Effect of heat treatment on the formation of adiabatic shear bands in high strength steels impacted by AP projectiles

M. Übeyli[1]*, T. Demir[1], R. O. Yıldırım[2], M. F. Aycan[1]

[1] *TOBB University of Economics and Technology, Mechanical Engineering, 06560 Ankara, Turkey*
[2] *Middle East Technical University, Mechanical Engineering, Ankara, Turkey*

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Abstract

This study presents the effect of heat treatment on the adiabatic shear band formation in the steels AISI 4340 and DIN 100Cr6, which were impacted by 7.62 mm armour piercing (AP) projectile. Adiabatic shear band formation was investigated in the steel samples having different hardness levels and thickness values. Examinations were carried out using both optical and scanning electron microscopy to see the microstructural variations apparently. Moreover, microhardness measurements were also made to correlate structure-property relationships. Results showed that transformed bands were seen in the samples having the hardness of 49 and 59 HRC but deformed bands were observed in all investigated samples. Moreover, a fine grain structure with carbide precipitates was observed in the transformed bands.

Key words: adiabatic shear band, armour, ballistic test, heat treatment

1. Introduction

Adiabatic shear band (ASB) formation is observed in metals subjected to high strain rates and very large strains. Therefore it can take place in many processes, namely, metal forming, ballistic testing, machining, dynamic impact, and high strain rate deformation. Although the first study on the adiabatic shear band by Zener and Hollomon [1] dates back to 1944, most of the investigations have been made after the year 1970. Adiabatic shear band formation takes place due to thermo-mechanical instability [2]. There occurs a heat generation in the localized bands which cannot be transferred to the surrounding material easily [2]. Therefore, a local temperature increase is observed which may alter the microstructure of the material [3]. ASBs can be classified into two main groups: deformed and transformed [2]. In the deformed ASBs, microstructure remains the same with base metal but grains or structure is highly distorted or sheared. However, in the transformed bands, a crystallographic phase change occurs. Formation of adiabatic shear bands can cause a catastrophic failure in the materials under high strain rate deformation [4, 5]. Microstructure change in armour steel was tested by a hollow charge earlier [6]. In the ASBs, a microstructure having fine delta ferrite grains with very narrow martensite laths was detected. In addition, the ASB formation was examined after applying torsion loads at high strain rates in different grade steels [7]. The shear bands were found in all steel samples but their types (deformed or transformed) changed depending on the steel grade. In another study [8], ASB formation in the AISI 4340 steel was investigated by a torsion split Hopkinson bar system. It was concluded that specimen geometry and dimensions contributed to the development of ASBs. Moreover, the ASB formation in medium carbon steels by tungsten projectiles [9] and in various steels (4130, AISI 1045, modified rolled homogeneous armour steel, and AerMet 100) by 44 grain fragment-simulating projectiles [10] was investigated. In these studies, change in type of shear band depending on the steel grade was observed apparently. Recently, influence of thermal treatment on the ASB formation in AISI 4340 steel, tested by Split Hopkinson Pressure Bar, was examined [11]. It was reported that heat treatment did not lead to a significant impact on microstructure and hardness of ASBs. In a more recent work, microstructural char-

*Corresponding author: tel.: +90-312-2924085; fax: +90-312-2924091; e-mail address: mubeyli@etu.edu.tr

acterization of ASBs in steel deformed at high strain rates ($> 2.8 \times 10^4\,s^{-1}$) was carried out [12]. Deformation twins were seen in the microstructure of ASBs.

In this study, ASB formation in the steels, AISI 4340 and DIN 100Cr6, tested under the impact of 7.62 mm AP projectile, was investigated. The ballistic testing of these steels was performed in a previous study [13]. The main objective of this study was to investigate the effect of heat treatment and area density on the ASB formation in the steels AISI 4340 and DIN 100Cr6.

2. Material and method

The steel samples (AISI 4340 and DIN 100Cr6), which were tested against 7.62 mm AP projectile in the previous study [13], were considered in this study. They had five different thickness values of 7.2, 9, 10.8, 12.7, and 14.4 mm, and three hardness levels of 40, 49 and 59 HRC. The mechanical properties of the specimens before ballistic testing and heat treatment procedure were mentioned in [13] and so are not repeated here. The main objective of this study was to see the effect of heat treatment on the ASB formation in the steels AISI 4340 and DIN 100Cr6.

The steel samples were coded by taking into account the hardness and thickness to nominate them more easily. In coding, the first number represents the steel type (1 for AISI 4340, 2 for DIN 100Cr6), the letters X, Y and Z show the hardness of ~ 40 HRC, 49 HRC and 59 HRC, respectively, whereas the numbers on the end: 1, 2, 3, 4, and 5 sign the thickness of the steels, respectively. Microstructural characterization was carried out with the aid of both an optical and a scanning electron microscopy (SEM) to clarify the change in the microstructure of the steels and the ASB types upon the ballistic testing with 7.62 mm AP projectile. Before metallographic examination, the tested specimens were etched by 5 % nital solution. Then, microstructures of the samples were taken at the impact surfaces through thickness of the steel. Furthermore, the microhardness measurements were performed to determine the hardness of the ASBs for comparison to the base microstructure.

3. Results and discussion

ASB formation was recorded in all the investigated samples after the impact of 7.62 mm AP projectiles. However, the type and density of ASB changed significantly with respect to the hardness and thickness of the steel. For the specimen 1X, only deformed bands were observed at all investigated thickness values. The formation of the ASBs was observed at a greater extent for the thickness values ≥ 9 mm. Figure 1 shows

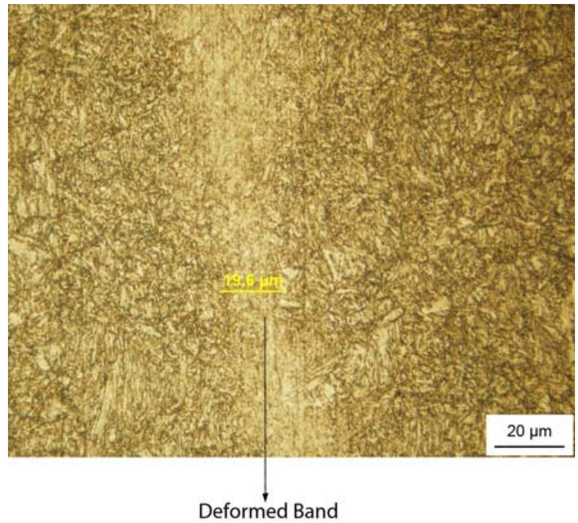

Fig. 1. Deformed band formation in the sample 1X5 after the impact of AP projectile (1000×).

a typical deformed band formation in the sample 1X5. A colour difference between the main microstructure of the sample (tempered martensite) and the band is seen apparently. In fact, shearing action causes the re-orientation of the martensite laths in deformed bands with respect to the matrix material. This case can be differentiated easily by the change in colour. Lighter and longitudinal band having a width of ~ 20 μm was detected apparently from Fig. 1. On the other hand, an increase in the specimen hardness caused the formation of transformed bands as well as the deformed bands for the steel AISI 4340. These might be due to an increase in the resistance of the projectile advancement in the target material with both the target hardness and thickness. Increase in the friction between the projectile and the target material causes more heating and so higher local temperatures. Figure 2 illustrates the transformed band in the sample 1Y2. It is seen as a white line and no microstructure can be observed.

Figure 3 depicts the formation of both transformed and deformed bands in the samples 1Z2. Again, the transformed bands are viewed as white lines whereas the deformed bands are detected as lighter areas by optical microscopy. Especially, the transformed bands were more severely obtained for the hardest specimens, 1Z. Frequency of the formation of these bands increased remarkably with increasing the thickness of the steel. Furthermore, the bandwidth was recorded in the range of 15–50 μm depending on the hardness and thickness of the AISI 4340 specimens. However, there was no correlation seemed between the bandwidth and hardness or thickness. Figure 4a represents the microstructure of the sample 1Z4 after testing by 7.62 mm AP projectile. One can see apparently both transformed and deformed bands as in the case of

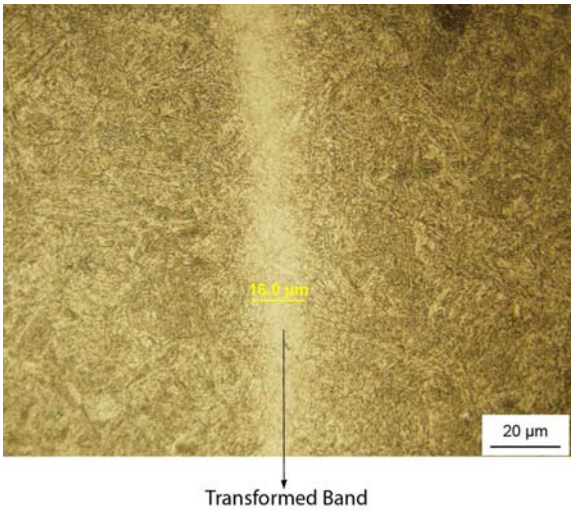

Fig. 2. Transformed band in the sample 1Y2 after ballistic testing (1000×).

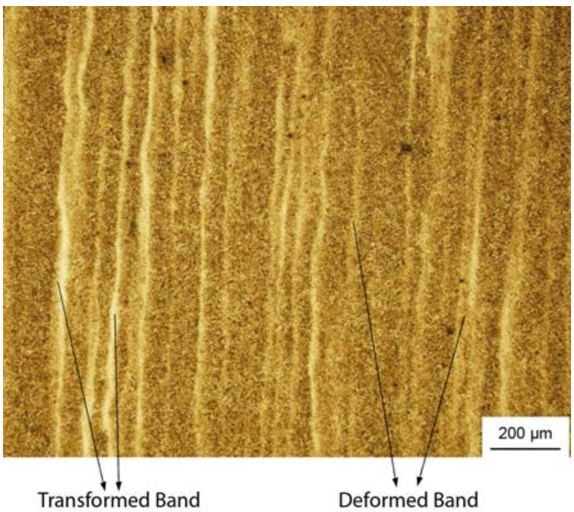

Fig. 3. View of the microstructure of the sample 1Z2 after ballistic testing (100×).

1Y samples. Furthermore, a semi-transformed band formed in this sample is shown in Fig. 4b. Thinning of the martensite laths can be seen clearly. SEM images of the main microstructure and band microstructure also support this situation (Fig. 5).

As in the case of AISI 4340 steel, although only deformed bands were found in the 2X samples (having the lowest hardness), both transformed and deformed bands were formed in the samples of 2Y and 2Z. Figure 6a represents a typical microstructure of 2Z5 after ballistic testing. Impact of projectile caused the formation of many ASBs throughout the thickness of the specimens. The bandwidth generally varied in the range of 10–60 µm depending on the sample thickness and hardness for DIN 100Cr6 steel. A transformed band formed in the 2Z5 is shown in Fig. 6b. Again, the general appearance of the band is seemed as a white line containing some small particles, which are not resolvable, by an optical microscopy. Therefore, SEM observations are very helpful to reveal the microstructure of transformed bands. Figure 7 illustrates the SEM images of the transformed band occurred in the sample 2Z5 more clearly. Fine grains with carbide precipitates (as small spherical particles) constitute the microstructure of the band. The size of these precipitates is measured as ≤ 2 µm.

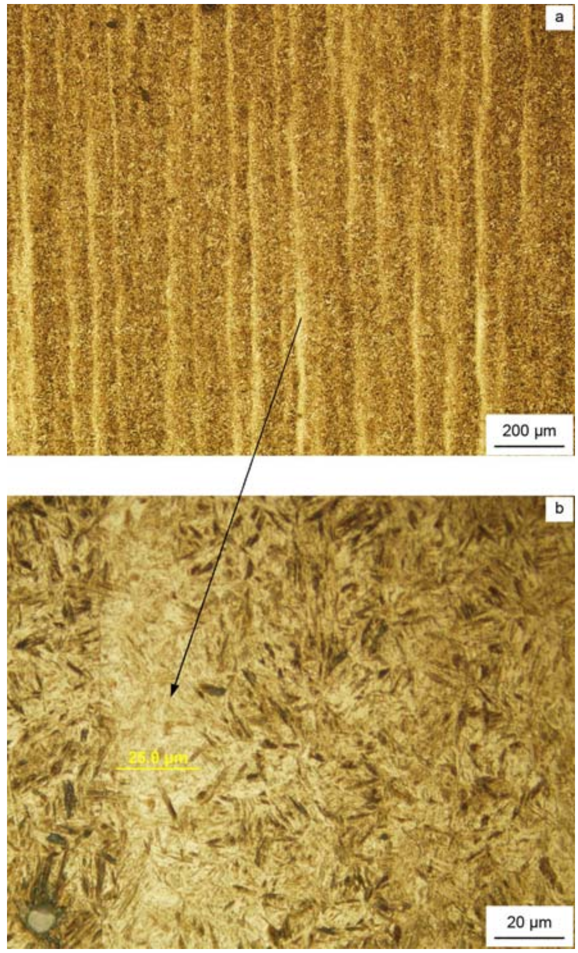

Fig. 4. a) Representation of the band formation in the sample 1Z4 (100×), b) semi-transformed band in the sample 1Z4 (1000×).

Tables 1 and 2 give the microhardness values for the bands and base microstructure for the investigated steels: AISI 4340 and DIN 100Cr6, respectively. The average hardness of deformed bands in the specimens 1X, 1Y and 1Z was 378, 483 and 632 HV, slightly greater than the base matrix. On the other hand, a significant increase in the hardness of the transformed bands was recorded with respect to the base matrix for the specimens 1Y and 1Z. It was due to the fine grains and precipitates formed in the microstructure

Table 1. Hardness of the ASBs and the base metal for the AISI 4340

Sample	Band type	Hardness of the band HV	Hardness of the base material HV
1X	Deformed	378	356
1Y	Deformed Transformed	483 512	453
1Z	Deformed Transformed	632 694	614

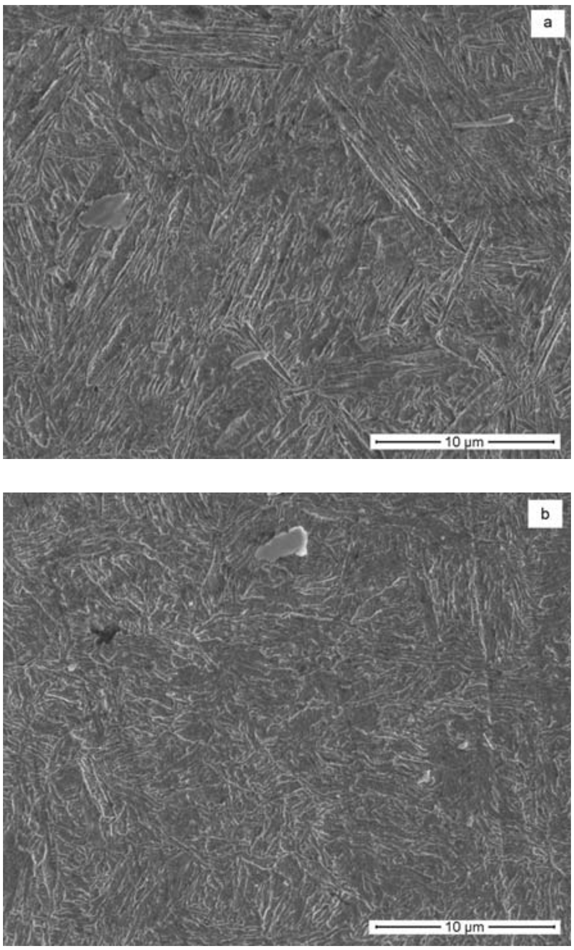

Fig. 5. SEM images of the sample 1Z4: a) base microstructure, b) transformed band structure (8000×).

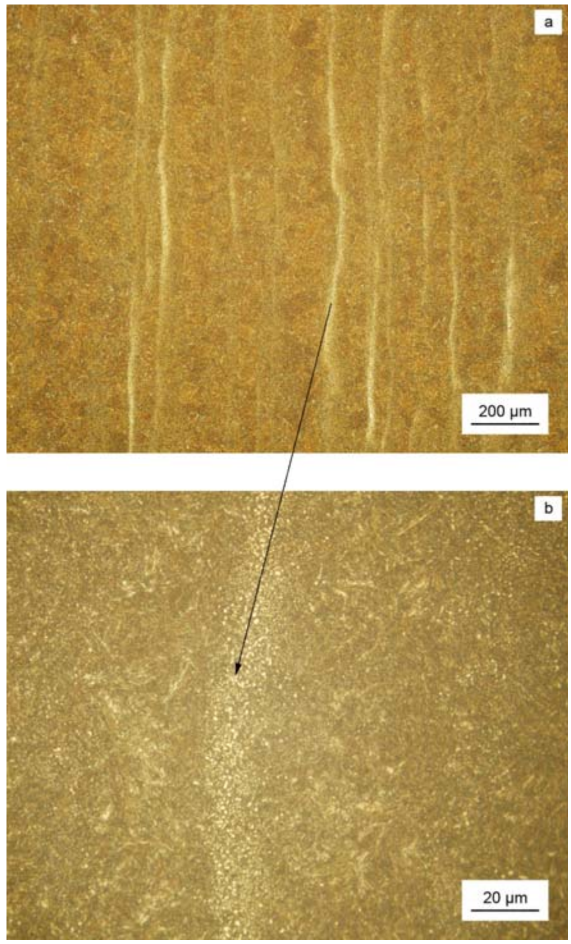

Fig. 6. a) General view of the microstructure of the sample 2Z5 (100×) after testing, b) view of the transformed band in the same sample (1000×).

of these bands. A similar trend is also available for the specimens of DIN 100Cr6. Although the difference between the band and the base microstructure for the samples 2X and 2Z is relatively at low or moderate values, it becomes much greater for the sample 2Y.

4. Conclusions

Impact by 7.62 mm AP projectiles led to the formation of ASBs in all investigated steel samples. The bandwidth varied in the range of 10–60 μm depending on the specimen types. The transformed bands were seen in the samples having the hardness of 49 and 59 HRC but the deformed bands were observed in all samples. On the other hand, the band formation took place more seriously for the sample thickness values > 9 mm. There was a significant difference occurred between the hardness of the transformed bands and

Table 2. Hardness of the ASB and the base metal for the DIN 100Cr6

Sample	Band type	Hardness of the band HV	Hardness of the base material HV
2X	Deformed	392	376
2Y	Deformed Transformed	532 574	443
2Z	Deformed Transformed	704 725	681

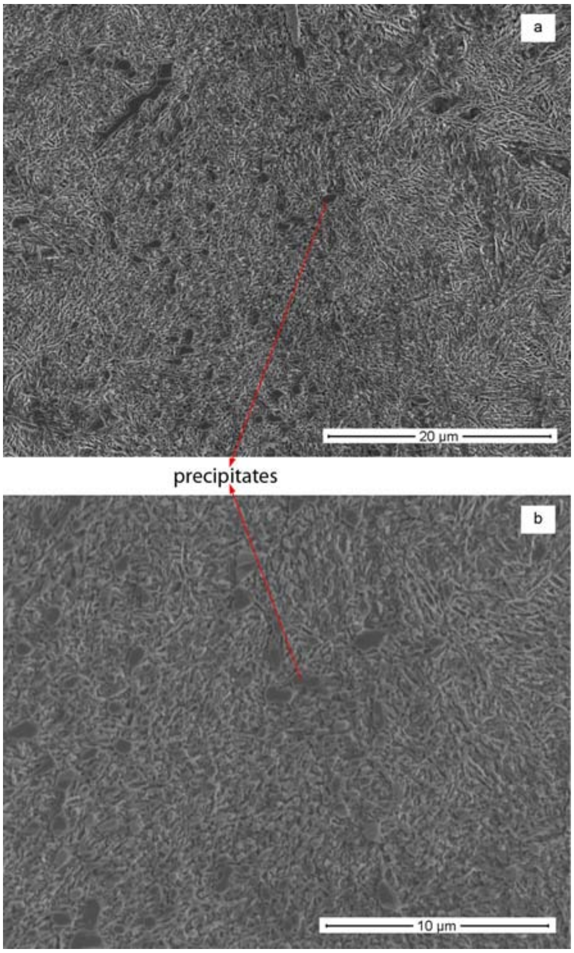

Fig. 7. SEM photos of the transformed band formed in the sample 2Z5: a) 5000×, b) 10000×.

the matrix materials. However, the hardness of deformed bands was found not much higher than the matrix material.

Acknowledgements

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