fig. 12 (b)), while at 180 degrees, only the center beam is present (Fig. 12 (c)), which affects the diffraction efficiency of each ring. As shown in Table 3, the diffraction efficiency of the ring beam, which is the sum of ± 1 st to ± 3 rd orders, is 99%.

This new design is characterized by a high diffraction efficiency for the ring beam and results in a triple ring beam. In other words, energy loss during laser welding can be reduced, and the area of the molten pool can be expanded by the extensive triple ring beam irradiation, which is expected to further improve the quality of the laser welding process. The implementation of this new design will be further evaluated.

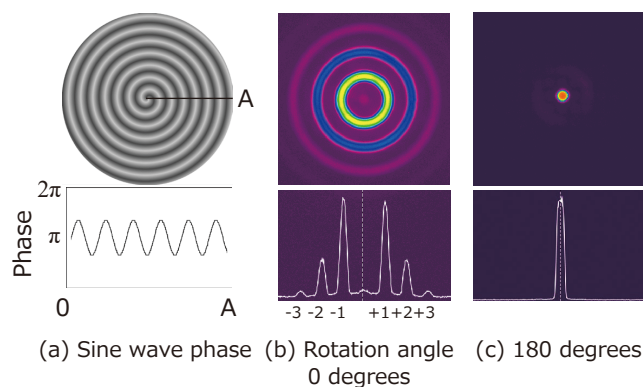


Fig. 12. Intensity distribution on the focusing surface and the phase of the newly designed DOE

Table 3. Diffraction efficiency of each ring beam in the new design

Cross-sectional phase shape		Sine wave	(Reference) Rectangle
Diffraction efficiency	± 1 st order (1st ring)	53%	81%
	± 2 nd order (2nd ring)	38%	0%
	± 3 rd order (3rd ring)	8%	9%
	Total of ± 1st to 3rd orders	99%	90%
	Total of ± 4 th and higher orders	1%	10%

5. Conclusion

We have developed the Adjust-Shaper that enables the realization of dual beams aimed at improving laser welding quality. By installing this product into existing laser welding machines, it is possible to adjust the intensity ratio between the center beam and the ring beam to optimize process conditions. Moving forward, we plan to expand our product lineup to include options compatible with green lasers and blue lasers, which are expected to see increased use in copper welding, as well as new designs with high diffraction efficiency.

6. Acknowledgements

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Technical Term

- *1 DOE: An abbreviation for diffractive optical element. Various optical functions that utilize the diffraction phenomenon can be achieved by adding complex microstructures designed through computer simulation to the surface of the element. Typical examples include beam splitting and beam shaping.

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