

Preliminary study on theory and experiment of photo-mechanics manufacturing and detecting technologies based on laser thermal stress

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Abstract: Mechanics effect of laser thermal stress is a new manufacturing technology, which uses thermal stress by high power laser acted on the surface of metal material to produce stress field. The technologies such as sheet metal formation by laser thermal stress, measurement by laser scratching and measurement by XRD (X-ray diffraction) are formed based on mechanics effects of laser thermal stress. The mechanisms of sheet metal formation by laser thermal stress, measurement by laser scratching and measurement by XRD are analyzed, and the theory of photo-mechanics manufacturing and detecting technologies based on laser thermal stress is originally put forward, whose experiment is primitively researched, and the manufacturing theory by mechanics effects of laser thermal stress is established.

Key words: photo-dynamics manufacturing; sheet metal forming by laser thermal stress; laser scratching; X-ray diffraction (XRD)

1 Introduction

According to the differences of photo-dynamics effects from the interactions between laser and materials, laser technologies can be divided into two major types in the applications of machine building as follows: 1) Material properties can be improved by laser shock processing (LPS), which is referred to as mechanics effect of laser shock wave; 2) Materials can be processed to remove or improve material properties by laser thermal effect, which is often referred to as laser induced thermal effect. Sheet metal forming by laser induced thermal stress is a new technique in the flexible forming, which is a forming method by inducing sheet metal forming asymmetric temperature field. Traditional scratching and laser detecting are synthesized by XRD, which uses non-contact laser loading instead of diamond indenter. Acoustic emission method in scratching is taken place by XRD, and the result is quasistate interfacial bonding strength of the coating, which accords with the quasistate working environment in the coating-substrate. The evaluation of bonding strength of the coating-substrate is expressed with the coating stress, and photo-dynamics detecting technique comes into being on the foundations of the above investigations.

2 The forming by laser thermal stress

The forming by laser thermal stress is a kind of flexible forming technique, which is used thermal stress to replace the outside force and realize sheet metal forming^[1]. Laser beam with certain defocusing length irradiates on the sheet metal surface, and scans the surface with opposite speed, accordingly temperature gradient in its thickness direction is formed, and the sheet metal produces permanent plastic deforming by laser thermal stress. Because laser energy is easily controlled, the forming is not suffered from working environment and workpiece shape restriction, therefore the forming by laser thermal stress is accurately controlled by optimizing craft parameters^[2].

When sheet metal is formed by laser thermal stress, material thermal physical performances and parameters are different, and the forming mechanisms are different^[3]. According to the difference of craft terms and the formed temperature during the forming by laser thermal stress, the forming mechanisms can be divided into 4 types, such as temperature gradient, elastic, warp and incassation mechanism^[4].

When the surface of bending sheet metal is irradiated by laser beam with high energy density, which produces strong temperature gradient in its thickness direction, the thermal expansion of the upper surface is

larger than that of the bottom, and the reverse bending is produced consequentially in the direction of laser beam.

When laser beam irradiates on only a point or partial piece, thermal expansion of the heated zone is larger than that of temperature gradient, because of big expansion potential, it will dissolve plastic compression produced by ambient cold materials, and only leaves elastic expansion compression. And the compression forms internal stress, which makes the sheet produce small rebound bending.

When the scanning diameter of laser beam is bigger, laser feed speed and intensity is lower than that of temperature gradient in the heated zone, the temperature gradient in the material thickness direction is lower, which causes the whole heated zone produce compressive stress owing to ambient material restrictions. And at the same time, because of the temperature going up in heated zone, the material stress decreases. When compressive stress exceeds yield stress, the heated zone will produce wrinkle of plastic deforming, which causes the sheet metal bend.

When scanning diameter of laser beam is very small, and the feed speed is very slow, the sheet is evenly heated in its thickness direction, the temperature gradient is very small, and does not produce the reverse bending. Because the material thermal expansion in the heated zone is restricted by ambient cold material, and forms high internal compressive stress, and the heated width is very small, which is apt to compress, accordingly the incassation effect is formed in its thickness direction. The result of incassation makes the heated zone shorten, and the sheet metal thickness in the heated zone will increase^[5].

3 Measurement of bonding strength of the film interface by laser scratching

The film technique is one of the important means to increase material surface performances^[6]. When the film technique is adopted, the special performances of the parts such as surface resistance corrosion, resistance fatigue, resistance radiation, and etc. may be increased, which can reduce the cost of resources and energy, and lower the production cost^[7]. Currently, the film technique is already extensively used in the fields such as aviation, spaceflight, machine building and etc., the bonding properties of the film-substrate interface that is a basic term to develop the film functions is an important index that affects the surface film quality^[8], and decides its dependability and service life.

3.1 The measuring principle

Laser scratching of measuring interfacial bonding strength of the film is utilized by IR (infrared) laser directly loading on the film surface by quasi-static heating. The temperature field is formed in the film-substrate with thermal conduction. Because of the difference of thermal expansion coefficients of the film materials, thermo-stress is formed in the film interface. When thermo-stress exceeds the certain value, the interface produces debonding, and further cause interface cracks spread, elastic instability warp of the debonding layer, penetrating crack initiation and spreading, till the debonding layer rupture and peeling off, such as Fig. 1 shown.

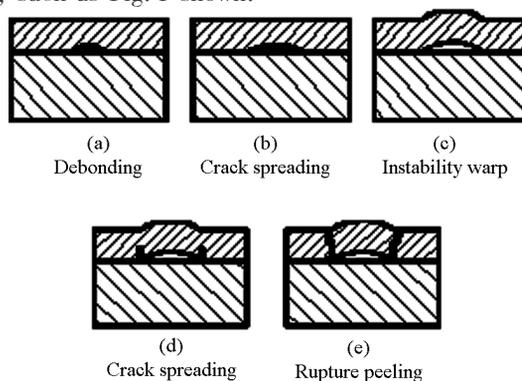


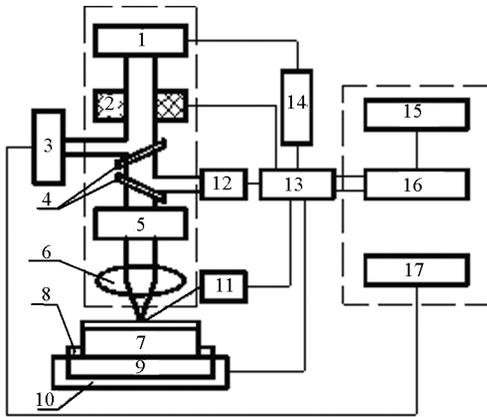
Fig. 1 Diagrammatic sketch of the coating interface failure

3.2 The measuring device

The equipment of IR laser scratching (Fig. 2) is composed of 5 parts shown as follows: 1) Scratching system is made of scratching laser and light path system of incidence; 2) Clamp-worktable system is made of feed machine, worktable, clamp and sample, and etc.; 3) The system of measuring and diagnosis with XRD; 4) Control system is made of controller, laser power supply and etc.; 5) Data handling system is made of computer signal disposal. Laser beam directly radiates on the film surface by the path system of incidence light, which is made of adjustable fiber cable, light-transferring system, focus lens, and etc. Laser energy increases continuously by laser power and controller, at the same time, the controller makes feed system drive movement of the clamp and sample on the worktable, until the interface of the film-substrate is damaged, and stress parameters are inputted into signal analysis and processing system, and the critical point, which is damaged on the film-substrate interface, is determined.

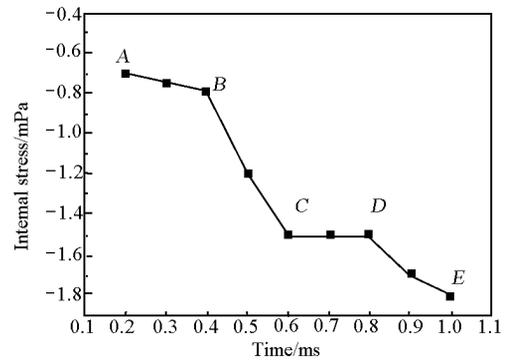
3.3 Token parameters of interface failure

The film surface is heated quasi-statically by laser, and temperature field is produced. The materials

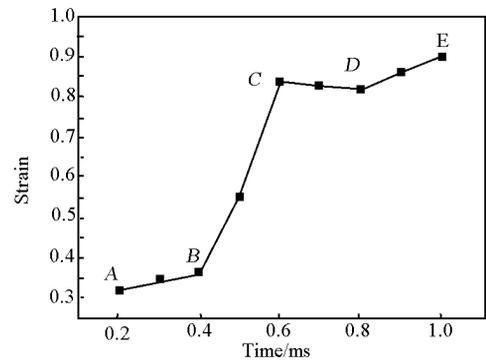


- 1—Scratching laser; 2—Adjustable optic cable;
- 3—Photodiode triggered switch; 4—Splitters;
- 5—Light guiding system; 6—Focusing mirror;
- 7—The sample; 8—Clamp; 9—The worktable;
- 10—Feed mechanism; 11—The system of measuring signal;
- 12—The measuring module of measuring laser beam parameters;
- 13—Controller; 14—The module of controlling laser power supply;
- 15—Printer;
- 16—Computer; 17—Oscillograph

Fig. 2 The equipment of measuring bonding strength of the coating with laser scratching^[9]



(a) Internal stress vs. time in radius direction



(b) Strain vs. time in the thickness direction

Fig. 3 The changed laws of node stress and strain in the film center^[9]

are expanded by thermal and limited by laser inflection zone and substrate materials, there is compressive stress in the film-substrate. The difference of thermal coefficient and temperature filed causes the difference of strain field, and further causes boundary material offset, slide and other defects. When the stress and strain of the film-substrate interface achieves a very value, there will appear cracks. The expansions of the cracks make the boundary debond. If there are initial cracks in film-substrate interface, the cracks will extend, and lead to debonding.

The temperature distribution decreases gradually in its thickness direction, and the temperature of external surface is high, thermo-stress is big, deformation is big too, so this will produce two trends^[9]: 1) The debonded layer is tended to bend outside, i. e. warp instability of the debonded layer is behaved as forming convex drum, which is processed by thermal stress on the film surface. 2) When the debonded layer is warp instability, it has two inward and outward deforming tends, but inward warp is restricted by the substrate materials, it is only inward warp and forms convex drum. When critical condition is satisfied, elastic warp instability of the debonded layer occurs. The stress of the center node and normal displacement are increased rapidly (such as *BC* segment shown in Fig. 3). After the debonded layer is warp instability, stress will occur in the interface of the debonded layer and the substrate, and decrease stress in the interface. The stress

and normal displacement of the center node will tend to decrease or fix (such as *CD* segment shown in Fig. 3). Because of effects of interfacial bonding energy, the film intension, crystal lattice defect and etc., the cracks penetrate when the warp of the debonded layer expands a certain degree. The penetrated cracks will further expand, and compressive stress of the center node will fluctuate, and normal displacement of the center node will increase (such as *DE* segment shown in Fig. 3), finally the debonded layer peels off, and forms a nick on the film surface^[6]. During various phases of the film-substrate, interfacial cracks spreading, elastic warp instability, the penetrated cracks spreading, the debonded layer peeling off and etc., residual stress of the center node will bring corresponding variety. When the debonded layer is warp instability, residual stress of the center node occurs break, therefore residual stress of the center node is a measured signal of interfacial bonding status, the point (i. e. *B* point) that is a peak value of residual stress occurred break is a critical point of interface damage, where bonding strength is expressed with laser param-

ters, residual stress, material parameters, and etc.

4 Measurement of interfacial bonding strength based on XRD

Residual stress is a widespread phenomenon during coating preparation, which is a main factor that influences on its bonding strength. A lot of elastic energies are saved up in the coating with residual stress, which acts on the coating-substrate interface. When elastic energy is very big, the coating will be cracked and even peeled off, which makes the coating-substrate fail. In all kinds of nondestructive methods of measuring residual stress, XRD has many advantages such as high accuracy, non-destructive, convenient, and etc., which is one of the most dependable and practical measuring technique^[10,11].

4.1 The measuring mechanism of XRD

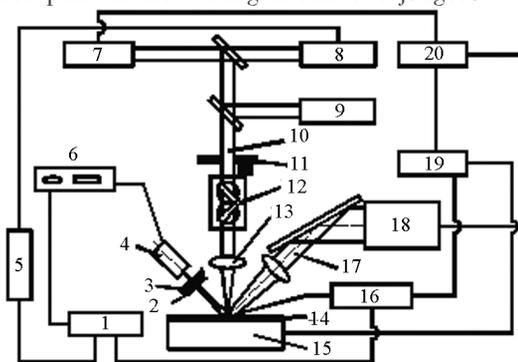
When the traditional method of XRD is applied to measure residual stress of the coating, there are many difficulties^[12], such as lower diffraction strength, serious diffraction breadth because of big stress, bending and concussive $2\theta\text{-}\sin^2\psi$ curve, material texture, and etc. The XRD method has been put forward now, such as *S-B* grazing incidence, grazing incidence heeling method, etc^[12,13]. Residual stress of the coating interface is constituted by two parts^[14,15] 1) Because thermal expansion coefficients are different, the coating comes into being thermo-stress when it is cooled from high temperature to room temperature. 2) Internal stress is formed of non-hot influenced zone, and accelerates thermo-couple action of the coating, it is a hypersensitive factor of the coating damaged because of residual stress. Residual stress of the coating is a function result of the coating growth and deposit circumstance. Its properties and sizes are correlative with the coating-substrate material, deposition technology and condition, and later processing craft. The forming of the coating stress is a complicated process, and it is formed and developed step by step during the coating growth and aging course.

The changed laws of the coating-substrate stress under laser thermal radiation is measured with XRD, and theory of measuring interfacial bonding strength is researched. Its originality is shown as follows^[16]: 1) The diamond indenter in scratching test is replaced by IR laser radiation to load, and the theory of measuring bonding strength under laser radiation based on XRD is established, and its results have a higher dependability and credibility than the traditional scratching. 2) Dynamic loading with short pulse and high strain in laser spalling is replaced by pulse laser with quasi-static radiation, the new craft of measuring interfacial quasi-

static bonding strength in engineering is formed by laser radiation. 3) Interfacial bonding strength is measured with XRD, and bonding strength is expressed with residual stress of the coating-substrate, and a new method of measuring bonding strength of the coating is established.

4.2 The experimental device

Interfacial bonding strength is researched with XRD, and the theoretical model is revised and perfected. The quantitative relations among residual stress, laser beam parameter, physical parameters of the coating-substrate are established, and residual stress of the separated point is solved further. Finally quasi-static bonding strength of typical coating-substrate systems is measured with XRD. Its quantitative relations are researched according to the typical database of the coating interfacial dynamic bonding strength and scratching, accordingly the theory and method of measuring bonding strength with XRD is established. The detecting device based on laser scratching is shown as Fig.4. When the coating surface is radiated on the coating surface directly, laser energy is continuously increased by laser power and control module, at the same time, the controller makes the feed system drive the clamp and sample on the worktable to move, accordingly the coating surface is radiated by laser until the interface fails. The coating stress parameters are measured by XRD stress analyzer, and are inputted into signal analysis processing system, and the critical broken point of the coating interface is judged.



- 1—Computer; 2—Slit pore; 3—Filter; 4—Photoelectric detector;
- 5—Oscillograph; 6—Signal amplifier; 7—YAG laser;
- 8—Photodiode; 9—Power meter; 10—Laser beam;
- 11—Breaker; 12—Attenuator; 13—Lens; 14—Coating sample;
- 15—The numerical control worktable; 16—XRD stress analyzer;
- 17—The detected beam; 18—He-Ne laser;
- 19—Controller; 20—Laser power supply

Fig. 4 The device of measuring of bonding strength of the coating with XRD^[16]

4.3 The characteristics of XRD

Quasi-static bonding strength of the coating inter-

face such as single layer and multi-layer coating, organic macromolecule coating, optics coating, decoration coating, soft film, etc. is measured accurately, service life and failure model of the coating under particular terms such as hardness tool coating, optics film, etc. is estimated, and the coating preparation craft is further optimized, which controls the coating quality. The technological parameters such as residual stress, bonding strength, coating thickness and coating morphology are measured on line, which may control the coating quality, and the actualities such as preparation, measuring, discarding, recoating, etc. are changed. The experimental method of measuring the coating quantitative bonding strength based on XRD are established and bonding strength of single layer and multilayer crystal coating is measured accurately. Other problems such as interfacial strength of metal-based composite materials, matching effects among electronic materials, bonding strength of metal materials, etc., are solved.

5 Conclusions

1) The residual stress distribution of metal sheet is controlled by laser thermal effects, which may quantitatively control of material forming by thermal stress.

2) The theory and experimental device of laser scratching are built, and bonding strength of the film is expressed by laser beam parameters, physical parameters, detecting parameters, and etc.

3) The detecting system of measuring bonding strength of the coating interface based on XRD is established, and bonding strength of the coating interface is expressed with its residual stress, which is used to measure bonding strength of the coating nondestructively.

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