Thermo-Mechanical Characteristics of Adiabatic Shear Band of Pure Titanium under Impact Loading

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Abstract. One of the most important issues related to dynamic shear localization is the correlation among the stress collapse, temperature elevation and adiabatic shear band (ASB) formation. In this work, the adiabatic shear failure process of pure titanium was investigated by dynamic shear-compression tests combined with high-speed photography and infrared temperature measurement system. The time sequence of stress peak, ASB initiation, temperature rising and crack formation was directly recorded by experiments. Key characteristics of ASB, such as width, temperature, critical strain, propagation speed and cooling rate were carefully studied. The results indicate that thermal softening mechanism itself is not enough for the ASB initiation and the micro damage induced by large strain should be an important causation. The propagation velocity of ASB is dependent on the impact velocity and the maximum velocity in this work is about 1900m/s, about 0.6Cs (Cs the shear wave speed). The maximum temperature within ASB is in the range of 350-650℃, while the material close to ASB is also heated.

Introduction

Adiabatic shear localization (ASL) is one of the failure mechanisms those are commonly observed within ductile materials under dynamic loading. ASL process is always accompanied with the formation of ASB and followed by the final fracture of the material. As ASL phenomena are generally encountered in industries such as metal-forming, high-speed machining, car crash, debris impact on aircraft, ballistic impact and penetration, etc., it is of great importance to reveal the insight into the nature of ASB[1-3]. Temperature rise within ASB is a key issue for investigating ASL, as it is closely related to both mechanical behavior (such as softening and stress collapse) and microstructure (such as phase transformation and recrystallization). Combining high-speed photography and temperature measurement into a mechanical test is very helpful for investigating the dynamic failure mechanism of materials. The roles of impact loading, deformation and temperature in ASL process could be intuitively obtained by comparing the sequence of important observations such as stress drop, strain localization, temperature rise, ASB initiation etc. In this work, we will investigate the shear localization behavior of a commercially pure titanium by Kolsky bar system combined with high-speed camera and IR temperature measurement system. Benefiting from fast development of high-speed photography technique in recent years, high resolution deformation fields around ASB are able to be presented.

Experimental techniques

The material used in this work is commercial titanium with grade Ⅱ purity. The specimens are similar with those from the work of Rittel et al.[4, 5]. The shear tests were conducted by SHPB apparatus that is conventionally used for dynamic compression test. The temperature measurement system includes an optical system with 1:1 magnification and an eight channel IR detector. The detector is made of InSb (indium antimonite) that responds to radiation in the 1μm to 5.5μm range corresponding to temperature from 60℃ to 1200℃, which is adequate for measuring shear band temperatures. The response time for the detector is less than 1μs, fast enough for SHPB tests. Each of the elements in the detector array is square with 0.15mm on a side. The separation between two adjacent elements is 50μm. Thus, the total length of the array is 1.55mm. The deformation process of the specimen is recorded by a high-speed camera with the highest image frequency of 5 million per second. The flash, camera and IR system are all triggered by the incident pulse of stress wave. The time sequence for each device can be easily derived by calculating the time period during which the loading pulse travels from the incident strain gauge to the specimen. The arrangement of the SHPB, temperature measurement and high-speed camera is shown in Fig.1. Calibration of the IR system is of vital importance to the reliability and accuracy of temperature measurement. A relationship between temperature and voltage needs to be built before test.

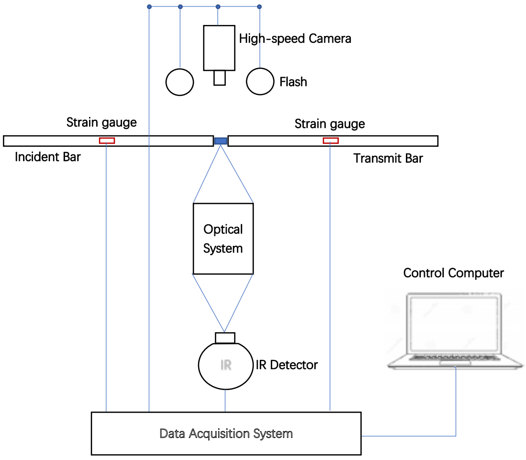

Fig.1. Arrangement of the SHPB apparatus combined with high-speed photography and temperature measurement system

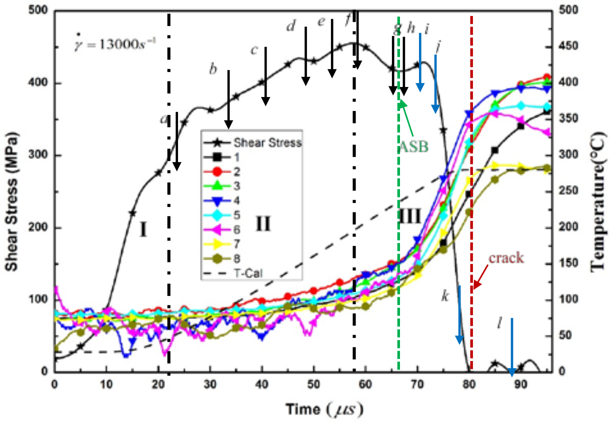

Fig.2. Deformation process of a shear-compression test. The arrows *a~l* indicate the time of camera shot, as shown in Fig.3. 1~8 represent the elements of IR measurement. T-Cal is the calculated temperature based on the conversion of mechanical work to heat (taking 1.0 as Taylor-Quinney factor). The dashed green line and red line denote the appearances of ASB and crack, respectively.

Results and Conclusion

A total of thirty dynamic tests with IR temperature measurement system were conducted in this work, among which eight tests were equipped with high-speed photography simultaneously. Fig.2 presents an example of the shear stress evolution with respect to time. The temperature evolution was also given. The deformation of process was recorded by the high-speed camera as shown in Fig.3. From the in-situ photography, the local critical shear strain for ASB initiation is as large as 1.3, much larger than the nominal shear strain. ASB always initiates after the stress peak, indicating it should not be the first reason of the stress collapse. The measured temperature rise at the maximum stress is in the range of 50-90℃, which by itself is not enough to overwhelm other strengthening mechanisms (such as strain rate hardening). The micro damage induced by the large shear strain should also be responsible for the stress drop. The fraction of mechanical work converting into heat, i.e., Taylor-Quinney factor was derived to be 0.25 to 0.55 and it is also positively dependent on the loading rate. This experiment result indicates the commonly used values of 0.9-1.0 should be reconsidered. The measured temperature within the ASB is about 350-650℃, whereas the material close to the ASB is also heated. About 30 μs after the stress collapse, the temperature reaches its maximum, which is due to the continuous development of the shear band until macro crack formation.

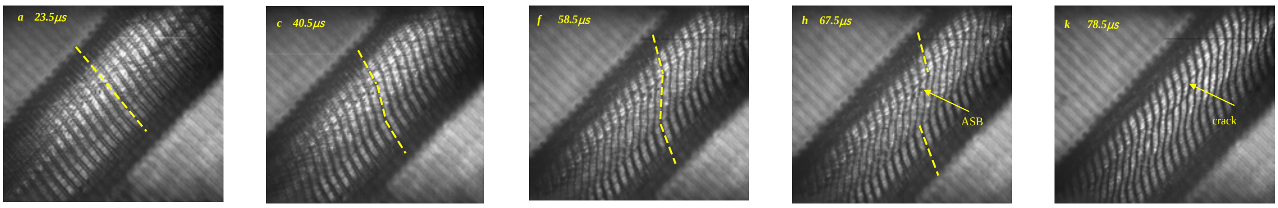

Fig.3 Deformation of a SCS under dynamic loading. Pictures *a-k* are corresponding to those in Fig.2.

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