Laser Shock Forming of Titanium Alloy and Its Simulation Using Abaqus Finite Element Software

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Abstract: ***Laser shock forming, LSF, is characterized in non-contact load ,high pressure and high strain ratio.This new forming process using laser-induced shock pressure can shape sheet metal without complicated forming equipments. The know-how of the forming process is essential to efficiently and accurately control the deformation of sheet metal.In this paper , a dynamic super-speed forming method driven by laser shock waves .The initial exploration of laser shock forming ,LSF is done through bulge testing with specimen using a neodymium –glass laser of pulse energy 10-30 J and duration 20ns (FWHM).The experiment revealed that the plastic deformation during the Laser shock forming is characterized as ultra-high strain rate and is indicated that the plastic deformation increases non-linearly with the increase of the energy density of the laser shock itself.Experiment and numerical simulation are the important approaches for forming analysis .Taken the titanium alloy (T4Ti6Al4V) sheets with a specified thickness as specimen for the experiment , the finite element analysis for laser shock forming was performed. In this paper, a Q-switch Nd:YAG laser type with a maximum power density of 4.5 GW/ cm2 was used..***

Keywords: Laser shock forming, pulse energy, sheet metal , laser-induces shock pressure, plastic deformation

1. Introduction

The recently developed laser shock forming technique has been applied to the metal industries in recent years in the manufacturing of different engineering components. Laser shock forming is a non-thermal laser method using the shock forming wave induced by laser irradiation to modify the curvature of the target .Though controllable laser beam and laser shock induced high pressure ,laser shock forming can precisely shape complex parts without pre-processing of the material.

It has the advantages of laser thermal (non-contact ,tool – free and high efficiency and precision) but its non-thermal character allows the preservation or even improvement of material properties through the induction of compressive residual stress over the target surface , a feature enabling an improved resistance of shaped metal to resist corrosion and fatigue.Plastic deformation or forming is generated through mechanical pressure or thermal variation. These pressure variations can be secured by a variety of means such as press forming ,hydro forming ,imploding detonation and so on .

The key problem for shaped metal by laser shock forming is the deforming mechanism and the relationship between laser shocking forming parameters and desired shape. The experiment.. Based on experiment ,Zhou et al [1] . proposed convex modes to explain the phenomena shown in laser peen forming of sheet metal . Laser shock micro forming was studied using both numerical and experimental methods for a thin metallic film in a one-side pinned configuration by Wang et al [2] . studied the short pulse laser micro forming of thin sheet metals for MEMS. These works studied the laser shock forming in different ways with some appropriate results .However, the occurrence of the determining mechanism in laser forming has been determined by the laser parameters , the dimensions and geometry of the specimen. The mechanisms of laser shock forming of thin sheet metal have not yet been discussed in detail in most application because of the complexity of the laser shock forming. Furthermore, there is rare application of laser shock forming on precise metal shape-righting e.g the correction of the curvature of sheet metals. Because of the concave and convex deformation with one side shock , it could be widely used to correct.In this paper, the laser shocking forming mechanism for thin titanium ally T4Ti6Al4V,sheet in one side shock configuration were studied combined with numerical and experimental method . The concave-convex mechanism for the laser shock forming is introduced and developed .By specifically selecting process parameters, the sheet metals could be formed in concave or convex shapes. The different deformation mechanisms were investigated experimentally and data obtained from experiments was then used to validate the corresponding simulation model. With the finite element analysis module the deforming mechanisms were validated Ocana et al [3].

2. The Modeling of Laser Shock Forming

2.1 Principle of Laser Shock Forming.

Laser shock forming is realized by applying a compressive shock wave generated by a laser shock on the surface of the metal sheet. Figure 1. below Shows the generation of the compressive shock wave. A high intensity pulsed laser beam impacts the surface of an energy transforming medium black paint plus K9 glass which consists of an opaque layer and a transparent layer. The thin opaque layer is vaporized immediately . This vapor and plasma absorbs the incident laser energy , then expands and explodes violently against the surface of the metal sheet and the transparent confining layer .The confining layer traps the expanding vapor and plasma and consequently causes the pressure to rise much higher than it would if the confining layer were absent Liu et al [4].

The sudden high pressure against the surface of the metal sheet causes a shock wave to propagate into the sample. The peak pressure of the shock wave induced by the laser at the sample surface is large than the dynamic yield strength of the material ,thus the metal sheet yields and deforms according to the desired shape. The peak stress of the shock wave decreases as the shock wave propagates deeper into the metal sheet .The plastic deformation of the metal sheet continues until the peak stress falls below the dynamic yield strength. As the duration of the shock wave is less than 40ns ,the forming time of metal sheet is very short (less than 80ns) and the strain rate is ultrahigh at up to 107 S^{-1}.

The same as for laser shock strengthening ,strain Hardening and residual stress remain at the surface of the metal sheet. This is the most useful effect produced by laser shock peening. Since laser shock forming is also realized under deep compressive stress ,the surface of the metal sheet will remain in residual compressive stress. Thus , this current method is a combination technique of laser shock strengthening and metal forming.Laser shock forming is a non-thermal laser forming method to adjust the curvature of the target by using the shock wave induced by laser irradiation .It has the advantages of laser thermal forming, such as non-contact, tool-free, high efficiency and high precision. Furthermore ,the non-thermal process makes it possible to maintain material properties or even improve them by inducing desirable compressive stress at the target surface ,which is very important in industry for shaped metal parts to resist cracks initialization and propagation resulting from corrosion and fatigue.

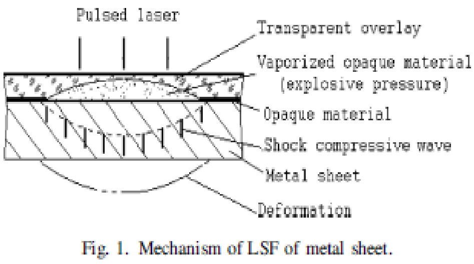


Figure 1: Schematic of laser shock forming

3. Analysis Procedure

In laser shock forming, the pressure pulse duration is very short and the load therefore is very severe, the response of the material changes rapidly and the will take much longer to become stable owing to the interaction of the various stress waves. The explicit algorithm is well suited to efficiently solve high-speed dynamic analysis, most elastic strain energy induced by high –speed dynamic deformation process has been stored in the material, which will be gradually released with the increase of the solution time .The convergence toward the stable residual stress field is extremely low and time-consuming with the explicit algorithm. Thus implementing an explicit-to –implicit sequential method will be necessary to efficiently release the elastic strain energy to obtain the final stable desired deformation .The finite element simulation of a single laser shock peening impact can be described in two major steps.

The first step is that the ABAQUS finite element analysis software method performs the short duration shock waves induced by laser shock forming until all plastic deformations in the target have occurred .After the dynamic analysis is completed , stress field of the model obtained from the dynamic analysis was input into the ABAQUS finite element analysis software. The second step is to determine the residual stress field in the target with ABAQUS software .Therefore , finite element analysis of laser shock forming is composed of the two distinct steps including dynamic analysis and static analysis Grandhi et al [5].

3.1 Finite element models of laser shock forming of Titanium alloy, T4Ti6AL4V.

In the experiment, a large number of shocks are needed to produce the large deformation of sheet metal. In this paper , the main focus is on the forming mechanism of laser shock forming itself. The forming mechanism of one shock is the same as multi-shock .Assuming that yielding occurs at the same strain rate (around 106S-1)when the peak pressure in the direction of the wave propagation reaches HEL , the dynamic yield strength (σydyn) under unaxial stress conditions can be defined in terms of HEL by

$$\sigma_y^{dyn} = \frac{1-2v}{1-v}\,\sigma_{HEL} \quad (1)$$

Table 1: Thermal physical properties of the Ti-6Al -4V alloy.

Temperature (℃)	Heat Capacity (J/KgK)	Thermal conductivity (W/mK)	Thermal expansion coefficient ($10^{-6}K^{-1}$)	Elastic modulus (Gpa)	Poisson's ratio
20	-	8.37	-	117.00	0.31
100	678	8.79	7.89	--	-
200	691	9.79	9.01	106.80	-
300	703	10.47	9.10	-	-
400	741	12.56	9.24	95.08	-
500	754	14.24	9.39	-	-
600	879	15.49	9.40	82.68	-

Table 2: Mechanical Properties and parameters of Ti-6Al-4V.

Properties and parameters	Notation	Value
Density	ρ	4430kgm^{-3}
Thermal diffusivity	λ	2.95 m^2s^{-1}
Specific heat	c	520 $Jkg^{-1}k^{-1}$
Initial yield stress for J-C model	A	452 MPa
Hardening modulus for J-C model	B	287 MPa
Strain rate dependency coefficient for J-C model	C	0.0028
Work-hardening exponent for J-C model	n	0.28
Thermal softening exponent for J-C model	m	1
The reference strain rate for J-C model	$\dot{\gamma}_{ref}$	1.7325 x 10^{-5} S^{-1}
Melting temperature rise for J-C model	θ_{melt}	1580 k
Thermal softening coefficient	α	6.5 x$10^{-4}K^{-1}$
Strain hardening coefficient	η	0.75 Pas^{-1}

Where V represents Poisson's ratio .It is reasonable to assume that the pressure pulse induced by the plasma is uniform in the entire surface of the laser spot and also the plastic strain follow the Von misses plasticity criterion , in which the dynamic yield strength δydyn is defined in Equation (1) above .

There are some methods to calculate the load.One dimensional model for the confined plasma induced by laser irradiation was deduced to numerically to predict the shock pressure profile.Study was centered on the simulation of the hydrodynamic phenomena arising from plasma expansion between the confining layer and the Titanium alloy specimen .In this paper, the laser shock forming conditions and the impulsive press were estimated because of the same load condition except of duration of the pulse .The pulse duration only effected to the load time .So , the pressure value and load wave cited the results. Geometry and meshed model（20mm*20mm*3mm）

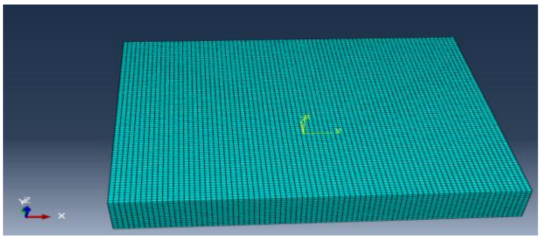


Figure 2: Geometry model

Boundary conditions and load（Bottom is fixed，Laser spot dimension 2mm*2mm） Laser spot energy（equivalent pressure）：2e9Pa

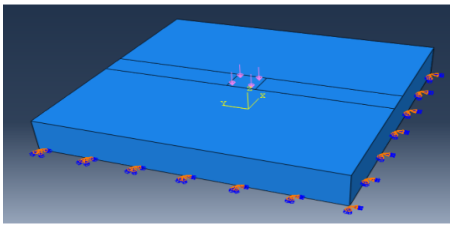
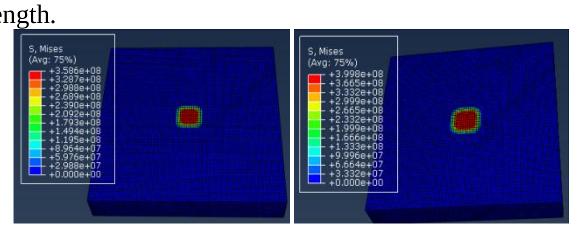


Figure 3: Loading and boundary condition

3.2 Different shock times and their results

Laser spot dimension 2mm*2mm, Laser spot energy（equivalent pressure）：2e9Pa，According to the design of the model 1 time，2 times，3 times，4 times laser spot strength.



a) 1 time shock b) 2 times shock

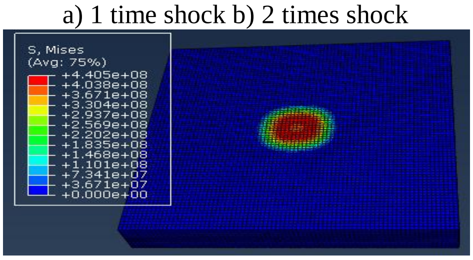


Figure 4: d）4 times shock.

Fig.5 Simulation results of residual stress for different shocking time

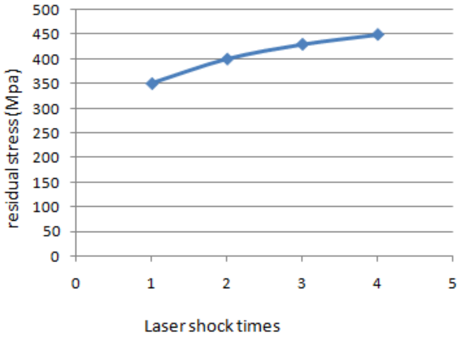


Figure 5: Change of residual stress with shocking time

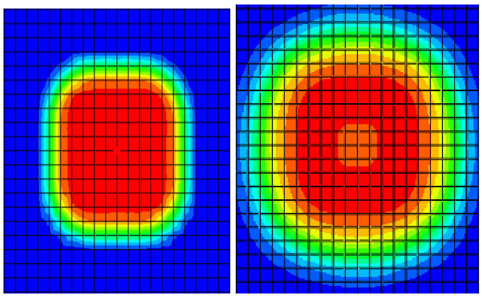


Figure 6: change of shocking area with shocking time

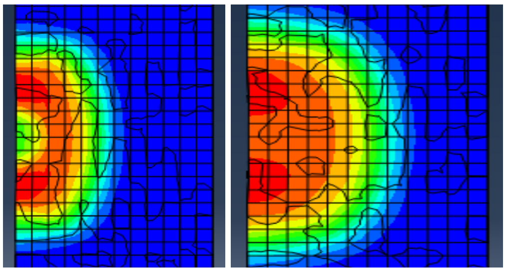


Figure 7: change of shocking area with shocking time

Conclusion

1) When the material piece was laser shocked on a given area and depth some residual stress were produced in the material of about 300-400Mpa.
2) When a material piece is laser shocked a number of times, residual stress is produced and increased on the surface. Both the area and depth all increase with the increase in the number of laser shock times.
3) Simulation results shows that for a number of shock times done on the material piece the residual stress is distributed unevenly though some results are specific to some specific cases.

3.3 Different shock energy simulation results.

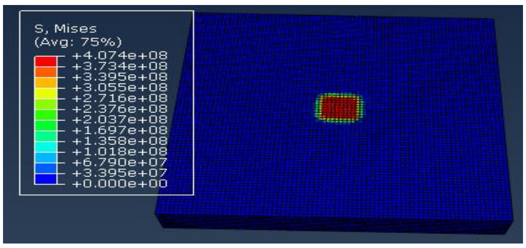
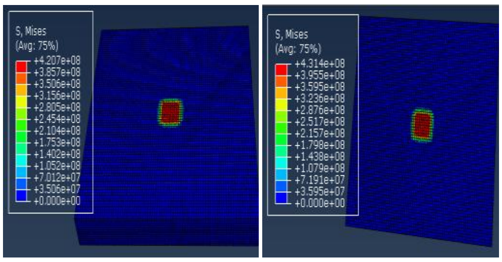


Figure 4: a）4e9pa b)4e9pa

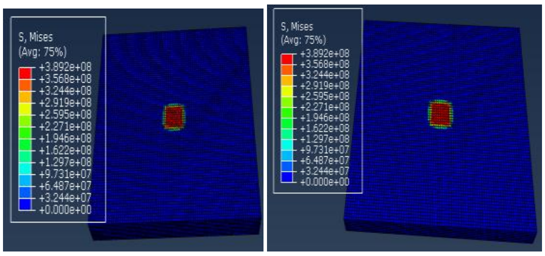


a）8e9pa b)10e9pa

Figure 9: Simulation results of residual stress for different laser energy.

Conclusion:Residual stress is produced on the surface of the material increasingly as the number of shocks is increased twice, this increases by approximately 5%. With the further increase of the laser energy impact, the surface residual stress is also increased significantly.

3.4 Effects of laser shocking on different sheet metal thickness

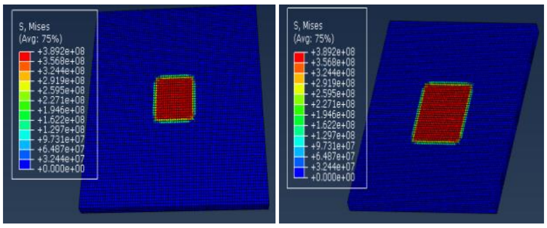


a)Workpiece thickness 3mm b)Workpiece thickness 2mm

Figure 10: Simulation results of residual stress for different part depth.

Conclusion: From the simulation results, its concluded that the thickness of the material piece does not affect the amount of residual stress induced onto the material piece surface, however laser shock pressure has some impact effect to a certain depth on the surface of the sheet metal Hua et al [6]

3.5 Effects of different spot size



a)Spot size 4mm*4mm a)Spot size 6mm*6mm

Figure 11: Simulation results of residual stress for different laser spot size.

Conclusion: During laser shocking when the impact is equivalent to the shock pressure, the workpiece surface residual stress values do not change with the spot size. However, if the laser impact energy remains unchanged the equivalent impact pressure will decrease with increasing impact area.Therefore, meeting the surface residual stress conditions and efficiency of an optimized spot size.

4. Experiment Setup and Procedures

The laser used is a high-power , Q switched ,pulsed neo-dymium-glass laser ,producing a pulse of 20ns duration and 1.064μm wavelength ,with an energy per pulse of 10~30 Joules. The profile of the laser pulse approximates to a Gaussian distribution .An energy meter (TP-1 type) is used to monitor the output energy of the laser during each shot. The laser beam is directed from the laser through an optical chain of mirrors and lenses onto the surface of the specimen being treated as shown in the diagram below.

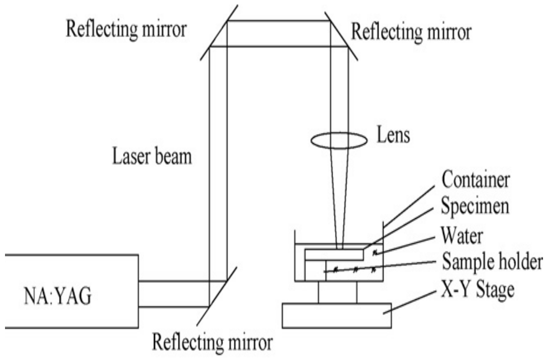


Figure 12: Layout of laser shock forming experiment setup

The laser system Q-switched neodymium (Nd)-glass laser with the following parameters , λ = 1064 , £=0.75J , radius =1mm and tFWHM = 7 ns .The specimen of titanium alloy of $50mm^2$ and 2mm thick were prepared . Each experiment was carried out on a different area dimension i.e $16mm^2$, $32mm^2$ and $64mm^2$ areas and different results and effects were obtained as discussed below.Titanium alloy sheet metal pieces were used in the experiment with three different size square areas onto which the laser beam was focused thus a 4mm x 4mm , 6mm x 6mm and a 8mm x 8mm square area. All the three sheet metal pieces were of 2mm thickness and 50mm x 50mm whole blank material.

5. Results and Discussion

5.1 Laser Energy versus Bulging Profile

Figure 13 below shows the typical profile of the bulging obtained by a single laser shock , the displacement of the cross-section profile being obtained using the Taylor Hobson contour meter. As a result of the laser shock , a bulge forms in the metal sheet in the form of a spherical cap , it is circular in shape with a depth ho at the center. The depth of bulging is dependent upon the intensity of the laser pulse. As the incident pulse energy is increased , more ablation occurs the peak pressure of the resulting bulge increases and consequently the strain energy in the metal sheet increases , so that the bulging height is increased Zhao et al [7].

Using a spherical cap assumption , the profile of the bulge can be determined by relating various parameters including the radius of the top and the bottom opening d_1 and d_2 ; the thickness of the metal sheet ,δ ; the metal sheet modulus ,£ ; the radius of the curvature of the bulge , R ; Poisson's ratio of the metal sheet , V ; and the power density of the laser spot.

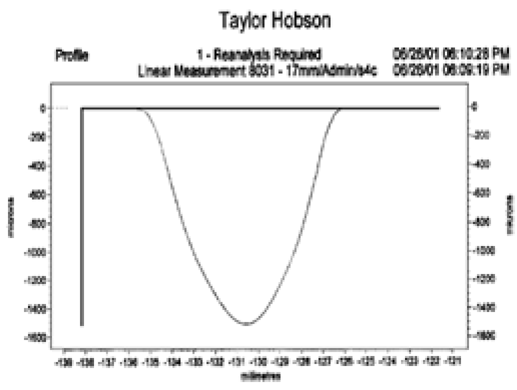


Fig. 3. The typical cross-section profile of the bulging tested by Taylor Hobson.

Figure 13: Taylor Hobson diagram

The normal maximum displacement which equal the depth ho of the bulge at the center at the center has a fixed relationship to d_2 and R. The curvature of the bulge R is the reverse of the radius of the spherical cap .For a certain sample and boundary condition , the curvature of the bulge is a function of the pulse energy . As the incident pulse energy is increased, the peak pressure of the resulting bulge increases and consequently the curvature of the bulge decreases linearly.

6. Residual Stress Analysis

The surface distribution profile of residual stresses is like its bulging shape a spherical cap. At the apex of the cap the residual stress reaches a maximum .As the distance to the top point increases , the bulge outside edge it tends to spread to the original surface . If the thickness of the titanium alloy metal sheet is above a threshold or the laser energy intensity is above a threshold,the residual stress may be compressive Shen et al [8]Thus, it can be concluded that laser shock forming can shape thick components without inducing unwanted tensile stress at the metal surface.

7. Conclusions

In this paper, we have researched, experimented and presented the technique of metal sheet forming, in this case used titanium alloy and carried out a series of bulging tests experiment, an ultrahigh strain rate dynamic forming process utilizing laser shock waves being established.

In conclusion, laser shock forming is a mechanical process , not a thermal process realized by applying a compressive shock wave generated by laser peening on the surface of the metal sheet , being a combination technique of laser shock strengthening and metal forming both of which introduce a compressive residual stress on the surface of the work piece . The investigation shows the potential of the process for becoming flexible manufacturing process with excellent reproducibility and very short manufacturing time.

Even more importantly, an uncovered but significant research field is found including deformation mechanism, mechanical response, ductile –brittle transition, phase transition, dislocation, failure behavior etc. of materials under ultra high strain rate. This not only provides large new research areas but also implies many more applications.

8. Acknowledgements

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