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Laser heating induced plastic deformation in a pre-elastic-stretched titanium alloy strip

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ABSTRACT

Experiment was carried out to reveal the plastic deformation of pre-elastic-stretched titanium alloy strip partially subjected to localized heating via Laser beam irradiation. The temperature profile in the strip under Laser beam irradiation was computed with finite element method. The strain redistribution and localized plastic deformation were analyzed by a one-dimensional model. The results indicate that both the pre-strain level and the ratio of the length of heated range to the total effective length of the strip influence obviously the final plastic strain.

1. Introduction

Temperature elevation could improve the ductility of most materials by decreasing the resistance to dislocation sliding etc. Therefore many manufacturing processes adopted heating in metallic alloy plate forming [1–3]. Attracted by the advantages of Laser as a heating source, many investigations have been conducted on the forming mechanism by pure laser heating [4,5]. In these processes, the thermal loadings are commonly exerted on the work pieces no latter than the mechanical loadings or even without the mechanical loadings. A new process technique of Laser aided pre-stressed forming was reported to be successfully applied to sheet forming, in which the plastic deformation is developed in a pre-elastic-bended panel by Laser beam heating [6]. In such a process, the non-uniform heating is used to induce plastic deformation in these discrete small regions of the pre-elastic-stretched panel skin. This technique may make full use of the controllability of the heating source to obtain plastic deformation at specific regions [7]. Although the mechanism on the plastic deformation under the thermo-mechanical circumstance need more detailed description.

Actually, a great many of pre-stressed structures may practice non-uniform temperature elevation due to external localized heating [8,9]. In a structure subjected to tensile stress high enough, the plastic strain will be developed and concentrated on some region wherein the material weakening arises due to the defects or other disturbances, which will in turn enhance the material weakening. The plastic deformation concentration of the materials under pure mechanical loading was extensively discussed by many literatures. For instance, Doghri and Billardon [10] investigated the localized plastic deformation for rate-independent plasticity, Haddag et al. [11] set up a large deformation anisotropic elastic–plastic model to describe the plastic strain concentration, Kobayashi [12] analyzed this phenomenon via a proposed theory of ultrasonic wave velocity, Bychkov and Karpinskii [13] studied the localized plastic behavior in a thermo-viscoplastic rod in dynamic tension by the methods of linear perturbation analysis. Considering that fact that temperature elevation is also a kind of disturbance, the plastic strain concentration of the structure subjected to both thermal and mechanical loadings also attracted many interests. In particular, Elfmark [14] revealed that plastic instability shall develop in a hot tensile test specimen, in which the specimen was assumed to be evenly heated. Bychkov and Karpinskii [15,16] investigated the plastic deformation concentration phenomena in a tensioned thermo-viscoplastic rod heated by an electric current and found out that the action of the joule heat developed by the alternating electric current influenced obviously the plastic behavior in the rod. Fressengeas and Molinari [17] studied the effects of thermal softening on ductility of the material with a one-dimensional model for uniaxial tension and described the dynamic growth of the voids and the adiabatic decrease of ductility. Benallal and Bigoni [18] investigated the influences of temperature elevation due to thermo-mechanical coupling effect on the plasticity of some inelastic material. Basically, these researches mainly

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focused on the plastic deformation behavior in the rod subjected to uniform heating or under the action of the heat converted from the strain energy due to thermo-mechanical coupling effect.

This work is focused on such a problem to describe the plastic deformation of pre-elastic-stretched titanium alloy strip subjected to Laser heating. First, the experiment was carried out to verify the plastic deformation arising in a pre-elastic-stretched strip sample subjected to local heating via Laser irradiation. Then, the temperature characteristic was analyzed numerically. Finally, the strain redistribution behavior was discussed by a one-dimensional model and the effects of the various parameters on the strain redistribution and final plastic strain were investigated.

2. Experiments

The equipments as shown in Fig. 1(a) were used to stretch the strip and locally heat the strip. The Nd-YAG Laser was adopted to partially irradiate the sample to realize the non-uniform temperature elevation, of which the effective power is about 48 W evenly distributed over the circular region of radius 3 mm. The initial strain was controlled to be low enough to ensure that no plastic strain arises in the pre-elastic-stretched sample.

The geometry of the specimen is shown in Fig. 1(b), of which the thermo-mechanical parameters are listed in Table 1 by referencing to the available database and literatures [19,20]. In Fig. 1(b), the test points CH1 and CH2 are located on the back side of the specimen relative to the irradiated surface. The virtual test point CH3 represents the center of the irradiated region, for which the temperature history will be investigated only by numerical simulation.

The experiment mainly includes such three stages. That is:

1st step: Stretch the sample to some level of elastic deformation and keep that elastic deformation;
2nd step: heat the segment of little length to some temperature level and then remove the heating via shutting down the laser;
3rd step: Unload the mechanical stretch after the sample is cooled to be identical to the ambient.

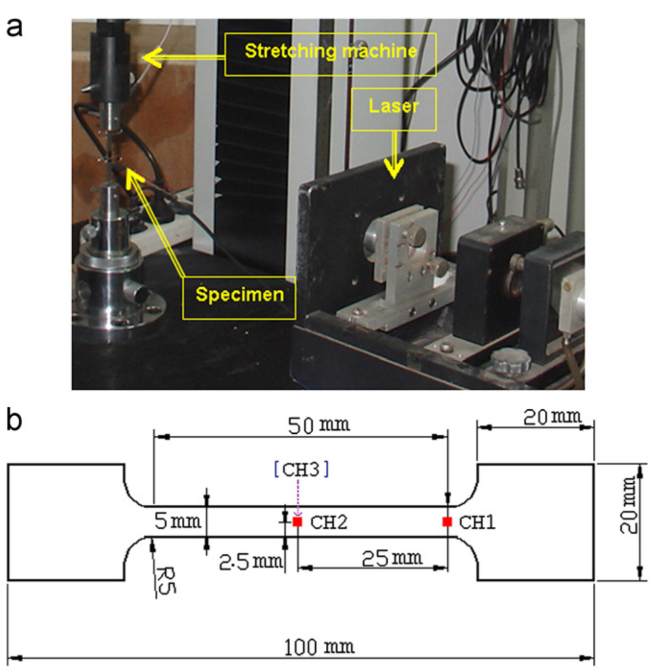

Fig. 1. (a) Photo of the experimental equipment and (b) sketch of the specimen.

Fig. 2 presents the temperature histories of the test points CH1 and CH2, which shows that the temperature at the point CH2 changes very slightly throughout the test. This means that only the heat conduction within the central strip of length about 50 mm needs to be considered in the computation to obtain accurate enough theoretical description of the temperature profile in the specimen.

The front view of the final deformation of the sample is shown in Fig. 3, which indicates an obvious necking around the center of the heated region.

The side view profile of the necked region is magnified shown in Fig. 4(a), in which one can see that the plastic strain concentrates around the center of the heated segment. Further, it is indicated that there exists a trapezoid plastic deformation zone with the bottom base of length 4.3 mm being located at the heated side of the specimen while the top base of length 2.3 mm at the other side. Moreover, the macroscopic defects already can be found at the unheated side. In detail, voids arise around the unheated side of the sample within the necked region as shown in Fig. 4(b). Such characteristic of the distribution of deformation

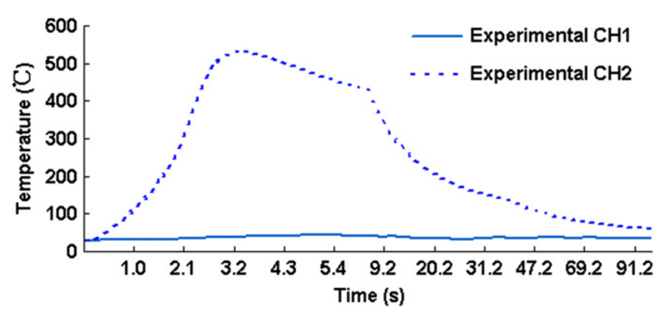

Fig. 2. Temperature histories of the test points CH1 and CH2.

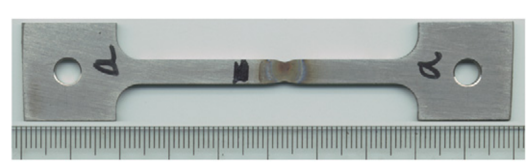

Fig. 3. Global profile of the processed specimens.

Table 1
Temperature dependent mechanical properties.

T (°C)	25	93	205	315	427	538
α ($\times 10^{-6}$ K^{-1})	4.90	5.0	5.18	5.35	5.52	5.69
E (GPa)	110	105	99.1	93.3	86.9	70.6
σ_s (MPa)	916	827	695	594	480	313
ε_s ($\times 10^{-3}$)	8.33	7.88	7.01	6.37	5.52	4.43
E_T (GPa)	35.5	30.2	30.2	32.3	34.5	31.2
v	0.3475	0.3515	0.3575	0.3545	0.369	0.375