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BIDIRECTIONAL BENDING OF THIN METALS WITH FEMTOSECOND LASERS

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ABSTRACT

Lasers have a wide range of manufacturing applications, one of which is the bending of metals. While there are multiple ways to induce bending in metals with lasers, this paper examines laser peen forming with femtosecond lasers on thin metals of 75-micrometer thickness perpendicular to the laser. The effects of multiple parameters, including laser energy, scan speed, scan pitch, and material preparation, on the bend angle of the metal are investigated. The bend angles are generated in both concave and convex directions, represented by positive and negative angles, respectively. While it is possible to create angles ranging from 0 to 90 degrees in the concave direction, the largest average convex angle found was only -26.2 degrees. The positive angles were created by high overlapping ratios and slow speeds. Furthermore, the concave angles were made by a smaller range of values than the convex angles, although this range could be expanded by higher laser energy. The positive angles also had a higher inconsistency than the negative angles, with an average standard deviation of 6.8 degrees versus an average of 2.6 degrees, respectively. The characterization of bending angles will allow for more accurate predictions, which will benefit traditional metal forming applications and more advanced applications such as origami structures with metal.

Keywords: Laser forming, femtosecond laser shock peening

1. INTRODUCTION

Sheet metal forming refers to the range of processes that change a piece of sheet metal from a basic planar shape to a more complicated geometry during manufacturing [1]. These forming processes include deep drawing, stamping, and bending. Bending is traditionally a mechanical process, where dies shape the metal. Although, there are some drawbacks to mechanical bending like springback: where the elastic properties of the material resist permanent plastic deformation after bending and partially return toward its previous state [2]. However, as technology continues to expand, new methods reveal themselves as alternatives to traditional practices. One of these advancements is laser forming, where lasers are utilized to cause geometric changes in sheet metals.

The commonly used laser forming method is the process known as the temperature gradient method (TGM) [3-5], typically used with continuum lasers. TGM operates under the application of thermal expansion and contraction to deform the sheet metal. The laser beam will heat the metal sheet which will thermally expand and be partially plastically deformed. The amount of energy absorbed by the metal will play a large part in how much of the sheet is bent. Therefore, the thickness, thermal conductivity, absorptivity of the material, and laser energy level will determine the amount of material heated and thus deformed.

Another method to form sheet metals is laser peen forming (LPF). This process derives from laser shock peening. Thus, instead of depending on thermal properties like TGM, LPF is driven by mechanical properties, and the only thermal effects manifest in a thin layer on the surface. The pulsed (short or even ultrashort) lasers ablate some material, forming a strong plasma over the surface and a shock wave into the material, which is the driving force of LPF. Since LPF is a mechanical process rather than a thermal one like TGM, it yields some advantages such as reduced thermal stress and material enhancements like increased hardness and improved fatigue life [6-8].

As proposed by Hu et al [6], there are two potential mechanisms that cause the metal to bend in two different directions for LPF. The mechanism that causes the convex angle, or negative angle, as shown in Figure 1 A, is known as the stress gradient mechanism (SGM). In essence, the shock wave that is sent into the part forms a compressive stress gradient that causes the part to bend with a negative moment. The other mechanism is known as the shock bending mechanism (SBM). Here, the material is thin enough and the shock wave intense enough that the wave continues through the thickness of the sample, plastically deforming it and causing a concave, or positive, bending angle, as seen in Figure 1 B [6,9-14]. It was also reported that both SGM and SBM can act together, and effectively cancel each other out, to cause the part to stay straight instead of bending [6]. The general process of LPF with SGM and SBM is illustrated in Figure 1.

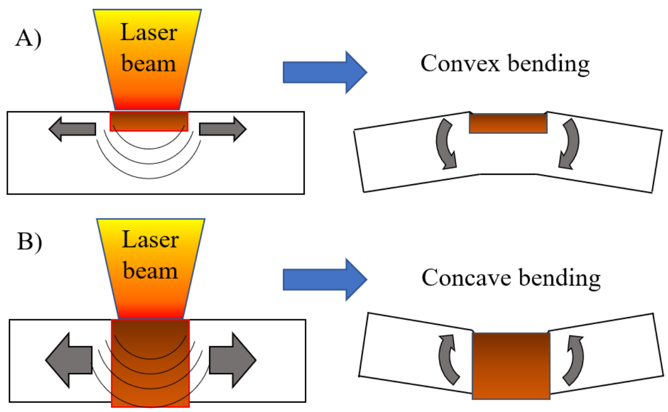

FIGURE 1: LASER PEEN FORMING WHERE A) IS THE SGM PROCESS AND B) IS THE SBM PROCESS [12,13].

A range of research has been performed on laser bending from the specific effects on advanced alloys or metals foams to analytical and numerical models of LPF [15-17]. Nanosecond (ns) lasers have been studied extensively for LPF, even for bi-directional bending [6,18,19]. These studies formed the basis for describing the underlying mechanisms of LPF bi-directional bending, as well as defining how the tuning of different parameters can control the forming results. Though, ns LPF requires a confining medium and protective layer because its shock wave is not strong enough in air and it will cause severe thermal damage to the surface of the part. However, femtosecond (fs) lasers do not have these limitations since their shock waves are much stronger and thermal effects are minimal, making them a great alternative to nanosecond lasers. The pioneer studies on fs LPF were conducted by Sagisaka et al, researching on the various variables involved in LPF and the resultant bending angle or radius of curvature including defocus distance, laser fluence, pulse energy, laser stability, scanning velocity and pitch, and sheet thickness [9-11]. However, the previous studies mainly focus on the unilateral bending direction by fs LPF. To the best knowledge of the authors, there has been no published research reporting bi-directional bending from one-sided scanning with a femtosecond laser. Typically, it was believed that the bi-directional forming is reserved for ns lasers, particularly concave bending, whereas fs lasers were thought to only be capable of convex bending. The proposed reason is that fs laser-induced shock waves are much weaker than shock waves by ns lasers and thus can only induce convex bending by SBM. However, it has been recently reported that the shock waves by fs laser shock peening (over 200 GPa) are over 10 times stronger than those by ns laser shock peening (<10 GPa) [20]. This study will explore the feasibility of bidirectional bending by fs LPF and elucidate the underlying mechanisms.

2. MATERIALS AND METHODS

Within this work, experiments were conducted to examine the effects of the following parameters: laser power, scan pitch, scan speed, material preparation, and scan width. All of the tests used fully hardened 18-8 stainless steel shim stocks of 0.003" thickness or approximately 76.2 µm. The laser used in all experiments was a Yb:KGW femtosecond laser (Pharos by Light Conversion) applied perpendicular to the metal sample from above. The experimental setup for the laser peen forming tests is depicted in Figure 2. Furthermore, all tests had the following variables listed in Table 1 held constant.

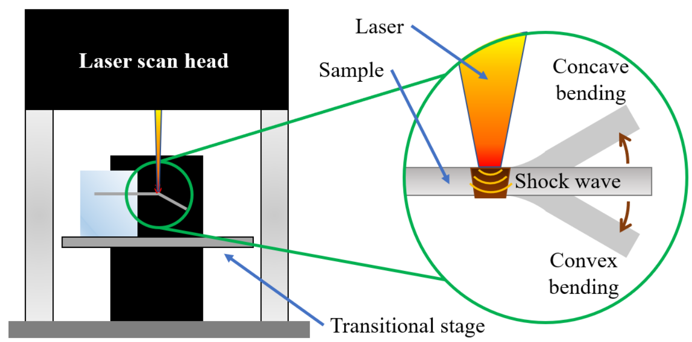

FIGURE 2: EXPERIMENTAL SETUP FOR LPF TESTING.

TABLE 1: CONSTANT VARIABLES.

Variable	Value
Workpiece size (mm)	50 x 10 ± 0.5
Laser spot diameter (µm)	34
Pulse duration (fs)	165
Wavelength (nm)	1030
Repetition rate (kHz)	10
Scan area width (mm)	4

Note that for all test samples, the entire width was scanned. The first laser variable examined is the scan pitch, which is the distance between the centerlines of the laser scanned lines. This parameter can also be evaluated as the overlapping ratio, as the pitch in reference to the laser spot diameter will determine the amount of overlap between laser lines. In this test, three different average laser powers were evaluated: 2.5, 3, and 3.5 W. Both 3 W and 3.5 W were scanned at a speed of 30 mm/s, while 2.5 W was scanned at 25 mm/s. This variation leaves the energy density of the 2.5 W and 3 W cases the same, but the energy density of the 3.5 W is different.

The second variable tested was the scan speed of the laser. Like the scan pitch, three average laser powers were tested: 2.5, 3, and 3.5 W. All the tests had a scan pitch of 10 µm. The scanning strategy that represents the effects of scan pitch and scan speed can be seen in Figure 3.

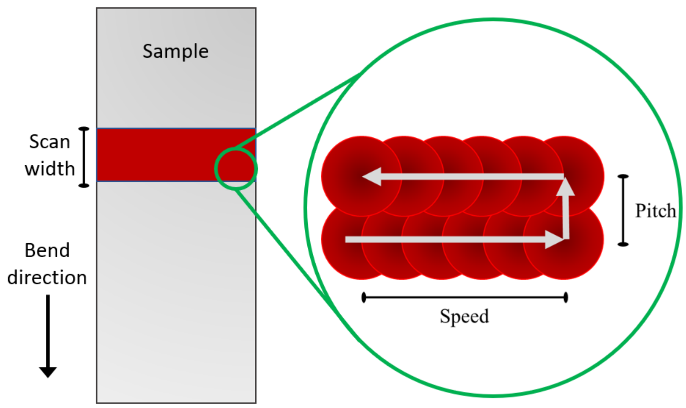

FIGURE 3: A TOPSIDE VIEW OF THE METAL SAMPLE, WHERE THE SCAN WIDTH IS DEFINED, WITH A DEPICTION OF HOW SPEED AFFECTS OVERLAP BETWEEN CONSECUTIVE LASER IMPACTS AND PITCH AFFECTS OVERLAP BETWEEN LASER LINES.

Both the scan pitch and scan speed experiments used samples created from a sheet of stainless steel stock. However, the next test completed compares samples made from the stainless steel sheet versus the same stainless steel, but from a roll. As such, to have a flat sample piece and maintain a constant distance from the focal point of the laser, the roll samples had to be slightly bent due to their curvature. For this test, the laser power was set to 3 W and the speed to 30 mm/s, and the scan pitch was varied.

The final test completed was an evaluation of the effect of scan width, which is depicted in Figure 3. As such, a set of parameters from previous tests that resulted in a consistent 90 degrees was chosen: an average power of 3 W, a scan pitch of 7 µm, and a scan speed of 30 mm/s. Then, this test was repeated for every 0.5 mm of width, up to 4 mm, the parameter used for all other tests.

The pictures of all processed samples were taken by a camera and then processed to measure bend angles, which were rounded to the nearest degree to account for uncertainty in the measurement. Each test likewise had a minimum of three samples made, and the results show the averages of these measurements. It should also be noted that the samples were limited in the concave direction to approximately 90 degrees. This is due to the geometric constraints of the laser setup. Since the laser irradiation is perpendicular to the sample, if the sample bends past 90 degrees, the end of the sample will intersect the laser and keep it from continuing to form the sheet.

3. RESULTS AND DISCUSSION

3.1 The effects of scan pitch, speed, and laser energy

Figures 4 and 5 graph the results of both the scan pitch tests and the scan speed tests. For these tests, positive values represent concave angles and negative angles represent convex angles. Included with the data is a spline trendline for each test, to visualize the trend shown by the data points. The error bars depicted in the figures represent one standard deviation for the given data. For reference, Figure 6 gives a comparison of an unbent sample to both concave and convex samples.

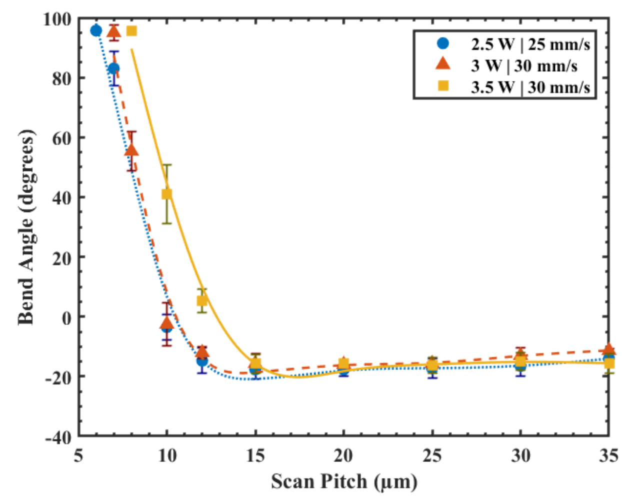

FIGURE 4: THE EFFECT OF SCAN PITCH ON BEND ANGLE FOR VARIOUS LASER POWERS AND SPEEDS.

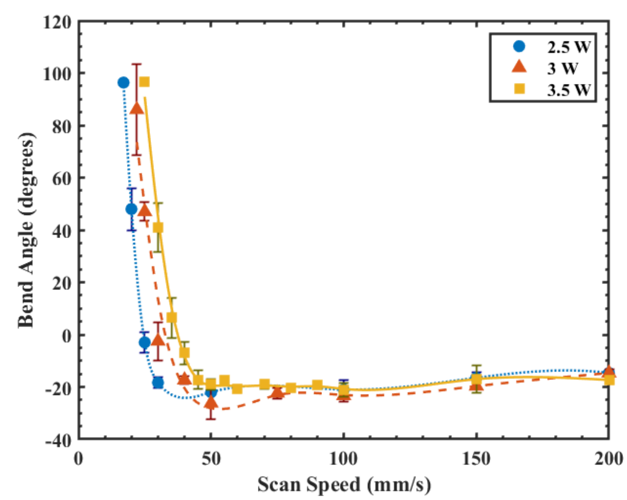

FIGURE 5: THE EFFECT OF SCAN SPEED ON BEND ANGLE FOR VARIOUS LASER POWERS.

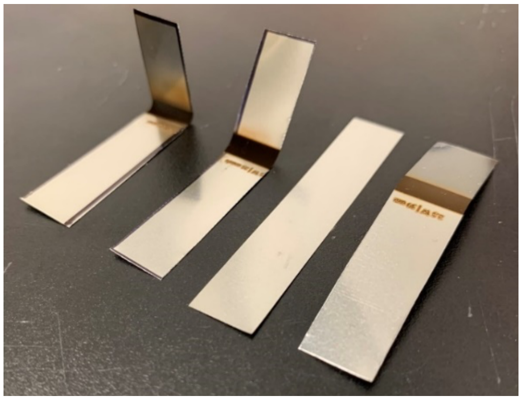

FIGURE 6: EXAMPLE OF LASER PEEN FORMED SAMPLES WHERE TWO CONCAVE SAMPLES ARE ON THE LEFT, AN UNFORMED SAMPLE IN THE MIDDLE, AND A CONVEX SAMPLE ON THE RIGHT.

The first conclusion that stands out from the data, is that both concave and convex angles were produced through the experiments, something not accomplished before now with fs lasers. The maximum average angle achieved was 90 degrees and the minimum average angle was -26.2 degrees. Notice the trend that, regardless of power, between 15 and 35 µm pitch and between 50 and 200 mm/s there is a similar result in bend angle. All results between these values are only separated by at most 5 degrees between power levels. While there is a slightly increasing trend as both pitch and speed increase, the values still fall within -10 to -26 degrees. However, as the speed and pitch values decrease, the slow and steady decrease in angle changes once a certain threshold is reached and the angles quickly increase and turn concave. Furthermore, the concave values have a higher range of 0 to 90 degrees compared to the convex values that can achieve a window of -26 to 0 degrees. Inversely, there is a small window to achieve between 0 to 90 degrees with a range of approximately 10 mm/s for speed and 5-7 µm for pitch. To mirror this, the variance had a similar trend where the positive angles had a higher average standard deviation of 6.8 degrees than the negative angles with an average of 2.6 degrees.

As for the influence of the laser average power, there is no visible trend on the influence of convex angles or variance in results. The main impact of laser power is on the concave angles. While the slope seems to be nearly the same across powers, the parameter values needed to achieve the same bend angle are increased. This trend can be clearly seen in comparing the values needed to get to a 90 degree or higher angle between powers. In the instance of scanning speed, 90 degrees is reached at 17 mm/s for 2.5 W, 22 mm/s for 3 W, and 25 mm/s for 3.5 W. This relationship between power and concave angles gives a key clue into understanding the underlying mechanisms at work in laser bending.

As explained in section 1, it was proposed that for laser peen forming there are two mechanisms at work to create either a concave or convex angle: SGM and SBM, respectively [6]. For SBM, the theory is that the shock wave is powerful enough, and material thin enough, to penetrate consistently throughout the thickness of the material and generate a concave angle. On the other side, the theory claims that SGM works from the theory that the shock wave is weaker and creates a gradient, with the highest intensity at the surface where the laser ablates, and results in a convex angle. When the metal sheet thickness is fixed, as in this study, its bending behavior is essentially impacted by the shock wave strength determined by the effective laser fluence. For a scanning mode, it can be roughly evaluated by $\frac{pulse\ energy \times repetition\ rate \times laser\ spot\ diameter}{scan\ speed \times scan\ pitch}$ (Gaussian spatial distribution should be taken into account for a more precise estimate). The tested parameters, including laser power, scan speed, and scan pitch, are all influencing the bending behavior by affecting the effective laser fluence. The laser fluence increases when laser power is raised or scan speed and scan pitch are reduced, resulting in stronger laser-induced shock waves. The enhanced shock waves could cause the bending mechanism to convert from SGM to SBM, changing the bending angle from convex to concave. Therefore, concave angles are constantly formed at low scanning speeds or scan pitches while convex bending occurs at high speeds and pitches. If the bending is already concave, by increasing laser fluence (raising power or reducing speed and pitch), stronger shock waves can be produced to further increase the positive bending angle as observed through the tests.

The comparison of the tests with 2.5 W, 25 mm/s and 3 W, 30 mm/s, as shown in Figure 4, provides clear evidence for this argument. The effective laser fluences for these two cases are the same with the same scan pitch, and the bending behaviors are identical, as shown in Figure 4.

Another discovered characteristic is that within the convex bending regime, the bend angle first rises and then falls when the scan speed or scan pitch increases (Figures 4 and 5). It is because when the bending is initially converted from concave to convex, by reducing the effective laser fluence (increasing scan pitch or speed), shock wave penetration depth is reduced, benefiting the SGM mechanism for higher negative bending angles. However, when the laser fluence is dropped too low, the laser-induced shock waves are insufficient to effectively deform and bend the metal sheet, resulting in a decrease in bend angle. Thus, for creating convex angles, there is a balance point where the power isn't concentrated enough to allow SBM to take over, but the consecutive laser spots aren't too separated such that the metal doesn't have the sufficient energy input to the system.

To further expand on these mechanisms, Table 2 gives the minimum average bending angles achieved during the scan and pitch tests and reveals an important concept. Notice, the scan pitch test could only achieve a maximum negative angle of -17.7 degrees compared to the -26.2 degrees in the scan speed test. The scan speed test had a higher effective laser fluence at a scan pitch of 10 μm, and the change occurred in the speed of the laser. This trend implies that the power can be condensed with the scan pitch but kept from allowing the sample to bend inwards by increasing the speed. Thus, in theory, it follows that if a smaller scan pitch and a higher scan speed are combined, a higher convex angle could be achieved. This follows the previous theory that by increasing scan speed, the overlapping ratio can be decreased enough to let SGM control the overall bending mechanism, but the dense pitch increases the total amount laser lines and thus bending applied to the metal. This is not evaluated within the scope of this paper and deserves more investigation.

TABLE 2: MINIMUM AVERAGE BENDING ANGLES.

Variable parameter	Energy (μJ)	Speed (mm/s)	Pitch (μm)	Minimum angle (θ)
Scan Pitch	250	25	15/20	-17.7
	300	30	20	-16
	350	30	25	-16.3
Scan Speed	250	50	10	-22
	300	50	10	-26.2
	350	100	10	-21

3.2 Effect of scan width

Note that a constant scan width of 4 mm was used to evaluate the effects of the scan speed and scan pitch for a common area. However, as the scan width increases, the effects on bending angle will increase and vice versa since laser bending is an iterative process. In other words, if there is a larger scan area, a more negative angle can be achieved with the necessary parameters. Or a higher scan pitch or scan speed could attain a more positive angle. Yet, the radius will increase. Thus, to achieve a smaller area of effect and smaller bend radius, a lower pitch or speed will be required to make a high positive angle, and the largest possible negative angle will decrease. This trend is shown in Figure 7, which depicts the experiment where the width was changed, and the laser power was 3 W, scan speed was 30 mm/s, and scan pitch was 7 μm. Note that the error bars represent one standard deviation. Also, the results of 3, 3.5, and 4 mm are limited to approximately 95 degrees due to the geometric limitations of the laser setup. Past this angle, the metal sample will bend in front of the laser, blocking the laser from reaching the surface of the sample.

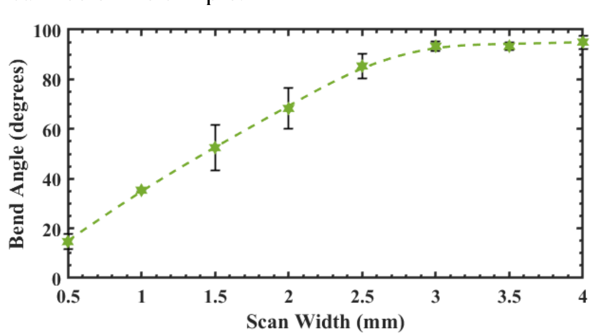

FIGURE 7: THE EFFECT OF SCAN WIDTH ON BEND ANGLE.

3.3 Material preparation comparison

Finally, Figure 8 compares the scan pitch tests for samples gathered from the steel sheet and the steel roll. There are a few differences to note between the roll and sheet tests. The first is that the negative angles found were smaller for the roll sample with an average of -9 degrees and a maximum of -12.8 degrees compared to an average of -14 degrees and a maximum of -16 degrees for the sheet samples. The second is that the roll sample transitioned to a positive angle at a higher scan pitch, where the average value at 10 μm is 22.71 degrees for the roll samples, and the sheet sample had an average value of -2.5 degrees. Finally, the standard deviations were higher for the roll samples with an average of 4 degrees for the negative angles and 18.4 for the positive angles compared to the sheet samples, which were 2.3 and 6.5 degrees, respectively. In summary, the rolled samples had a higher variance and worse results with lower negative angles than the sheet samples. This discrepancy outlines why material preparation is an essential variable in LPF. This change could result from the focusing of the laser. If the material is not perfectly straight, there are parts of the sample that will fall outside the focal point. If this happens, then the average power and spot diameter of the laser will change, affecting the amount of ablation and the scan pitch from the laser. To counteract this, the rolled sheets were bent slightly in preparation. But this deformation of the metal introduces plastic deformation and residual stresses in the samples. These stressors will cause the metal to behave differently, as shown by the results in Figure 7. Similarly, the pre-bending of the metal roll could have introduced plastic deformation into the material which increases the resistance to forming. Therefore, with laser forming, it is necessary to have a material that is kept consistent to ensure accuracy in the bending results.

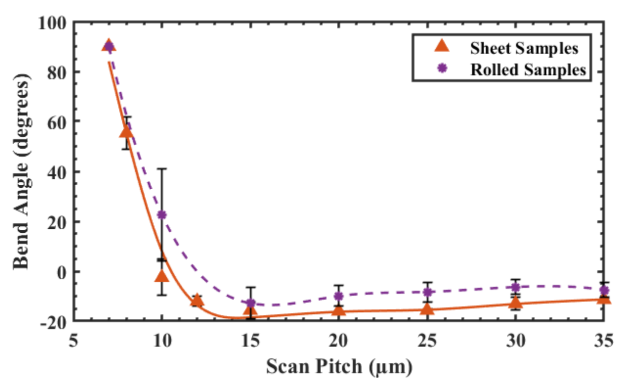

FIGURE 8: A COMPARISON OF STEEL SAMPLES PREPARED FROM A ROLL OF METAL VS A SHEET OF METAL.

4. CONCLUSION

This paper has demonstrated that bidirectional bending is not only possible with ns laser LPF, but also with fs lasers with sufficient power and the right parameters to alter the laser fluence. Scan speed and scan pitch can be decreased to create high overlapping ratios and generate concave bending or increased to decrease the laser energy density and create convex angles. Furthermore, since laser forming is an incremental process, the larger the scanning width, the larger the bending angle generated. By defining the parameters and range of abilities available with LPF, these processes can more accurately predict the angles with given parameters leading to better design and implementation of LPF. Furthermore, the knowledge on the limits of angles in two directions allows for more flexibility in design as these angles can be formed from application in a single laser direction. Additionally, ultrafast LPF has shown to be a viable process for two directional bending that does not require either a confining medium or protective layer like nanosecond LPF, making fs LPF more flexible with a broader possibility of applications, as it has a more accessible and user-friendly setup.

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