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Effect of Cooling on Bending Angle and Microstructure in Laser Tube Bending with Circumferential Scanning

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ABSTRACT

Laser tube bending is a flexible forming process. Two irradiation methods of axial and circumferential scanning are generally used to form metal tubes. The two most important disadvantages of circumferential scanning are its lower bending angle and the time interval required between each scan for cooling purpose. In this research, a novel cooling strategy during laser tube bending with circumferential scanning is proposed to eliminate these disadvantages. The effects of this method on the bending angle and total production time are experimentally investigated. Also, the changes in the microstructure of the tube after bending are studied. The bending angle obtained at each scan using this strategy was increased more than 1.5 times with much less production time and energy consumption. Besides, the undesired effect of HAZ was significantly reduced. It is shown that this new cooling technique can highly improve the efficiency of laser tube bending by the circumferential scanning method.

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1. Introduction

Forming of metal tubes is of particular importance in manufacturing and production of steam boilers, motors, heat exchangers, and air-conditioning systems. Hence the development of new methods in this field may expand optional choices in industries. Literature review shows that laser tube bending is far more complicated than sheet laser bending. Therefore, it is necessary to investigate this method more to eliminate the disadvantages of this technique.

Until now, considerable numerical and experimental studies have been done for a better understanding of the governing mechanisms during this thermal forming process and also of the influence of the effective parameters. Silve et al. [1] studied the laser bending methods of carbon steel tubes with square cross-sections. Finite element analysis of the laser bending of square tubes was performed by Kraus [2]. Li and Yao [3] investigated laser tube forming numerically and experimentally using the circumferential scanning method. In that study, the effects of tube geometry, laser and process parameters on the bending angles were investigated. The effects of the ellipticity of the cross-section and symmetry in the laser forming process were also studied. Zhang et al. [4] investigated, both numerically and experimentally, the effects of various scanning strategies on the bending angle of the tube. It was found that axial scanning has the highest efficiency in laser tube bending compared to circumferential scanning in terms of time and energy consumption. Considering the fact that in this study the laser profiles for axial and circumferential scanning methods were not

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identical, Safdar et al. [5] studied these two scanning methods under the same parametric conditions. In this study, it was also determined that with the same control parameters, the axial directional strategy provides a double bending angle compared with the circumferential scanning.

Wang et al. [6] succeeded in the coil-shaped laser forming of a tube using a proper scanning strategy based on the circumferential strategy. In this research, the path of scanning to achieve the three-dimensional form was obtained using a combination of both scanning strategies in a two-dimensional space. Sheikholeslami et al. [7] studied the effects of different laser scanning strategies for square cross-sectional tube bending. He et al. [8] reviewed all the advances and trends in the tube bending forming techniques, and mentioned laser tube bending as a flexible forming method. CheJamil et al. [9] presented experimental and numerical investigations on the laser bending of thin-walled micro-tubes. Imhan et al. [10], who studied the changes of material properties during the laser tube bending due to the temperature rise, proposed an analytical model and enhanced it by the Particle Swarm Optimization method. They also reviewed the features of laser tube bending processing [11]. In another research, they tried to improve the absorption coefficient of the material and improve the laser tube bending process by using the laser softening heat treatment [12]. Li et al. [13] studied the mechanism of laser tube bending and the influence of processing parameters on the bending angle both numerically and experimentally.

The mentioned literature review showed that most researchers agree that the dominant mechanism in laser tube forming is the shortening mechanism. In the shortening mechanism, the ratio of the beam diameter to tube thickness is high. Therefore, the scanned region is heated almost homogeneously in the direction of the tube thickness. Due to the resistance of the material around the irradiated area against the thermal expansion in the direction of the tube axis, the compressive plastic strain is created in this region. Subsequently, the shortening along the tube length causes the tube to bend toward the laser beam [3]. In cases where more than one scan is used to reach a higher bending angle, a cooling time is considered between successive scans in order to achieve the maximum temperature gradient between the scanned area and its surrounding materials. This time interval between each scan highly increases the production time resulting in higher production costs.

In general, both axial and circumferential scanning schemes have been used to form tubes by means of laser irradiation. The implementation of the axial scanning is much easier than that of the circumferential scanning [4, 5]. The bending angle, total process time and energy consumption to create a bending angle in the axial scanning is much more efficient than those in the circumferential scanning. In multi-scan circumferential scanning, the number of scans may affect the corrosion behavior.

Despite the benefits of the axial scanning, the circumferential scanning has several advantages over the axial scanning. These benefits include:

- The possibility of designing a path strategy to achieve two-dimensional and three-dimensional bends [6, 7].
- Repeatability of the scans to obtain an accurate bending angle by increasing the number of iterations [14].
- The final bend angle in the circumferential scanning is not dependent on tube length [4, 5].

If the advantages of both scanning strategies could be put together, the laser tube bending process, economically speaking, could be used in industries. However, further research is needed in this regard. Since the bending of a tube with the laser is a complex and highly specialized process, it is important to make practical suggestions which do not complicate it more. In this research, a new cooling strategy that is applicable to the circumferential scanning method is proposed, which can perform the cooling process with water at a certain distance from the irradiation path. The effects of this design on the tube bending angle, energy consumption, symmetry, and microstructure of the tube are also experimentally investigated.

2. Materials and Methods

Basically, one of the two methods of the axial or circumferential scanning is utilized in the laser bending of tubes. As mentioned before, the usual governing forming mechanism during the laser tube bending is the shortening mechanism. Zhang et al. [4] introduced a strategy for cooling the tube during the axial scanning. In spite of their remarkable results, it seemed that the practical application of this method was complicated. In the current research, a simple and efficient solution is proposed to highly increase and improve the productivity of the laser tube bending with the circumferential scanning.

Figure 1(a) shows the mechanism of the circumferential scanning. In this strategy, an unconcentrated laser beam with a specific power is irradiated over the surface of a rotating tube. The rotational angle of the tube is usually considered to be 180 degrees or more.

Since the heat transfer coefficient in water is higher than that in the air, in this study a novel design for cooling the tube with water is proposed based on the nature of the shortening mechanism and that of the circumferential scanning method. According to this strategy, the need to apply the time interval between each radiation in the multi-scan mode is eliminated. Fig. 1(b) shows how this plan works. According to this strategy, the materials around the scanned area are cooled by water in order to apply an axial mechanical restraint against the thermal expansion of the heated zone. In addition, due to the fact that the variations in the temperature and coefficient of thermal expansion are directly related to the thermal strain value, cooling increases the thermal gradient between the irradiated materials and their surrounding materials. This will cause a high reduction of the time interval required between successive irradiations in order to achieve the maximum thermal gradient. In this method, two adjustable spacers create a specified distance from the center of the beam path. One of the advantages of this cooling scheme is that the scanning path remains dry during the process. This is important because a wet surface reduces the surface laser absorption coefficient. The effect of cooling on the bending angle is discussed later.

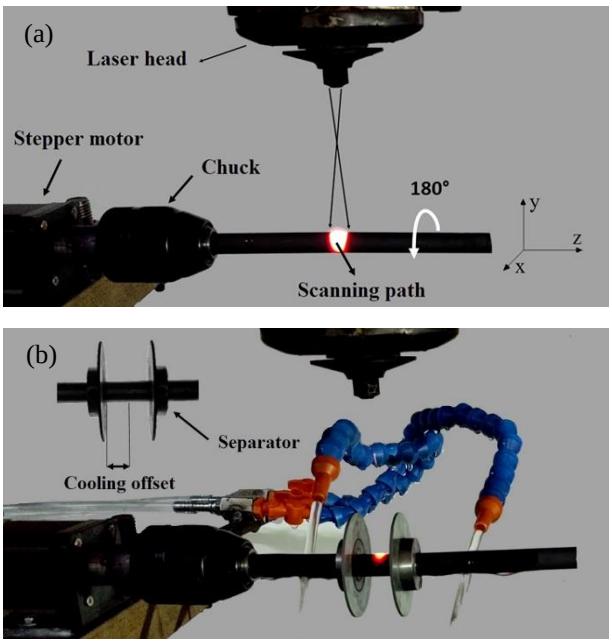


Fig. 1. (a) Experimental setup, (b) Cooling setup for the circumferential scanning.

To prevent the thermal gradient in the thickness direction, the ratio of the beam diameter to tube thickness should be high. In this research, the outer diameter of the tube is 11.8 mm, wall thickness 0.89 mm and length 180 mm. A seamless tube made of AISI 1010 low carbon steel is used for the experiments. A CO2 laser device provides the required energy with a maximum output power of 3000 W to form the tube. The scanning velocity (i.e. the tube's rotational speed) is 1.57 rad/s. The beam diameter is 11 mm, so the ratio of the beam diameter to the tube thickness is 12.4. The power used for each scan is 780 W, and the total rotational angle is 270°.

The scanning along the determined path is repeated 16 times reciprocally. It is expected that the reciprocating scanning will reduce the processing time and prevent undesirable deviation along the x-axis direction. The time intervals between successive scans with forced cooling and no cooling are considered to be 12 and 120 seconds, respectively. To investigate the effect of a cooling offset from the center of irradiation on the bending angle, three offsets of 10, 20 and 30 mm are considered. The outer surface of the tube is cleaned using propanol. Next, it is coated with graphite 33 spray in order to increase the laser absorption coefficient of AISI 1010 tubes.

One of the important issues in the circumferential scanning is to provide a certain angular rotation of the tube at a specified speed. In this research, an automatic chuck is coupled to a stepper motor. The speed and rotation direction of the stepper motor are controlled by an Arduino board which is linked to LabVIEW software. In this way, the tube clamping is easily provided, simultaneous with the rotational movement under the specified angle and velocity.

3. Results and Discussion

As shown in Fig. 2, the bending angle increases considerably using the forced cooling system with water. Temperature variations and thermal expansion coefficients are directly related to the thermal strain value. Therefore, cooling also increases the thermal gradient between the irradiated materials and their surrounding materials. This will increase the amount of the thermal strain. Increase in the thermal strain and circumferential constraints will ultimately increase the bending angle using this cooling strategy. In this case, it takes only 12 seconds between every two passes, which is due to the starting setup time. It should be noted that the previously mentioned 120-second cooling delay in the no-cooling scan does not provide the sufficient time to reach the ambient temperature and the maximum temperature gradient. As a result, if this interval increases, the bending angle in the non-cooling state will also increase, but it takes a lot of time, which is not economical.

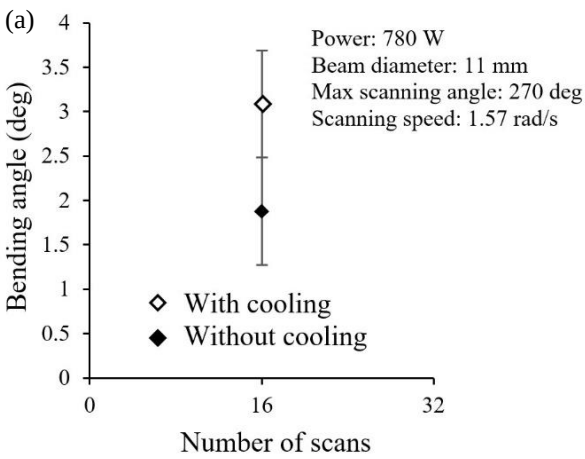


Fig. 2. (a) Comparison of the bend angle under the condition of the circumferential scanning with and without cooling after 16 passes; (b) tube after laser bending with cooling (cooling offset: 10 mm); (c) tube after bending without cooling.

The relationship between the cooling offset and bending angle is shown in Fig. 3. The cooling offset is the distance between the center of the beam and the separators, which was shown in Fig. 1(b). As can be seen, the maximum bending angle is obtained with a 10 mm offset. As the offset increases, the bending angle per pass decreases. This shows that the increase in the offset will decrease the cooling efficiency of water on the irradiated area. However, the bending angles obtained in the defined offsets are still higher than the one without forced cooling. It should be noted that a very low offset distance reduces the possibility of providing sufficient time to achieve the maximum mechanical restraint.

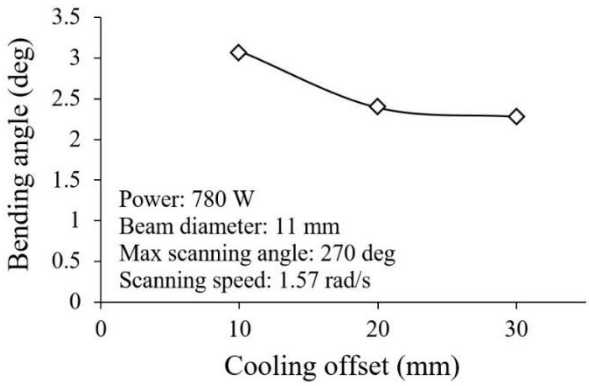


Fig. 3. Variation of the bending angle with cooling offset.

It is known that the final bend in the circumferential scan has an undesirable deviation in the direction of the x-axis [3,5]. The x-axis direction was shown in Fig. 1(a). This issue is because of the thermal gradient differences between the scanned material and its surrounding material at the beginning and end of the scanning path. To overcome this problem, two solutions were proposed by Li and Yao [3]; a) using one scanning path in two steps, and b) using variable scanning speeds.

In this research, the reciprocal scanning is used to reduce the complexity of the process and total production time. In this case, the number of scans is selected as an even number. In this way, it is possible to finish the bending in the shortest possible time using the proposed cooling scheme along with the reciprocal continuous scanning. As shown in Fig. 4, the obtained symmetry is acceptable using this method. The angle is measured by the back-lighting technique using NI Vision Assistant software. If the number of individual scans in order to obtain a precise angle is odd, then n-1 scans can be reciprocally performed. At last, the final scan can be fulfilled according to Li and Yao [3] in a two-step way. In this way, the implementation will be easier and the total time of the process reduces.

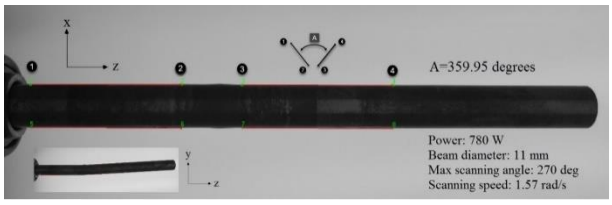


Fig. 4. Tube deviation in x-direction after 16 passes (10 mm cooling offset).

The efficiency of the process in the circumferential scanning both with/without cooling is compared in Table 1. Specific energy is the energy required to obtain a 1° bend. The comparison shows that the cooling design with water is more economical in terms of time and energy.

Table 1. Comparison of two circumferential scanning schemes; Scheme I: without cooling; Scheme II: with forced cooling (cooling offset: 10 mm)

Scheme	Bending angle (deg)	Energy input (J)	Specific energy (J/deg)	Number of scanning	Time (s)		
					Scanning	Delay	Total
Scheme I	1.88	37440	19914.9	16	48	1800	1848
Scheme II	3.10	37440	12077.4	16	48	180	228

As shown in Table 1, the duration of the bending process with 16 repetitions without cooling is about 31 minutes, while with cooling it is less than four minutes. It should be noted that the bending angle in scheme II is about 1.65 times higher than that of scheme I. These advantages will significantly reduce the overall cost of the process.

Previous studies have shown that the microstructure of the materials in the HAZ region undergoes recovery, recrystallization, and phase change [15]. Sometimes, a slight surface melting occurs in this area. These changes would change the chemical and mechanical properties of the material [16]. Therefore, it is necessary to carry out additional operations to reduce or eliminate these effects during or after the bending process. As shown in Fig. 5, the HAZ area is reduced by using forced cooling, and no surface melting occurs. Since most changes occur in this area, the microstructure of the HAZ is investigated in both cooling and no cooling conditions.

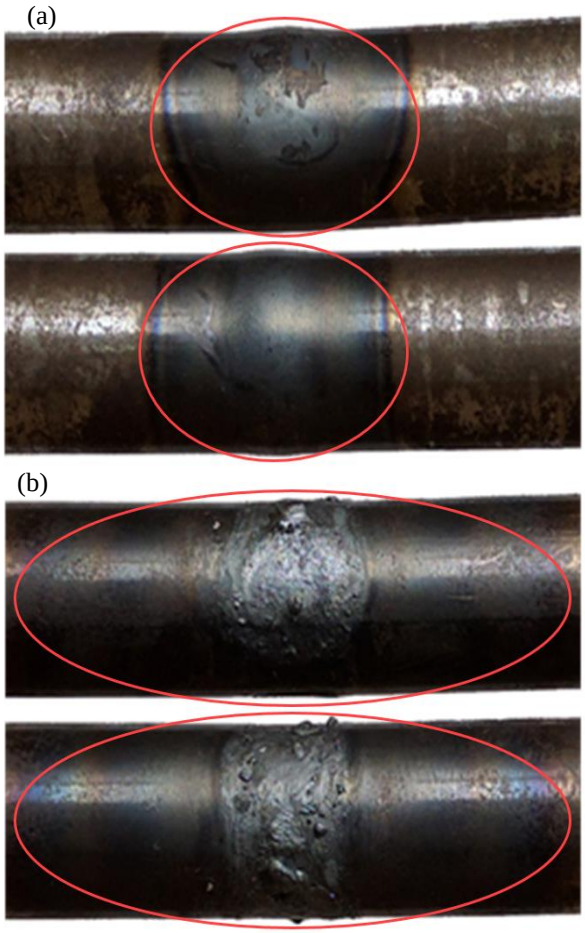


Fig. 5. Effect of cooling on the HAZ area; (a) circumferential scanning with cooling (Cooling offset: 10 mm, 16 passes), (b) circumferential scanning without cooling (16 passes).

The initial microstructure of the tube before the process has a ferritic matrix structure with pearlite (Fig. 6). Moreover, the microstructural banding along with grain elongation in the axial direction is quite apparent due to the process of tube production (cold extrusion).

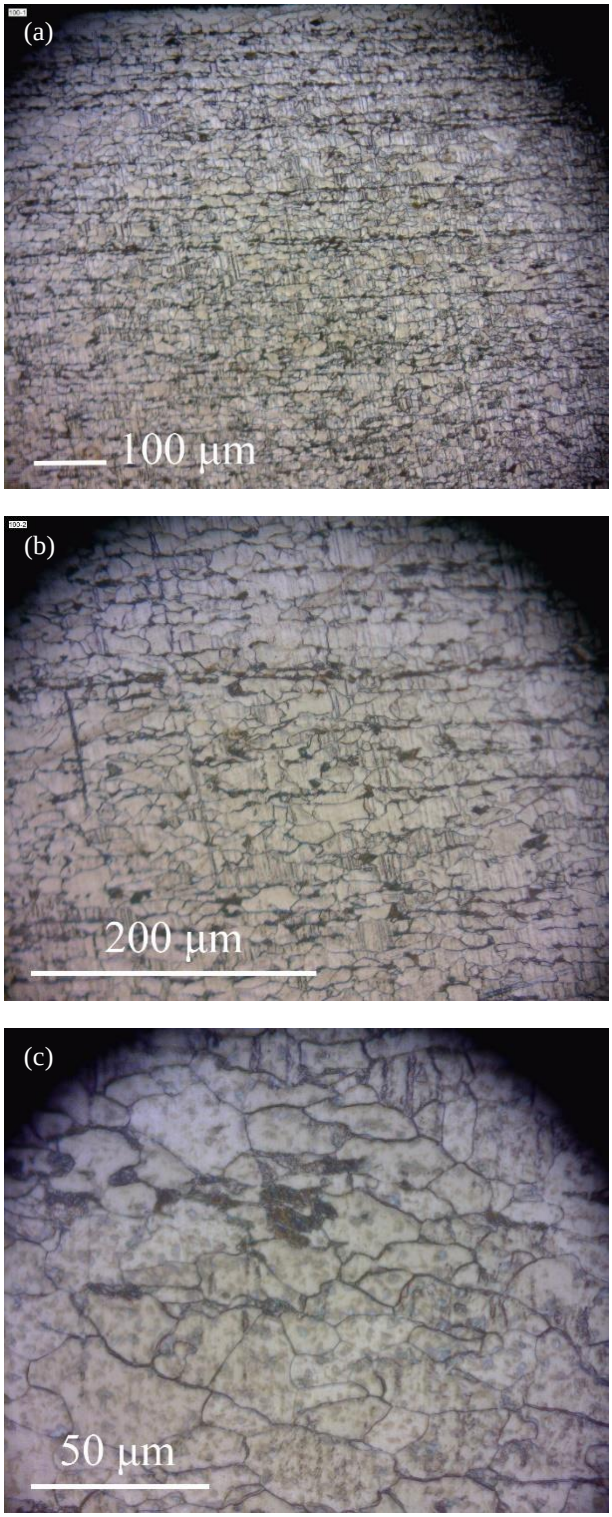


Fig. 6. Optical micrographs of initial AISI 1010 tube (16 passes, etched with Nital 2%); (a) Banded ferrite/pearlite microstructure; (b) Elongated ferrite grains on the longitudinal plane; (c) ferrite morphologies consisting of ferrite (light) and pearlite (dark).

Figures. 7 and 8 show the microstructures after forming with both strategies. In Fig. 7 with scheme I (without cooling), approaching the center of the HAZ shows considerable changes in the microstructure of the tube. At the beginning of this region, the initial structure is completely transformed into a fine grain structure, and the banding and elongation effects of the grains disappear. By approaching the center of the HAZ, the grain structure evolves gradually. With the growth of the lateral plates from the austenite grain boundaries, eventually the Widmanstätten structure is formed at the center of the HAZ. This is due to the faster cooling of the steel relative to the equilibrium state of the hypoeutectoid steel.

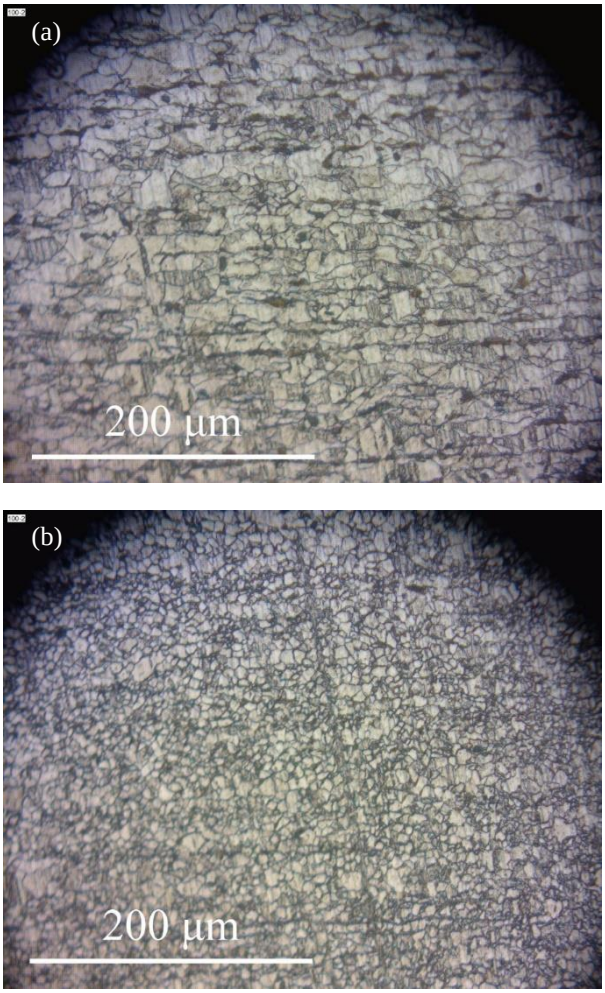
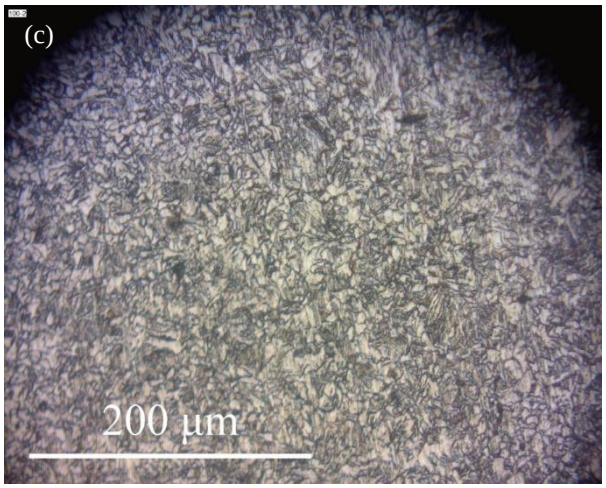


Fig. 7. Optical micrographs showing the microstructure of AISI 1010 tube after laser forming without forced cooling (16 passes, etched with Nital, 2%); a) unaffected base metal zone (ferritic base with pearlite with banded and elongated grains along the tube axis); (b) at the beginning of the HAZ (11 mm from the scanning path) the ferritic structure is completely fine-grained; c) growth of thelateral plates from the grain boundaries and formation of the Widmanstätten structure in a near HAZ area; d) formation of the ferritic Widmanstätten structure at the center of the HAZ.



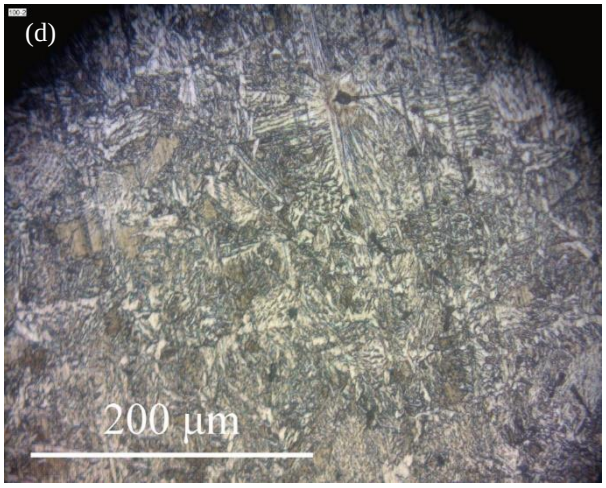
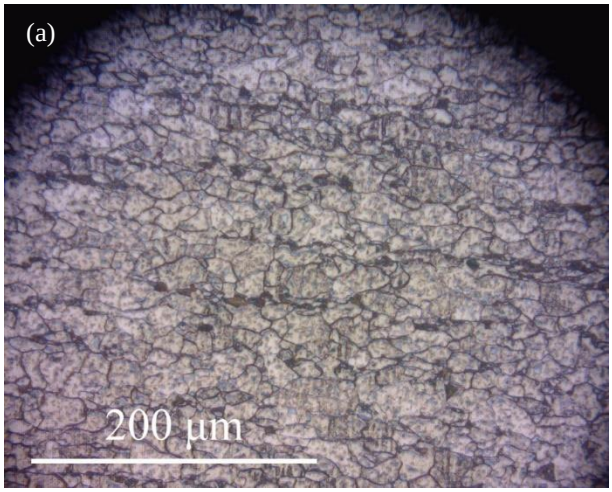
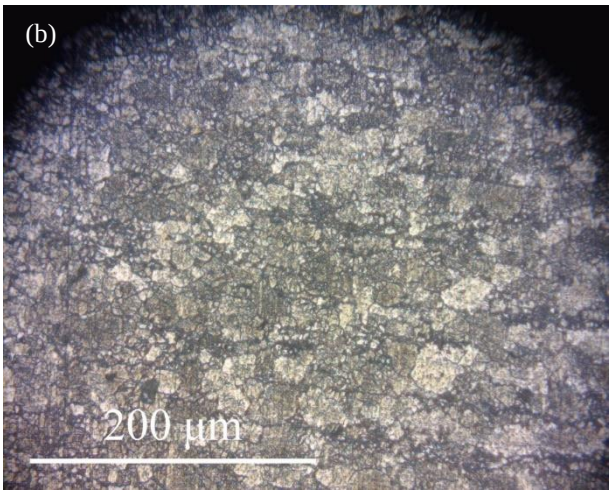
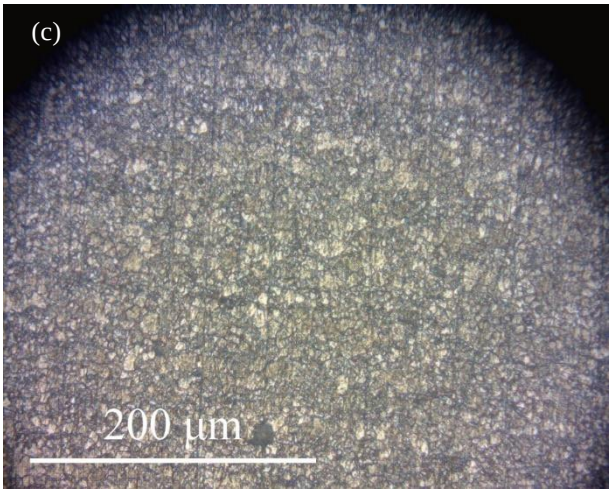


Fig. 7. continue







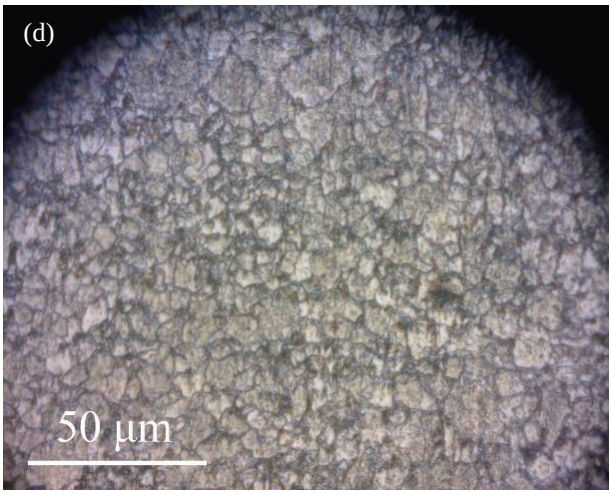


Fig. 8. Optical micrographs showing the microstructure of AISI 1010 tube after laser forming with forced cooling (etchant Nital 2%); a) unaffected base metal zone; b) decomposing coarse grains at the beginning of the HAZ; c) fine grained ferrite structure at the center of the HAZ; d) fine grained microstructure of ferrite with perlite at the center of the HAZ.

Unlike the previous state, in scheme II with forced cooling, as shown in Fig. 8, the initial structure has become a fine-grained structure by approaching the center of the HAZ. In the laser bending process, the speed of reaching the highest temperature with respect to the laser control parameters is very high compared to other thermal bending methods. Further, the scanned area cools down quickly after the irradiation. The cooling process according to the proposed scheme has led to an increase in the rate of temperature reduction compared to the usual ones. Therefore, the materials in the scanned area do not have the time to remain in the critical temperatures between the lines A1 and A3. Consequently, the structural evolution is much less than that of the previous scheme. In Fig. 8(b), although the structure of the region near the center of the HAZ has turned into fine grains, the shape of the coarse-grained structure is still recognizable. At the center of the HAZ, the microstructure consists of cementite particles dispersed in a matrix of ferrite. Therefore, the structural change in this case is much less than in no cooling condition. This becomes more important as these tubes are usually ordered in industry with additional heat treatment due to the nature of the cold working and the importance of recovering their initial physical and mechanical properties. Few changes in the structure resulting from the proposed method could also eliminate the need for the subsequent heat treatment operations.

4. Conclusions

The focus of this research was to propose an applicable economical solution for the utilization of the circumferential scanning plan in the laser tube bending process with the minimum time, energy consumption, and defects. Therefore, a forced water cooled strategy with a cooling offset was proposed and successfully tested. The bending angle obtained using this strategy increased more than 1.5 times for the selected parameters. This increase was achieved consuming a minimal amount of energy and much less time compared to the no-cooling condition. Besides, the undesired effect of the HAZ was significantly reduced. The irradiated surface was obtained without melting and with minor structural changes. In addition, the reciprocal scanning was effective in order to prevent undesirable deviation in the direction of the x-axis. The results showed that the use of the forced water cooling strategy will highly increase the production rate and decrease the costs.

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تأثیر خنک‌کاری بر زاویه خم و ریزساختار در خم‌کاری لیزری لوله با پویش محیطی

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چکیـــده

خم‌کاری لیزری لوله یک فرآیند شکل‌دهی انعطاف‌پذیر است. دو استراتژی تابش لیزر به‌صورت پویش محوری و پویش محیطی برای شکل‌دهی لوله توسط این روش استفاده می شود. مهمترین دو عیب پویش محیطی، زاویه خم پایین‌تر آن و فاصله زمانی لازم بین هر دو پویش متوالی برای خنک‌کاری است. در این پژوهش، یک استراتژی خنک‌کاری جدید در خلال خم‌کاری لیزری لوله با پویش محیطی برای رفع این معایب ارائه شده است. تأثیر این روش بر زاویه خم و زمان کل تولید، به طور تجربی بررسی شده است. همچنین، تغییرات ریزساختار لوله پس از خم‌کاری توسط لیزر مورد بررسی قرار گرفته است. زاویه خم به دست آمده طی هر پویش با استفاده از این استراتژی، با زمان تولید و مصرف انرژی بسیار کمتر، به بیش از ۱/۵ برابر افزایش یافته است. علاوه بر این، تاثیرات نامطلوب منطقه متاثر از حرارت نیز کاهش یافته است. نشان داده شده است که این استراتژی خنک‌کاری جدید با استفاده از روش پویش محیطی می تواند کارایی خم‌کاری لیزری لوله را بسیار بهبود بخشد.

واژه‌های کلیدی: خم‌کاری لیزری لوله، مکانیزم کوتاه‌سازی، پویش محیطی، خنک‌کاری