EXPERIMENTAL INVESTIGATION ON PROPAGATION OF ADIABATIC SHEAR BAND

Lu Ming¹, Tao Suo¹(∗), Chao Zhang¹, Busheng Zhang¹, Fengbo Liu¹
¹School of Aeronautics, Northwestern Polytechnical University, Xi’an 710072, China
∗Email: suotao@nwpu.edu.cn

ABSTRACT

Adiabatic shear failure is an important failure mode when metals undergo impact load. It is also a focus of impact dynamics research in recent years. However, research is rarely done in the propagation speed of adiabatic shear bands (ASB), which hinders our further understanding of ASB evolution. In the present work, we aim to investigate the propagation velocity of ASB. Double shear experiments based on the split Hopkinson pressure bar were carried out to activate ASB in copper. Meanwhile, high-speed camera and MATLAB were employed to measure the strain field in the shear zone. Based on strain gradient analysis, the velocity of ASB was estimated.

Keywords: adiabatic shear band; velocity; split Hopkinson pressure bar.

INTRODUCTION

When metals undergo impact loading, highly localized deformation occurs. As the localized deformation takes place during an extremely short time, the rate of heat loss is smaller than the rate of heat generation, and heat conduction can be neglected. Therefore, the localized band is usually referred to as adiabatic shear band [1]. The formation of ASB is thought as a result of thermo-mechanical instability. When the effect of thermal softening overcomes the effect of strain hardening, the instability will occur [2]. A remarkable temperature rise can be observed in ASB, of the order of several hundred degrees [3]. Meanwhile, the width of ASB was measured to be in the range of 5 to 100µm [4]. Since ASB has been widely observed in many situations, especially in high speed compression, machining and explosive fragmentation and it plays a significant role in material failure, it has been a focus of impact dynamics research in recent years.

However, experimental studies have been rarely done on the velocity of ASB propagation. Marchand and Duffy investigated in the formation of ASB in a thin-walled HY-100 steel tube experimentally. In terms of one-directional propagation, the speed was estimated to be about 510m/s. In case of two-directional propagation, the speed was 260m/s [5]. Mason estimated the velocity of ASB initiation in C-300 steel was about 320m/s [6]. Then Liao and Duffy studied the process of initiation and formation of ASB in Ti-6Al-4V, but the speed of ASB propagation was not a focus in their research [1].

To better understand the propagation speed of ASB, we analyzed the shear behavior of copper in dynamic situation by using the split Hopkinson pressure bar. The fixtures, synchronization trigger testing systems and the double-notched specimen were designed based on previous researches. A grid pattern was pre-printed on the shear zone of the specimen, and the deformation of the grid pattern was recorded by high-speed camera and analyzed through MATLAB. Based on the experimental results, the shear strain field in the shear zone was
obtained and the velocity of ASB propagation was estimated. It should be noticed that the reason why copper was chosen as the testing material is that ASB is hard to generate under impact load in copper and the propagation of ASB is not too fast and the width of ASB is relatively large. The difference between the critical strain of ASB initiation and the critical strain of crack initiation is apparent. Therefore, the process of ASB propagation can be distinguished from the process of crack propagation more easily.

EXPERIMENTAL DETAILS

Sample preparation
The raw material for sample preparation was commercially pure copper. The double-notched specimen was adopted in order to obtain the highly localized strain and high strain rate [2, 7], shown in Fig.1. During loading, ASB would propagate along the way between the two notches. Before the test, the specimen was polished and then a group of parallel grid lines were notched on the surface of the desired shear zone. When the flashlight shined on the specimen, the grid pattern produced diffuse reflection and the rest part of the specimen produced specular reflection. In the photograph, the grid pattern was bright and the surrounding was dark, which enhanced the contrast ratio of the photo.

![Fig. 1 - The double-notched specimen](image)

Mechanical testing
Dynamic shear experiments were performed using the modified split Hopkinson pressure bar (SHPB) in which only the strike and incident bar were employed while the transmitted bar was removed, shown in Fig.2. The side of double shear specimen contacts directly with one end of the incident bar as in traditional Hopkinson bar experiments. As soon as the compressive stress wave generated by the impact of strike bar on the incident bar propagates and reaches the interface between the specimen and incident bar, high rate of loading is applied to the specimen. The initial impact velocity applied on the specimen can be calculated by the following equation:

\[
v = C(\varepsilon_I - \varepsilon_R) \tag{1}\]

where \( C \) is the longitudinal wave in the incident bar, \( \varepsilon_I \) and \( \varepsilon_R \) refer to incident and reflected wave respectively.

To capture the evolution of adiabatic shear band, the high-speed camera and synchronization trigger testing systems were used. Before the stress pulse propagated to the specimen, high-
speed camera was triggered and recorded the process of shear deformation. To avoid repetitive loading, an incident tube and a reaction mass were used to generate a single incident stress pulse, which is same as the dynamic recovery split Hopkinson pressure bar proposed by Nemat-Nassor [8]. In previous research, the critical strain is used as a criterion to characterize the onset of adiabatic shear failure. Therefore, the critical value of shear strain is also determined before the ASB speed is estimated. To establish the critical strain criterion of ASB in copper, the specimens were loaded with different stress pulse time and velocity of incident bar. After the specimens were loaded, the microstructure was studied using metallurgical microscopy, transmission electron microscopy (TEM) and electron backscattered diffraction (EBSD).

Fig. 2 - The experimental setup

RESULTS

Plastic deformation process

According to the deformation of grid lines recorded by high-speed camera, the plastic deformation process can be divided into three continuous stages: homogeneous or uniform deformation stage, inhomogeneous deformation stage and the shear band propagating stage (Fig.3), which are in good agreement with the theory of Marchand and Duffy [5]. In homogenous stage (Fig.3(a)), the grid lines incline slightly but remain parallel to each other. In the second stage, the grid lines curved means inhomogeneous deformation. Then the slope of the grid lines becomes larger, the high local strain occurs and narrow bands appear around the notches (Fig.3(b)). After that, the discontinuity of the grid lines extends, indicating the formation and propagation of ASB (Fig.3(c)).

Fig. 3 - The three continuous stages of plastic deformation process: (a) homogeneous deformation stage, (b) inhomogeneous deformation stage, (c) the ASB propagating stage.

Microstructure observation

Microstructure of the specimens was observed by Nikon Epiphot30 metallurgical microscopy. It can be seen from Fig. 4 that when the applied pulse duration is 120μs, ASB penetrates the
shear zone and its width is measured to be about 110µm. The grains in ASB are stretched and the streamline form appears.

Comparatively, the grains in the middle of ASB are obviously refined. In the direction of ASB propagation, cracks are observed around notches (Fig.4). However, when the pulse duration decreases to 80µs, ASB does not penetrate the shear zone. It is found to generate from both notches and propagates for a distance but without connection.

The length of the zone in which ASB does not generate is 6.7mm. In Fig.5, there are obvious boundaries between ASB and the zone ASB not generating, and the microstructures in these two areas are distinct. The grains in the latter area are not refined and their size is larger than the size of the grains in ASB. With the pulse duration reducing to 60µs, ASB is hardly observed in the whole shear zone.

![Fig. 4 - The metallograph of ASB. The load pulse duration was 120µs.](image1)

In order to verify that ASB does not penetrate the shear zone in case of applied incident pulse 80µs, the EBSD technique was employed for microstructural observation (see in Fig.6). It can be seen from Fig.6 that the size of grains gradually increases along the direction of shear deformation and the grains in the left side of shear zone are much smaller than those far from the left side, indicating the partial propagation of adiabatic shear band.

Then the microstructure of ASB was also observed using TEM, the result is shown in Fig.7. The grains in ASB are stretched and refined apparently. Furthermore, the sub-grains and dislocation cells are observed, which means dynamic recovery occurs in ASB.

![Fig. 5 - The metallograph of ASB. The load pulse duration was 80µs.](image2)
Critical shear strain and the velocity of ASB propagation

The nominal shear strain was defined according to the photographs recorded by high-speed camera. In this work, the nominal shear strain is defined as the ratio of the horizontal displacement between two points of the same grid line to the vertical distance between these two points, as shown in Fig.8. To simplifying, the vertical distance between two points of the same grid line is fixed for all grid lines. That is, all the points from the upper part of shear zone have the same vertical coordinates, and the same for all points from lower part of shear zone. The photographs of dynamic shear process were analyzed by MATLAB through extracting the image pixel intensity. Two lines were created in the photograph. One of them was above the shear zone, named Line 1. Another below the shear zone was called Line 2. The pixel intensity of Line1 and Line 2 were extracted, shown in Fig.9. As the brightness of the grid pattern was the highest in the photograph, those points of which gray level was 255 represented the location of grid lines, and the slope of the grid lines could be calculated. Therefore, the shear strain was obtained.
In terms of the zone ASB not generating (loading pulse duration 80\(\mu\)s), the nominal shear strain corresponding to the boundaries between localized ASB zone and uniform shear zone (ASB not generating) is estimated to be 0.965. In this work, this value is taken as the critical shear strain for ASB propagation. That is, the region where the nominal shear strain larger than 0.965 is adiabatic shear zone, while the region with the shear strain smaller that 0.965 undergoes the uniform shear deformation. Therefore, the point with nominal shear strain equals to 0.965 refers to the front of ASB. By employing the concept of critical shear strain for ASB formation, the location of ASB front in each image can be determined, and the region of ASB not generating in the shear zone can be defined (shown as the line of dashes in Fig. 10). The area above the line indicates that ASB has already generated and propagated, while the area below it means ASB does not generate. In the stain field, the shear strain in the loading side (left side in Fig. 10) is always higher than that of the no-loading side, and the shear strain of the middle is always the lowest. Both two sides of the shear strain curve are above the critical strain curve. That means ASB generates not only on the loading side, but also on the no-loading side. Through the conversion from pixel to length, the distance of ASB propagation and the space of time between two photographs were then obtained and the
velocity of ASB propagation was calculated. Table 1 illustrates the velocity of ASB propagation for different cases. The short dashed line “...” in Table 1 means no ASB formation during the corresponding time duration. It can be seen from the table that ASB generates from the loading side firstly, and then from the no-loading side and propagates towards the middle of the specimen. Besides, the velocity of loading side is always larger than that of no-loading side. For specimen No.1 which was impacted at the initial velocity 4.16 with the duration 60µs, no ASB is observed. With the pulse duration rising to 80µs (specimen No. 2), the ASB generates and propagates partially. If increasing the loading duration further, the ASB is found to run through the whole shear zone. Meanwhile, if the initial velocity of impact is increased from 7.39 to 8.49 m/s, the ASB speed of both the loading side and the no-loading side increases. As a result, the load pulse duration and the velocity of incident bar are important factors which have remarkable effects on the propagation of ASB. The reason that the ASB propagation velocity of specimen No. 2 decreases with time, which is different from others, is attributed to short loading duration. In the stage of unloading, the velocity of ASB propagation cannot remain a higher value and declines with time. However, in the case of long loading duration, that is the specimen is kept loaded during the propagation of ASB, the velocity of ASB propagation is not a constant and increase during the dynamic shear process. It should be noticed that the ASB propagation speed was suggested to reach a saturated value if the impact loading speed is large enough [7, 9, 10]. However, in this work, the ASB velocity is observed to increase with impact velocity if comparing the results for specimen No. 3 and 4. It is believed that the current impact velocities are not large enough to promote the ASB reaching its saturated value.

Table 1 - Velocity of ASB propagation

<table>
<thead>
<tr>
<th>Number of specimen</th>
<th>Load Pulse Duration µs</th>
<th>Velocity of Incident Bar m/s</th>
<th>Time duration µs</th>
<th>ASB Propagation Velocity of Loading Side m/s</th>
<th>ASB Propagation Velocity of No-loading Side m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>4.16</td>
<td>103-106</td>
<td>267m/s</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>106-108</td>
<td></td>
<td>275m/s</td>
<td>205m/s</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>5.30</td>
<td>108 -111</td>
<td>223m/s</td>
<td>187m/s</td>
</tr>
<tr>
<td></td>
<td>111 -113</td>
<td></td>
<td>195m/s</td>
<td>160m/s</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>7.39</td>
<td>80-83</td>
<td>153m/s</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>83-85</td>
<td></td>
<td>210m/s</td>
<td>135m/s</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>85-87</td>
<td></td>
<td>235m/s</td>
<td>165m/s</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>87-90</td>
<td></td>
<td>263m/s</td>
<td>190m/s</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>90-95</td>
<td></td>
<td>298m/s</td>
<td>206m/s</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>8.49</td>
<td>76-78</td>
<td>195m/s</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>78-80</td>
<td></td>
<td>220m/s</td>
<td>205m/s</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>80-84</td>
<td></td>
<td>275m/s</td>
<td>240m/s</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>84-88</td>
<td></td>
<td>320m/s</td>
<td>258m/s</td>
<td>--</td>
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</table>
CONCLUSION

In this work, the dynamic shear experiment of copper was conducted through the modified split Hopkinson pressure bar. With high-speed camera recording the loading process, the propagation characteristics of adiabatic shear band were studied and the influence of loading condition was studied. It is found that the adiabatic shear band occurs as the nominal shear strain reaches the critical value. The velocity of loading side is always larger than that of no-loading side. Meanwhile, in the velocity range of current work, the ASB velocity is observed to increase with impact velocity.

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REFERENCES


