Micro parts processing using laser cutting and ultra-short-pulse laser peen forming

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ABSTRACT

A laser peen forming is a sheet metal forming method using laser induced shock waves. The laser peen forming with an ultra-short-pulse laser is a kind of non-thermal and die-less forming process, and is favorable for micro forming. The authors applied the laser peen forming to the bending of pure titanium thin sheet with a picosecond laser and a femtosecond laser. The changes of bending properties with atmosphere and pulse duration were investigated. The femtosecond laser irradiation in air showed the best bending efficiency. The femtosecond laser is applicable to laser cutting, also. Some thin sheets were cut into complicated shapes and bent by laser peen forming with femtosecond laser. The combined process allowed the production of various complicated small parts.

Keywords: Laser peen forming, Femtosecond laser, Picosecond laser, Laser cutting, Micro parts, Laser induced shock wave.

1. Introduction

The lasers are classified into continuous waves and pulse lasers. Recent improvement of laser-oscillating technology allowed the appearance of ultra-short-pulse laser, which has a pulse duration of picosecond (10^{-12} s) or femtosecond (10^{-15} s) order. They are called picosecond laser (ps laser) and femtosecond laser (fs laser) respectively. Such very short pulses show unusual processing behaviors. A laser is usually recognized as a heat source. However, the shorter pulse laser causes less temperature rise to a target. Especially, the fs and ps laser processes are often called non-thermal processes. This fact has been confirmed by a lot of researchers, for example Ostendorf (2002).

A typical application of laser to metal forming is a laser forming, which is a sheet metal forming based on the thermal stress induced by the laser irradiation. The formed sheet was usually bent, as irradiate surface is concave. This technology has been developed by a lot of researchers. For example, Sanada et al. (2009) have applied it to the mass production of magnetic head suspensions for hard disk drives. An ultra-short-pulse laser is not favorable for laser forming, due to its non-thermal property. However, it is usable for metal forming. It is because a focused ultra-short-pulse laser can induce shock waves at an irradiated target surface, as shown by Moore et al. (2001). The shock waves can deform a metal target plastically under some irradiation conditions.

Some applications of the laser induced shock waves to metal forming have been proposed with nanosecond (10^{-9} s) pulse laser (ns laser). Some researchers have irradiated ns lasers at a free end of strip cantilever and bent the strip with shock waves. For example, Wielage and Vollertsen (2011) have mounted a bending die behind the strip and performed single die bending. In contrast, Gu et al. (2013) have proposed die-less free strip bending. Vollertsen and Sakkiettibutra (2010) have proposed a sheet stretch forming, which has been called laser shock forming, using shock waves as a substitute of punch. They have formed a thin aluminum sheet into a dome

shape. Morales et al. (2011) have applied the similar deformation to the stretch forming of a small double pinned strip. Liu et al. (2010) have mounted a contoured die under a thin sheet and performed a sheet stamping by the laser shock forming. Some of these processes have been attempted with fs lasers, also. Ye et al. (2013) have adopted a fs laser for the laser shock **microforming**. Sagisaka (2008) has proposed a micro sheet stamping with a fs laser.

Another application of laser induced shock waves to sheet metal forming is a laser peen forming. The laser peen forming is based on the similar forming principle to a peen forming. The peen forming is an application of shot peening to sheet metal forming, as shown by Kopp and Hornauer (1981). The laser peen forming uses the laser induced shock waves instead of the shot impacts. O'Hara (2002) has reported aircraft skin panel production by the ns laser peen forming. A fs laser, also, is usable for laser peen forming. Sagisaka et al. (2010) have applied the fs laser peen forming to a thin-sheet-metal bending. The non-thermal processing property of the fs laser is favorable for the production of micro parts, **which are more sensitive to thermal influences**.

In the present paper, the laser peen forming with fs laser and ps laser were applied to the bending of pure titanium thin sheet, in order to find the best irradiation conditions for micro parts forming. The influences of atmosphere and pulse duration on forming properties were investigated. In addition, the authors attempted to propose a new micro process using the ultra-shot-pulse laser. The laser cutting is useful for producing various shaped small sheets. The bending after laser cutting will realize various complicated micro parts, which are effective in miniaturization of medical instruments and electronic equipment. Some trial productions of small parts were performed by the combined process of laser cutting and laser peen forming.

2. Principle of laser peen forming

When a high intensity short laser pulse is focused on a sheet metal, the irradiated top surface is ionized and removed instantaneously. This phenomenon is called laser ablation. A high pressure plasma is generated by the ionization. The plasma expands rapidly. However, the inertial force of atmosphere confines the expansion, as described by Hackel and Chen (2003). As a result, the irradiated surface is subjected to a momentary high pressure and a shock wave propagates into the sheet metal. When the sheet is irradiated in water, the large inertial force of water confines plasma expansion strongly and makes pressure larger. This effect has been confirmed by a lot of researchers, such as Fox (1974), with ns laser. The target is pressed and elongated to the lateral direction. The laser peen forming is achieved by scanning the laser and accumulating such deformations. Therefore, this process is not based on a thermal effect but a mechanical effect. In addition, it is a kind of incremental forming.

When the shock wave is strong or sheet thickness is small, the plastic deformation zone reaches to the backside of sheet and the sheet is curved, as the irradiated surface is concave. Such concave bending has been observed in a ns laser peen forming of thin-sheet-metal, as reported by Edwards et al. (2010). Ocaña et al. (2009) have analyzed the behavior by FEM simulation. The behavior is somewhat like that of the laser shock forming. However, when the shock wave is weak or sheet thickness is large, only the irradiated surface is elongated as shown in Fig. 1(a). The figure shows the case of hat shaped beam profile. Such plastic deformation zone has been shown by Ocaña et al. (2004) with FEM analysis. However, in the case of small spot, the plastic deformation zone approaches spherical shape, as shown by Zhang and Yao (2002). The sheet is curved, as the irradiated surface is convex (Fig. 1(b)). Hu et al. (2010) have confirmed these changes of bending direction by shock wave amplitude and sheet thickness. A fs laser can induce weak shock waves, which are usable for the

convex bending, with small pulse energy. The authors have applied the fs laser peen forming to the convex bending of thin-sheet-metals. The bending direction is opposite to that of usual laser forming. In addition, such thin-sheet convex bending has not been achieved with a ns laser. It is because ns laser needs much higher fluence to induced shock wave, and induced shock wave is much stronger than those by ultra-short-pulse laser. There is a threshold for fluence to induce shock wave, and the threshold increases with pulse duration, as reported by Fabbro et al. (1990). Therefore, ns laser induced shock wave generates deeper plastic deformation zone than thickness of thin-sheet and induces concave bending. These facts suggest the usefulness of the fs laser peen forming.

Fig. 1. Principle of laser peen forming: (a) Irradiation; (b) Deformation.

The fs laser peen forming has some other useful properties. It does not need dies. Therefore, it is favorable for multikind small lot production. In addition, the process is influenced by springback very little, because it is an incremental process. This property is favorable for the bending of thin spring sheet, which shows large spring back in press forming. Sagisaka et al. (2012) have shown that the fs laser is applicable to the bending of stainless steel and phosphor bronze, which are typical materials for spring.

However, the fs laser has serious troubles in the cost of oscillating system. The authors adopted a ps laser, which is more advantageous in cost, as a substitute for the fs laser. Griffiths et al. (2012) has reported the laser

forming with high-frequency ps laser of 500 kHz. High frequency pulse laser is easy to cause thermal storage on a target, and even the ps laser can cause thermal effects. However, a ps laser with low pulse frequency and high pulse energy will induce shock waves without thermal effects. Fabbro et al. (1998) have shown that the depth of plastic deformation zone is proportional to the shock wave amplitude and the pulse duration. Fabbro et al. (1990) have shown that the shock wave amplitude is proportional to the square root and two-thirds root of laser intensity under confining condition with transparent medium and under direct ablation in air, respectively. Intensity is inverse proportional to the pulse duration. Namely, the plastic deformations caused by a fs laser are based on its higher intensity, and those by a ns laser are based on its longer pulse duration. The ps laser has intermediate intensity and pulse duration. It has a possibility to induce shock waves, which exceed flow stress of material.

3. Comparison of forming properties

Pure titanium thin sheets were bent with a ps laser and a fs laser. The changes of forming properties with pulse duration were investigated. In order to clarify the influence of atmosphere, the irradiations were performed in air and in water.

3.1. Experimental set-up

The specifications of used ps and fs laser are shown in **Table 1**. The wave length and pulse frequency were different, because these specifications were originally decided for other laser processing. Especially the wave length will influence the deformation behaviors. Therefore, comparisons in this paper are not so general ones. The summary of laser processing equipment is shown in **Fig. 2**. The laser beam was transferred by some

mirrors. The pulse energy E was controlled by a neutral density filter. The laser beam was focused by a 35 mm focal lens. In case of irradiation in water, a workpiece was mounted in a transparent container filled with water.

An outline of experimental procedure is shown in **Fig. 3**. A pure titanium (JIS Grade I, 240HV) sheet was adopted as the workpiece. The sheet thickness t was 50 μm . It was cut into strips of 5 mm $\times$ 30 mm by laser cutting with the fs laser. **When the longitudinal direction of workpiece agreed with rolling direction, unfavorable large warping occurred in the workpiece. They were cut as the longitudinal direction is perpendicular to rolling direction.** The workpiece was mounted on the 3-axis motorized stage with a clamp. The hatched area of the workpiece was scanned by the laser. The scanning was performed by moving the motorized stage. Line scanning was repeated several times. The scanning speed was 5 mm/s. The scanning path is shown in Fig. 3(a). The lateral scanning pitch p_1 was decided by the pulse frequency. It was 5 μm and 4 μm for the fs and ps laser, respectively. The longitudinal scanning pitch p_2 was 100 μm . The spot diameter d was controlled by defocusing the workpiece axial to the direction of the laser beam. The focal point was defined as the original point of the defocus distance z . When the workpiece was shifted toward the beam source, z was defined as positive. The minimum d was about 40 μm for both the lasers. The bending angle θ was measured after scanning.

Table 1. Specifications of ultra-short-pulse lasers.

Laser	Wave length	Pulse duration	Pulse frequency	Pulse energy
ps	1064 nm	10 ps	1.26 kHz	$\leq 200 \mu\text{J}$
fs	800 nm	80 fs	1 kHz	$\leq 400 \mu\text{J}$

Fig. 2. Schematic diagram of experimental equipment.

Fig. 3. Schematic diagram of experimental set-up.

3.2. Experimental results

Examples of workpieces bent by the ps laser irradiations were shown in **Fig. 4**. They were bent, as irradiated surface was convex. The bending directions were same as the fs laser peen forming and were not varied by atmospheres. They show that the ps laser is applicable to laser peen forming.

Fig. 4. Examples of picosecond laser peen forming : (a) Irradiated in air; (b) Irradiated in water.

The changes of bending angles θ with defocus distance z are compared in **Fig. 5**. The θ obtained by fs laser irradiations were influenced by the atmosphere remarkably. Those in air were very large and sensitive to the z . The largest θ was obtained around the focal point. When pure aluminum workpieces have been irradiated in water, the largest θ has been obtained at the z of 0.3 to 0.6 mm (Sagisaka (2010)). However, pure titanium workpieces irradiated in water showed very small θ of almost zero. The plasma confining effect of the water was not observed.

The cross sections of grooves generated by the fs laser scanning are compared in **Fig. 6**. The grooves made by the irradiation in water are very shallow and hard to find. Berthe et al. (1997) has shown that a focused high peak power laser pulse is easy to be absorbed by transparent materials, as water. The fs laser pulses have very high peak power. They were absorbed and weakened by the water before arriving at the target. Such pulses cause insufficient laser ablations, which induce weak shock waves, at the target surface. Although such weak shock waves were enough to deform the pure aluminum, they were insufficient to deform the pure titanium. The fs pulses were absorbed by the air, also. However, the absorption was much smaller and did not influence the θ in air.

In contrast, the ps laser showed the similar changes of θ regardless of atmospheres. The ps laser pulse has much lower peak power than the fs laser pulse. It means that the absorption by the water is much smaller. Even the weakened ps laser pulses could induce enough shock waves. The θ obtained by the irradiations in water were larger than those in air. The plasma confining effect of the water would be stronger than the unfavorable effect of the absorption. The θ were insensitive to z . They will be favorable for the bending accuracy. However, the bending efficiency was inferior to the fs laser irradiation in air. The high intensity of fs laser was more effective in increasing plastic deformation zone than long pulse duration of ps laser.

Fig. 5. Change of bending angles with defocus distance.

Fig. 6. Profiles of grooves generated by the fs laser scanning ($E=150\mu\text{J}$, $z=0$) : (a) Irradiated in air; (b) Irradiated in water.

The changes of θ with pulse energy E are compared in **Fig. 7**. The experiments were performed at z , around which the largest θ was obtained in Fig. 5. Although the θ usually increased with the E , those of the fs laser irradiations in water were around zero. The large E of fs laser did not contribute to increasing the shock waves

in water. Most of the increased energy would be absorbed by the water. The best bending efficiency was achieved by the fs laser irradiation in air. It is favorable for obtaining small radius of curvature, which is necessary for micro parts.

Fig. 7. Change of bending angles with pulse energy.

4. Combined process of laser cutting and laser peen forming

A weak point of the laser peen forming is its long processing time required for the scanning. A micro part is one of favorable objects for the process, because its small scanning area reduces processing time. The fs laser, which showed the best bending efficiency, is applicable to a laser cutting. The laser cutting is one of favorable methods for preparing a complicate shaped small sheet. The bending of laser cut sheet will allow a new complicated micro part. The authors proposed a new combined process of cutting and bending with the fs laser.

4.1. Application of bending to one direction

A curling shape was tried at first. A pure titanium sheet of 50 μm thickness was cut into comb shape, as shown in **Fig. 8(a)**. The scanning was performed several times until cutting off. The scanning speed was 1 mm/s, which was slower than that of bending, because fast scanning made the quality of cut surface worse. However, when a lot of high energy pulses are irradiated at one point in a short time, even the fs laser generates thermal influences. The slow scanning is close to such condition and tends to generate thermal influences. In addition, large pulse energy E promotes the thermal storage at the irradiated portion also. The irradiation condition for cutting spoils the non-thermal property of the fs laser. When the E was too large and the tooth width w was small, the teeth were warped during the cutting, as the irradiated side is concave, due to the thermal effect. The warping should be avoided, because it made the defocus distance unstable in the following bending process. The bending deformation with the fs laser was sensitive to the defocus distance, as shown in Fig. 5. Although the processing time of cutting increased, the E should be restricted to a value, which could restrain the warping small enough. As a conclusion of some experiments, the maximum E for cutting was estimated as 150 μJ .

After the cutting, the comb teeth were scanned the surface and bent, as shown in Fig. 8 (b) (c). The scanning speed was 5 mm/s. The E was 400 μJ . The longitudinal scanning pitch p was 10 μm . The bent workpieces with various w are shown in **Fig. 9**. The minimum radii of curvature were 0.7 and 0.73mm for Fig. 9(a) and (b), respectively. The curling shapes were possible to form. However, when the w was small, the radii of curvature were not constant. The restraint of warping might not be perfect. The scattering of warping varied the defocus distance and influenced the curvatures. **Fig. 10** shows a comb shaped sheet, which was bent tooth by tooth with various scanning pitch p of 10, 15, 20, 40 and 100 μm . The smaller p realized the smaller radius of curvature. Various curvatures were possible by changing the scanning program.

Fig. 8. Combined process for one direction bending : (a) Cutting; (b) Bending; (c) After processing.

Fig. 9. Examples of curling shape : (a) $w=0.5\text{mm}$; (b) $w=0.2\text{mm}$.

Fig. 10. Bending in various curvatures ($w=0.2\text{mm}$).

4.2. Application of bending to both directions

A workpiece was cut into the shape of three-pronged fork, as shown in **Fig. 11**. After the cutting, it was bent

into S-shape by the irradiations on the front and backsides. The irradiations on the backside were performed after reversing the workpiece (Fig. 11 (c)). The reversing and scanning were repeated several times. The irradiation conditions were same as those of curling shape. The p was $10\text{ }\mu\text{m}$.

Fig. 11. Combined process for both direction bending: (a) Cutting; (b) Irradiation on front side; (c) Reversing and irradiation on backside.

An example of S-bending is shown in **Fig. 12**. The average radius of curvature was 0.62mm . This S-shape is difficult for conventional press forming, because of spring back. However, it is easy for the laser peen forming, which is free from spring back. Fig. 12(c) is comparison with a rice grain. It showed that the combined process of cutting and bending was applicable to the small parts production. However, the intervals between the teeth ends were not constant. It was caused by the unfavorable in-plane distortion during the bending. In addition, the ends of teeth were often scattered, owing to unevenness of curvatures, as shown in **Fig. 13**. This scattering would be caused by the teeth warping during the laser cutting, as mentioned above. The accuracy is the next theme for the process.

Fig. 12. Example of S-bending: (a) Front view; (b) Side view; (c) Comparison with a rice grain.

Fig. 13. Example of scattering at the end of teeth: (a) Front view; (b) Side view.

5. Conclusions

Some pure titanium thin sheets were bent by the fs and ps laser peen forming. The deformation behaviors were differed by the pulse duration and the atmosphere. The ps laser irradiations in water showed better bending efficiency than those in air. In contrast, the fs laser irradiations in water generated little deformation, due to the

absorption by the water. However, those in air showed superior efficiency, and were best for micro parts forming **among tested conditions**. The authors proposed a new combined process of laser cutting and laser peen forming with the fs laser. Some trials were performed, and the formed workpieces showed the potential of the process for micro parts production.

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Figure captions

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Table 1. Specifications of ultra-short-pulse lasers.

Figure 1

Figure 2

Figure 3

Figure 4a

Figure 4b

Figure 5

Figure 6b

Figure 6b

Figure 7

Figure 8

Figure 9a

Figure 9b

Figure 10

Figure 11

Figure 12a

Figure 12b

Figure 12c

Figure 13a

Figure 13b

Table 1

Laser	Wave length	Pulse duration	Pulse frequency	Pulse energy
ps	1064 nm	10 ps	1.26 kHz	$\leq 200\ \mu\text{J}$
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