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Study of anti-laser irradiation performance of shot-peened 40CrNiMoA alloy steel

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ABSTRACT

In this paper, shot-peening treatment was introduced to reinforce an alloy surface to protect it from laser irradiation, and experiments were carried out on 40CrNiMoA alloy steel. Macro-mechanical properties were studied and compared before and after both shot-peening and laser irradiation by conducting tensile and hardness measurements. Experimental results showed that the shot-peened alloy showed better mechanical properties after laser irradiation when compared to the alloy without shot-peening treatment. The enhanced ability of the shot-peened alloy for anti-laser irradiation was explained as due to the large residual compressive stress distributions over the shot-peening layer greatly reducing the thermal shock effect introduced by the laser. On the other hand, the growth of microstructures in specific shape absorbed the thermal energy during irradiation, giving a higher probability for the alloy to resist damage.

1. Introduction

In the last few decades, laser weapons [1,2] have become matter of increasing interest due to their high power and directionality, recently playing an important role in high-tech warfare. Since the 1970s, research has been undertaken into the study of metal failure modes induced by super-lasers using short pulses within the order of nanoseconds. In 1973, Fox and Barr [3] demonstrated this by irradiating an Aluminum target of 1 mm thickness with a 1 ns pulsed Nd:Glass laser. Bartholomeusz [4], Thompson et al. [5], Zhou et al. [6] and Long and Zhou [7] have all carried out theoretical and experimental studies on this topic and have already achieved some success. However, the tearing or impact failure of a target by a super-laser currently only involves laboratory based and experimental high-peak, short-pulse, macro-energy lasers.

As the target of a laser weapon is typically an aircraft traveling at high speed and under a working load close to safety tolerances, it would most likely be destroyed by a medium power laser. In addition, local stresses in some components are very close to a critical state of damage which may induce failure of the structure after continuous irradiation. This can, for example, result in a high-speed aircraft suddenly crashing under a relatively small externally applied load from an intense laser irradiation creating thermal–mechanical failure.

Taking all of this into account, some researchers are focusing on the study of failure modes of bearing structures under a continuous medium-density power laser. Since the 1970s, Adachi et al. [8] and Eliezer et al. [9] have carried out much research in this area, including studies on the failure modes of preloaded cylindrical shells and panels. Li et al. [10] and Chen [11] have analyzed and discussed damage mechanisms of internally preloaded metal structures induced by laser irradiation. They also carried out representative demonstration experiments using a continuous CO_2 laser and concluded that the evolution of micro-damage at high temperature is the primary factor for fracture origin during failure; the generation and development of internal micro-cracks may also result in a macro-thermal softening of the structure. Due to the sharp decrease of strength under the effects of thermal shock and pulse load induced by an intense laser, structures or devices under a working load tend to fail due to irradiation effects despite being far below that of the structural strength. Hence, to protect such structures from irradiation or enhance its anti-laser resistance, it is very important to explore failure mechanisms under thermal-mechanical effects, thus purposefully reinforcing the metals.

As a high power laser primarily interacts with the surface of a target, the processing of the metal surface to enhance its physical and mechanical properties is of great importance [12–14]. Current

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research in this area has mostly focused on adding a thermal barrier coating or transferring a reflective film to the surface in an effort to reduce the irradiation intensity, which has achieved some success [15,16]. However, there are still some disadvantages for such techniques; for example the barrier can be easily peeled off from the bonding surface by the returning wave of the laser irradiation and the film is not always strong enough to resist the resultant thermal impact and stress shock. The development of new techniques to reinforce the metal for anti-laser irradiation is hence very worthwhile.

Shot blasting [17,18], or pre-stressed shot-peening treatment, is an established and widely used surface strengthening technique, i.e. a surface nanocrystallization technique, in the machining field and is carried out by spraying fine steel balls or ceramic particles of 170–630 μm diameter onto a metal surface, which is functionally equivalent to a cold forging process, to form a positive and compressive stress distribution on the surface resisting against the generation and evolution of micro-cracks. Following a literature review, the strengthened surface usually exhibits greatly improved physical and mechanical behavior, such as high yield strength and plastic limits [19], high surface hardness [20] and abrasion resistance [21], anti-oxidation at high temperatures and corrosion resistance [22,23], and long service life and thermostability [24–27].

Since the impact of shot-peening has a gradient distribution along the thickness of the layer, its mechanical properties are also distributed in a similar fashion, as shown in Fig. 1. The grain size crossing the thickness of the metal is also distributed in a gradient fashion with the minimum next to the shot-peened surface, then increasing over the thickness of the layer. Therefore it can be inferred that the shot-peened layer, where no intrinsic interface exists, cannot be removed by the shock wave or shock stress compared with thermal barriers, where an interface does exist. The metal of the shot-peened layer is also much stronger in resisting thermal melting. Even if it is melted by extremely intense laser irradiation, it can still stick to the substrate for unique continuity of the metal, with no desquamation as a whole. Nevertheless, no research on the physical and mechanical properties of strengthened surfaces by shot-peening for anti-laser irradiation exists. Whether the nano-crystallization of the surface enhances the metal for anti-laser irradiation still remains for further discussion. If so it would be a great improvement indicating that much research on anti-laser irradiation techniques should be carried out due to its practical significance.

Considering all of these aspects, this paper is intended to give a study on effect of anti-laser irradiation of shot-peening treatment. Experiments were carried out on 40CrNiMoA alloy steel before and after both shot-peening and laser irradiation by conducting tensile and hardness measurements. And analysis of the effect mechanisms was established through evaluating the effectiveness of residual stress using moiré interferometry, and observing the changes of microstructures.

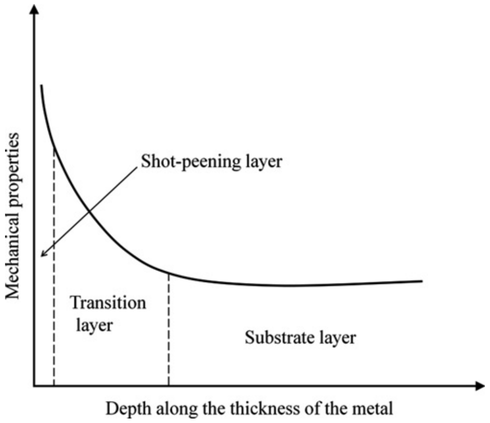

Fig. 1. The mechanical properties along the thickness of the shot-peened surface of the metal.

2. Experimental procedure

2.1. Specimens preparation

As a highly quenched and tempered steel, 40CrNiMoA alloy steel always exhibits a high yield strength and good toughness which allows it to be used in a large number of critical impact applications, such as the crankshaft and drive shaft in some machine tools. The main chemical composition of the steel is listed in Table 1 [28].

The shape and dimensions of the tensile specimens were designed according to previous literature [29]. The appearance of the specimens is as shown in Fig. 2.

After the ultrasonic shot-peening (USSP) processing [17], the alloy surface was largely plastically deformed. To estimate the ability of the strengthened surface, it is always very important to set a thickness of the shot-peened layer which, in this paper, was designed to hold about 20% of the specimen in thickness. By using a metalloscope observation, the average thickness of the shot-peened layer was accurately determined to be 190.7 μm.

2.2. Laser irradiation on the specimens

A CO_2 laser (type: PRC-3000) was used to irradiate both the shot-peened and pure substrate specimens using the following parameters; a work power of 1600 W, low-order mode, continuous beam, irradiation time of 1 s, and an irradiation diameter of 4.5 mm.

2.3. Mechanical loading on the specimens

An electric universal testing machine (type: WDW3050) was used to apply a mechanical load on the prepared tensile specimens with a loading speed of 0.2 mm/min. Before this, the initial strain of preloading was measured by an YJ-Z static digital strain gage unit. Two bold gage points were marked on the specimen surface, which were then tracked and recorded continuously by a CCD camera. By using a Gray Weighted Centroid (GWC) algorithm, [30] the longitudinal displacement of the specimens and the strain–time curve can be evaluated.

2.4. Hardness measurement

A HR-1500DT Motorized Superficial Rockwell Hardness Tester was used to measure the hardness of each specimen, and a diamond indenter and C Ruler were selected. The initial test force was set to 98.07 N and the total test force was set to 1471 N.

Table 1
Composition of 40CrNiMoA alloy steel (wt%).

	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
GB3077 ~88	0.37 ~ 0.44	0.17 ~ 0.80	0.50 ~ 0.80	≤ 0.025	≤ 0.025	0.60 ~ 0.90	1.25 ~ 1.65	0.15 ~ 0.25	≤ 0.20