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Single-row laser beam with energy strengthened ends for continuous scanning laser surface hardening of large metal components

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For laser surface hardening of metal components with large superficies, a binary grating is proposed to generate single-row laser beam with proportional-intensity diffractive orders. To obtain a uniform hardened band distribution and improve the wear resistance of the sample surface, the binary grating is designed to produce single-row laser beam with energy strengthened at the two ends. The profile of the laser beam spot was designed to be strip with high length-width ratio to improve the machining efficiency of the hardening of large surfaces. A new advantage is suggested to obtain proportional intensity spots with evenness. The design results show that the diffractive efficiency of the binary grating is more than 70%, and the uniformity is less than 3%. The surface profile of the grating fabricated was measured, which shows that the fabrication error is less than 2%. The application of the binary grating in the laser surface hardening of metal components with large superficies is experimentally investigated, and the results show that the hardness distribution of the modified layer is more uniform than that hardened by Gaussian laser beam or array spots with equal intensity distribution.

binary grating, beam shaping, laser surface hardening, diffraction

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1 Introduction

Laser surface hardening has become a major source of high-energy beam surface hardening technology [1]. As an important branch of laser processing technology, it is primarily used in automotive, aerospace, defense, molding as well as some light industry. The laser beam used in surface hardening of metal processes is focused or defocused original Gaussian spots. For the laser surface hardening of parts with large surface areas, continuous laser scanning surface hardening process is used. To improve processing efficiency and reduce overlap times between quenching bands in large area of quenching process, the spot size often needs to be increased to allow for larger laser scanning width. However, with the spot size becoming larger after laser beam has been defocused, the uniformity of heat quantity absorbed in the hardening regional is concurrently decreased. Even if the intensity distribution of the spot is uniform, according to the difference of action time, energy absorbed by the component surface points is not the same. As can be seen in Figure 1(a), with the defocused laser beam scanning the surface, the energy absorbed by point A and point B differs, because the activation time on the edge will always be less than that in the middle, thus resulting in no Gaussian laser beam intensity distribution. In this way, the laser transformation

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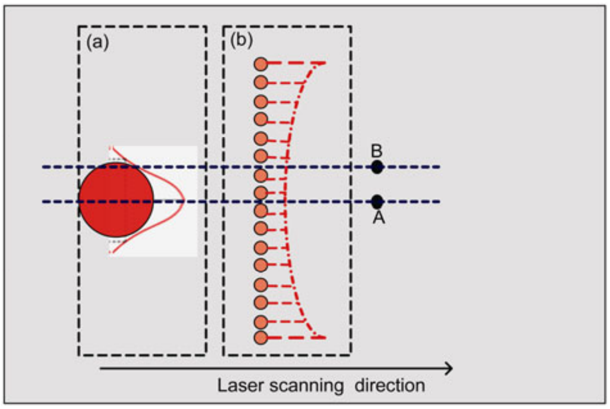

Figure 1 (Color online) Continuous laser scanning surface hardening with different shape laser beam.

hardening band is a crescent with deep center and the edge gradually altering to shallow, which differs from the uniform hardened band. Single-row laser beam with energy strengthened ends (Figure 1(b)) applied in a continuous laser scanning hardening process seem to show promise in improving the processing efficiency resulting in a uniform hardened band layer.

To get uniform hardened band, the laser beam was always transformed to rectangle spot with constant intensity distribution [2–4]. Recently we have reported a method of laser surface modification of ductile iron using laser beam with equal-intensity array spots [5]. Traditional Dammann Grating [6] was used to transform the Gaussian laser beam to equal-intensity array spots. The application of the Dammann gratings in surface modification allowed the ductile iron surface to show periodic gradient hardness distribution [7], the wear resistance of ductile iron thus improved [5]. In the other research [8], we have employed a quasi-Dammann grating (QDG) to transform the laser beam into array spots with edge intensity flow-up in the far field to obtain a uniform shaped hardened band with better wear resistance of the sample surface through hardened. Our research shows that the pulsed laser surface hardening process has more flexibly of the hardening of parts with small surfaces, and according to the hardening of parts with large surface, a continuous laser scanning surface hardening process is more efficiency.

The purpose of this paper is to employ a binary grating to transform the laser beam into single-row spots with edge intensity flow-up in the far field. With the application of the binary grating in continuous laser scanning surface hardening process, the process efficiency is increased, as well as the hardened band becoming more uniform.

2 Grating design and fabrication

The grating is a type of binary phase grating that can produce a high efficiency single-row pattern with proportional-intensity orders in the far field. Dammann gratings are typical binary-phase gratings that produce array beams with equal-intensity spots. As is known, the merit function is the critical factor in the design of the binary phase gratings. The advantage used in the design of Dammann gratings is to obtain even intensity but not the applicable for binary strip gratings to get proportional intensity arrays. Therefore a new advantage is suggested. In theory, encoding technology for conventional Dammann gratings is still applicable for binary gratings with proportional-intensity orders. In order to obtain high diffractive efficiency and uniformity, optimization algorithm was adopted to the design of the binary grating.

The experimental optical system is shown in Figure 2. A collimated laser beam illuminates the binary grating standing before the lens. In the focal plane, an array pattern with proportional intensity orders is formed, which is captured by a laser beam analyzer and displayed on a computer monitor. The key component of this optical system is the binary grating. The design of this kind of binary grating is shown as follows.

It is assumed that this type of binary phase grating satisfies the scalar diffraction theory. The laser beam is approximately expressed as a flat top laser beam. For high diffraction efficiency, pure modulation of the grating is preferred, that is, there should be no amplitude modulation. The phase modulation can be binary, multilevel, or continuous. For simplification of fabrication, binary phase modulation is used in this Letter. The phase distribution shown in Figure 3 which yields the intensity distribution measured at the output plane:

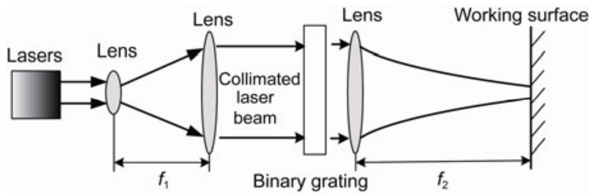

Figure 2 Experimental arrangement for laser beam shaping and application.

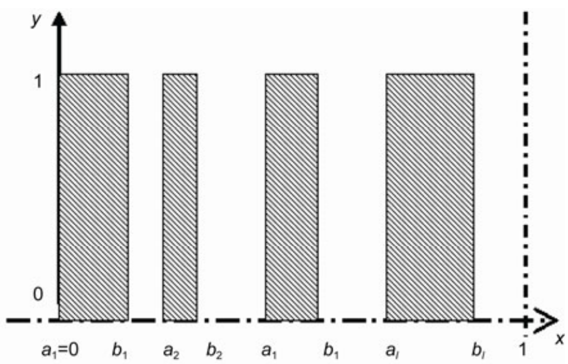

Figure 3 Illustration of the phase distribution of one period of the grating (with white cells for 0 phase delay and black cells for π phase delay).

$$I_0 = \left(\frac{A}{\lambda f}\right)^2 \left| \left\{ \left[\exp(\mathrm{i}\varphi_2) - \exp(\mathrm{i}\varphi_1) \right] \sum_{l=1}^{L} (b_l - a_l) \right\} + \exp(\mathrm{i}\varphi_1) \right|^2$$

$$I_{-m} = I_{+m} = \left(\frac{A}{\lambda f}\right)^2 \left| \exp(\mathrm{i}\varphi_2) - \exp(\mathrm{i}\varphi_1) \right|^2 \sin c^2 \left[(b_l - a_l) \frac{m}{d} \right] \times \left| \sum_{l=1}^{L} (b_l - a_l) \exp\left[-\mathrm{i}\pi (a_l + b_l) \frac{m}{d} \right] \right|^2, \quad (1)$$

where λ is wave length of the laser, f is the focal length of the lens. The length of one period is d, m is the diffractive order. The phase distribution of one period in the uniform sampling rectangle aperture grating is made of black and white strips (Figure 3). The phase delays of the cells are φ_1 (white strips) and φ_2 (black strips), respectively. L is the number of the cells, and the mutation point coordinate of the lth strip is (a_l, b_l).

The parameters for characterization of the binary grating are deformed as following. The uniformity of the binary phase grating including the total uniformity U_t and the proportional uniformity of the orders U_p: The former is defined as:

$$U_t = \sum_{m=0}^{\pm M} \left| I_m - \bar{I} \right| / I_s$$

to evaluate the total uniformity of the whole distribution, where I_m is the intensity of the points of the $\pm M$th order, $\bar{I}$ is the average intensity of these points and I_s is the sum of the intensity of all the points. The later one is defined as:

$$U_p = \frac{I_{(0)}}{I_0} : \frac{I_{(1)}}{I_1} : \ \dots \ : \frac{I_{(M)}}{I_M}$$

to evaluate the deviation of the designed and ideal intensity proportions, where $I_{(0)}, I_{(1)}, \dots I_{(M)}$ and $I_0, I_1, \dots I_M$ are the designed and ideal average intensities of the points of $0, 1, \dots M$ order, respectively. The diffraction efficiency is defined as:

$$\eta_E = 2\sum_{m=0}^{M} I_m \Big/ I_{\text{total}},$$

where I_{total} is the total intensity of the incident light.

The merit function is important for the design of the binary gratings. The merit function for the conventional Dammann grating is not the applicable to this type of binary grating, because the target output intensity distribution is proportional ordered rather than equal-intensity spots. Therefore the merit function of the strip binary grating could be defined as follows.

$$E^2 = \alpha \left\{ \left[\beta_0 \left(I_{(0)} - \eta_E \hat{I}_{(0)} \right) \right]^2 + \left[\beta_1 \left(I_{(1)} - \eta_E \hat{I}_{(1)} \right) \right]^2 + \dots + \left[\beta_M \left(I_{(M)} - \eta_E \hat{I}_{(M)} \right) \right]^2 \right\} + (1-\alpha)(1-\eta_E)^2, \quad (2)$$

where $\alpha \subseteq [0,1]$ is the weight coefficient, $\hat{I}_m$ is the ideal intensity of the orders, η_E is diffraction efficiency of the grating. $\beta_0, \beta_1, \dots, \beta_M$ are the weight coefficients of the orders, $I_{(0)}, I_{(1)}, \dots I_{(M)}$ are the intensities of the orders $0, 1, \dots, M$. To obtain the proportional intensity orders, the intensity deviation of each order should have the given proportion too, which means that the weight coefficients should have the inverse given proportion. In addition, because of the symmetrical characteristic of the binary grating, the weight coefficient of zero order should be doubled. If the design target is a binary grating with an intensity proportion as following:

$$I_{(0)} : I_{(1)} : \dots : I_{(M-1)} : I_{(M)} = k_0 : k_1 : \dots : k_{M-1} : k_M.$$

The weight coefficients should be

$$\beta_0 : \beta_1 : \dots : \beta_{M-1} : \beta_M = \frac{1}{k_0} : \frac{1}{2k_1} : \dots : \frac{1}{2k_{M-1}} : \frac{1}{2k_M}.$$

To get single-row laser spot with intensity blow-up in the edge for the application to laser surface hardening of metal, a 12-order binary grating with intensity proportion of

$$I_{(0)} : I_{(\pm 1)} : \dots : I_{(\pm 7)} : I_{(\pm 8)} : I_{(\pm 9)} : I_{(\pm 10)} : I_{(\pm 11)} : I_{(\pm 12)} = 1 : 1 : \dots : 1 : 1.1 : 1.2 : 1.3 : 1.4 : 1.5,$$

which indicates from zero order to the eighth order the intensity is the same as 1, from the ninth order on, the intensity grows 10% every one order.

With the binary searching algorithm, the initial phase mutation point coordinates were obtained. To improve the diffractive efficiency and the uniformity, the simulated annealing algorithm was adopted to optimize the results. The designed results of the 12-order binary grating are shown in Figures 4 and 5. There are eight group coordinates of the phase mutation points (Figure 4). Table 1 shows the phase mutation point normalized coordinate (a_l, b_l). Figure 5 is the designed intensity distribution of the binary grating. The total uniformities U_t and the proportional uniformity of the orders U_p of the grating is U_t =1.5% and $U_p \approx 1 : 1 : \dots : 1$, respectively, and the diffraction efficiency is η_E =74.36%.

The interval of the adjacent spots in the shaped laser beam is required to be less than the diameter of the single spot to meet the energy demand in surface hardening application. To be agreed with the size of the laser head, the diameter of the element fabricated is 50 mm. The diameter of the single spot of the shaped laser beam is D=0.1 mm. The

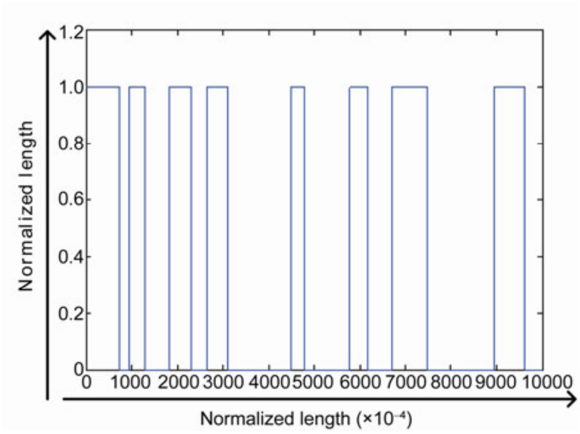

Figure 4 (Color online) Phase distribution of one period.

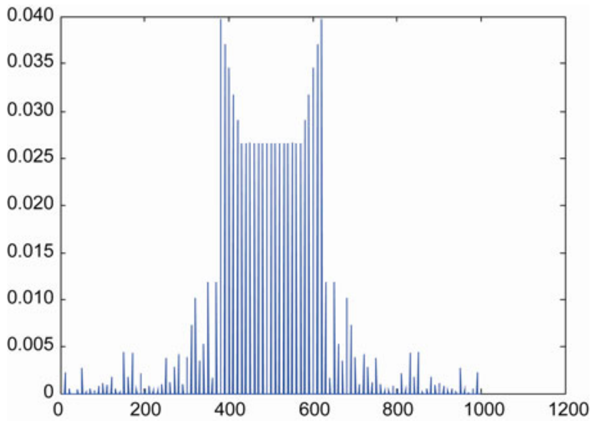

Figure 5 (Color online) Output intensity profile.

period of the optical element is d=1000 μm. With the wavelength 1.064 μm, and the focal length f=150 mm, the interval of the adjacent spots is $\Delta=\lambda f/d-D\approx 0.16-0.1\approx 0.06$ mm. Therefore the length of the shaped strip laser beam is approximately 4.0 mm, which is forty times the diameter of the original focal spot. The binary phase element was fabricated by the very large-scale integration (VLSI) technique [9]. The refractive index of the glass that was used at a wavelength of 1.064 μm is n=1.507, and the thickness corresponding to the phase difference of π is 1046 nm. The surface profile of the grating measured with Dektak8, which is an advanced surface texture measuring system, as shown in Figure 6, clearly shows that the average depth of this surface-relief element is 1033.9 nm, slightly deviating from the desired value. The fabrication error is less than 2%.

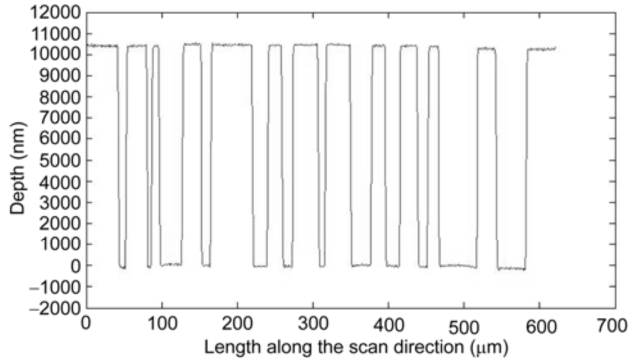

Figure 6 Surface profile of the fabricated binary grating with energy strengthened ends.

3 Results

The experimental optical system is shown in Figure 2. The surface to be hardened is put in the rear focal plane, where the shaped single-row laser beam was obtained. A collimated HLD1001.5 laser with 1.064 μm wavelength was used as the light source, and the focal length of lens is 150 mm.

The ZG42CrMo alloy steel, with the nominal chemical composition (at%) of 0.41C, 0.73Mn, 0.39Si, 0.006S, 0.017P, 0.99Cr, 0.30Mo and balance Fe, was selected as the tested material because it is one of the most common materials used in industry. The steel specimens, 105 mm×85 mm ×8 mm in size, were laser hardened by a HLD1001.5D Nd:YAG laser equipped with the designed binary grating. To give a comparison, a 12-order binary grating with equal intensity single-row spots was also introduced to do the surface hardening of the sample. The laser processing parameters were as follows: laser output power was set at 650 W, the scanning speed of laser as 20 mm/s for the binary grating with blow-up intensity and the contrast grating with equal-intensity single-row, respectively. The samples were hardened separately by the single-row spot with intensity distribution of energy strengthened ends and the 1×25 equal intensity array spots at the focal plane. To simplify the expression, the sample hardened by the proportional intensity single-row spots is termed sample A, and the sample hardened by the 1×25 equal intensity array spots termed sample B. Moreover, to compare the hardened result of Gaussian laser beam and the shaped laser beams, the defocused Gaussian laser beam was used for the hardening process. The laser power was set at 300 W, and the scanning speed

Table 1 Phase mutation point normalized coordinate

l	1	2	3	4	5	6	7	8
a_l	0	0.0947	0.1830	0.2650	0.4494	0.5791	0.6696	0.8934
b_l	0.0751	0.1304	0.2308	0.3096	0.4798	0.6186	0.7469	0.9614

of the laser at 5 mm/s.

To describe the hardened layer of the material, the uniformity of the hardened layer pattern can be defined as the area ratio of the hardened layer and the rectangle it occupies. Figure 7 shows the SEM micrograph of the hardened layer of the sample It can be clearly seen that the hardened layer pattern of the sample hardened with Gaussian laser beam is clearly crescent-like shape, The uniformity of the layer hardened by 1×25 equal intensity array spots is better. The hardened layer pattern of the sample hardened with single-row laser beam with energy strengthened ends is close to rectangular form, which indicates the use of the strip binary grating improved the uniformity of the surface hardened band. Figure 8 shows the microhardness of layers hardened respectively by shaped and Gaussian laser beam. The microhardness curves was obtained at 100 μm vertical downwards from the surface along the width direction. It could be seen that the complete phase transition zone hardness of the surface hardened with the shaped beam is higher than that hardened with Gaussian laser beam. The hardened layer width of the surface hardened by the shaped laser beam is seemingly wider. Moreover, the shaped beam side which is perpendicular to the scanning direction can be designed to have a longer length, which may improve the efficiency of the continuous laser scanning surface hardening process. Also, it may reduce overlap times between quenching bands in large area of quenching process.

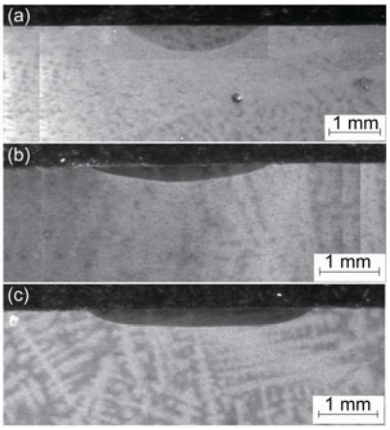

Figure 7 Microstructure of the hardened layer modified by Gaussian laser beam (a), 1×25 equal intensity array spots (b) and single-row laser beam with energy strengthened ends (c).

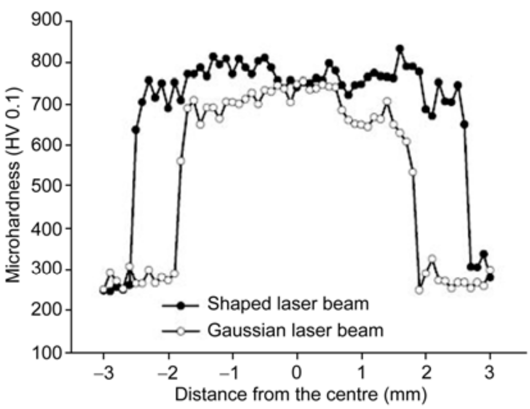

Figure 8 Microhardness of layers hardened respectively by shaped and Gaussian laser beam.

4 Conclusion

A binary grating for getting single-row laser beam with energy strengthened ends was obtained for continuous laser scanning surface hardening of large metal components. The laser beam shaped by the designed binary grating has a long side, which is perpendicular to the scanning direction in the application of hardening process. Hence the efficiency of the process is improved, and at the same time, the overlap times between the quenching bands are reduced. As to components with different size surface area and hardness distribution requirements, binary grating with corresponding orders and order intensity proportions can be prepared. This method is flexible and low cost for beam shaping in continuous laser scanning surface hardening of large metal components. The binary grating designed and fabricated in this paper can transform the Nd:YAG laser beam into single-row laser beam with energy strengthened ends. It is suitable for laser surface hardening of ZG42CrMo alloy steel. The experiments show that the application of the binary grating in surface hardening made by the ZG42CrMo metal surface have more uniform hardened band.

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