Deformation and failure of a rolled homogeneous armour steel under dynamic mechanical loading in compression

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Abstract

A Rolled Homogeneous Armour (RHA) steel was tested at strain rates in excess of 10^3 s^{-1} in compression using direct impact Hopkinson Bar. The dynamic stress-strain curves and microstructural evolution in this material at high strain rates were obtained. They were found to be dependent on the extent of thermal softening occurring during deformation and the accompanying visco-plastic instabilities, which lead to localization of shear strain along adiabatic shear bands (ASBs). The formation and the type of shear bands are found to depend on the impact momentum and strain rates. Depending on the loading mode, there is a strain-rate threshold below which plastic deformation is homogeneous. At slightly higher strain rate, deformation becomes localized leading to formation of deformed ASBs. As impact momentum and strain rate increase, another threshold value is reached above which strain localization become so intense that it triggers the formation of transformed ASBs. Ductile shear fracture occurs along these transformed bands.

1. Introduction

Failure of metals and alloys at high strain rates is initiated by development of an adiabatic condition, in which heat generated along certain paths does not have enough time to be conducted away within the very transient deformation time. Local rise in temperature ensures, which leads to thermal softening, loss of load-carrying capacity and shear strain localisation along the path of heat waves. The narrow paths of intense shear strain localisation, known as adiabatic shear bands, offer preferential crack initiation sites and crack propagation paths leading to catastrophic failure at high strain rates. Holloman and Zenner [1] first suggested that the occurrence of adiabatic shear bands is caused by localisation of deformation due to significant rise in temperature along narrow bands. Adiabatic shear failure has continued to attract considerable interest among researchers in order to understand the underlying mechanisms of occurrence and the microstructural evolutions accompanying the simultaneous effects of localised heating and intensely localised strain in various materials [2-8]. Temperature rise in the shear bands is suggested to induce phase transformation inside shear bands in ferrous and titanium alloys [6,7]. Hawang et al. [2] reported fragmentation of ferrites and cementite into equi-axed grains of less than 0.2 µm in sizes as a result of the intense strain inside the shear bands in a low carbon steel. Zu et al. [8] observed dynamic recrystallization inside the shear bands in Fe-Cr-Ni monocrystals. Excessive twinning is reported to play a role in dynamic recrystallizaton and development of adiabatic shear bands in iron [9,10].

Armstrong *et al.* [10,11] proposed a dislocation avalanche pile-up model to explain the occurrence of adiabatic shear bands in metals and used this model to explain the difference in susceptibility of fcc and bcc metals to shear banding. Intense localised strain caused a denser packing of ceramic particles inside the adiabatic shear bands in an alumina particle reinforced Aluminum 6061-T6 alloy during high velocity impact [12]. The presence of hard precipitates in micro-alloyed steel was suggested to promote the formation of adiabatic shear bands [13]. Zhou *et al*. [14] suggested that shear localisation originates from perturbation of the yield stress, which leads to unloading of the neighbouring material by a sudden decrease of local stress in the shear bands. They suggested that the number of shear bands depends on the strain rate and attributed the possibility of occurrence of multiple bands to the competition between the rate at which shear band grows and the speed at which the unloading propagates from a growing band. Another investigation has also shown the influence of microstructure on the number of shear bands that form in a high strength low alloy steel [15]. A minimum strain rate is observed in dual phase steel produced from inter-critical annealing of a low carbon-manganese-silicon steel, below which deformation is relatively homogeneous with no shear strain localisation. The critical strain rate is reported higher for the same steel when heat treated to have a fully martensitic structure [3].

In the current study, the influence of impact momentum on the occurrence and type of adiabatic shear bands in a rolled homogeneous armour steel is investigated. Dynamic shear stress-strain curves are generated from high strain-rate tests and discussed in relation to the microstructural evolution leading to the formation of adiabatic shear bands.

2. Materials and Method

A rolled homogeneous armour (RHA) steel with a high potential for use as armour plates in combat vehicles was used in this investigation. The testing took place at strain rates above 10^3 /s using direct impact Hopkinson bar. The equipment is fully instrumented to obtain stress-strain curves. The test specimens for the high strain rate compression tests have cylindrical shape with a diameter and length of 9.5 mm and 10.5 mm, respectively. The samples were impacted by a cylindrical projectile made of AISI 4340 steel having a hardness value of 47 HRC. The weight of the projectile was 1.905 kg. A light gas gun fires the projectile, which strikes the specimen at impact momentum that was varied between 40 and 60 kg.m/s. The corresponding strain rates generated in the specimens vary between 2800 and 6600 /s. Elastic waves that are produced on impact travel through the specimen onto the output bar. These elastic waves provide the dynamic stress-strain data that describe the dynamic behaviour of the material under the applied impact momentums. Following the impact tests, the specimens were subjected to metallographic investigation in order to determine the microstructural changes in relation to the applied impact momentum and strain rates.

3. Experimental Results

The experimental data for the impact test on the RHA steel is presented in Table 1, while the dynamic stress-strain curves for the steel are presented in Fig. 1. The higher the firing pressure of the gun, the higher is the impact momentum and higher is the strain rate generated in the specimen. Whether deformation is homogeneous or not, is a function of the applied momentum, so also is the type of adiabatic shear bands that occur (Table 1). The flow stress increases initially with strain, reaching a maximum and decreases with subsequent increase in strain. Thermal softening as a result of the conversion of impact energy to thermal energy dominates the later stage of deformation leading to observed drop in flow stress at high strain values. The maximum flow stress before stress drop caused by thermo-mechanical instability effect of adiabatic heating is influenced by the impact momentum of the projectile: It increases initially with impact momentum, reaches a maximum at an impact momentum of about 50 kg.m/s and decreases with further increase in impact momentum (Fig. 2). The initial increase in maximum flow stress with increase in impact momentum is traceable to the increasing strain hardening effect of the increasing deformation load. At impact momentum above the critical value, adiabatic heating and the accompanying thermal softening dominate the deformation mechanism, resulting in the observed decrease in maximum flow stress with further increase in impact momentum.

Table 1: Experimental data sheet

Sample No	*Firing pressure (kPa)	Impact momentum (kg.m/s)	Strain rate (s^{-1})	Nominal strain	Maximum flow stress (MPa)	Adiabatic shear band
1	180	41.95	2818	0.28	1180	None
2	200	44.54	3138	0.31	1230	Deformed ASB
3	220	46.56	3480	0.35	1340	Deformed ASB
4	240	48.12	3702	0.37	1350	Transformed ASB
5	280	52.16	4204	0.42	1430	Transformed ASB
6	320	56.34	4895	0.49	1110	Transformed ASB
7	340	57.66	4904	0.49	1050	Transformed ASB
8	360	59.34	6646	0.66	895	Transformed ASB
9	360	59.27	6740	0.67	900	Transformed ASB
10	400	62.10	6835	0.68	Failed	Transformed ASB

*Firing pressure of the projectile

Microstructural investigations of the as-received steel samples before impact show the microstructure to be martensitic. Shear strain localisation and occurrence of adiabatic shear bands play a prominent role in plastic deformation and fracture behaviour of the steel at impact momentum exceeding 44.5 kg.m/s (Fig. 3). No adiabatic shear band was observed in samples impacted at momentums below 44.5 kg.m/s, whereas deformed bands (Fig. 3a) were observed in RHA steel samples impacted at 44.54 kg.m/s. At impact momentums above 48 kg.m/s, white etching shear bands (also called transformed bands) were observed in the steel specimens (Fig. 3b). When impact momentum exceeded 48 kg.m/s, cracking occured along the transformed bands (Fig. 3c). An overview of a parabolic-shaped adiabatic shear band observed on the transverse cross-section of the RHA steel when impacted at a momentum of 48 kg.m/s is shown in Fig. 4.

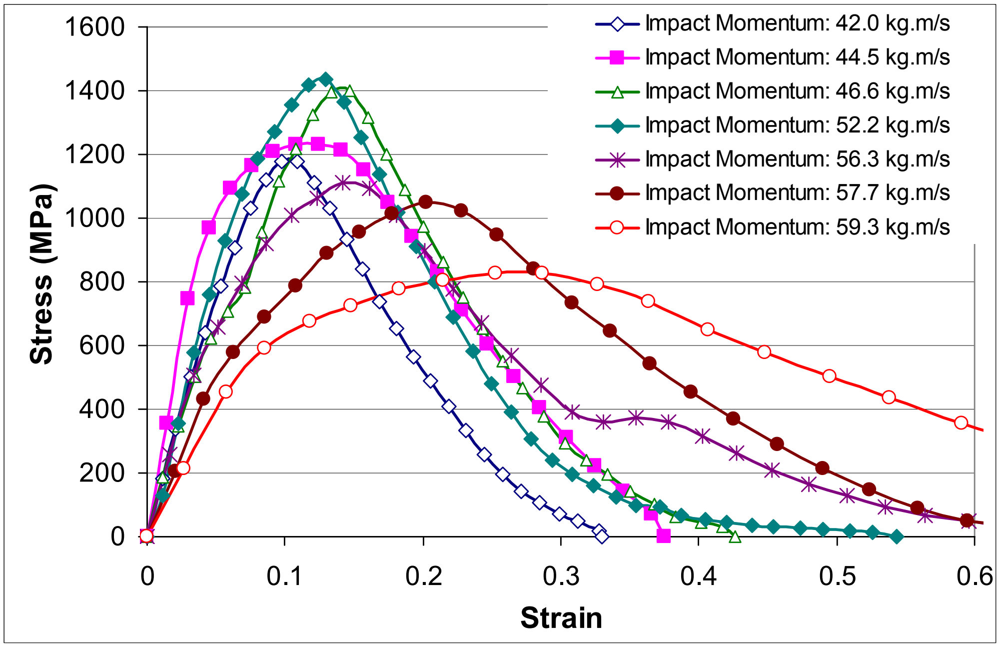

Fig. 1: Dynamic stress-strain curves for the RHA steel under different impact momentums

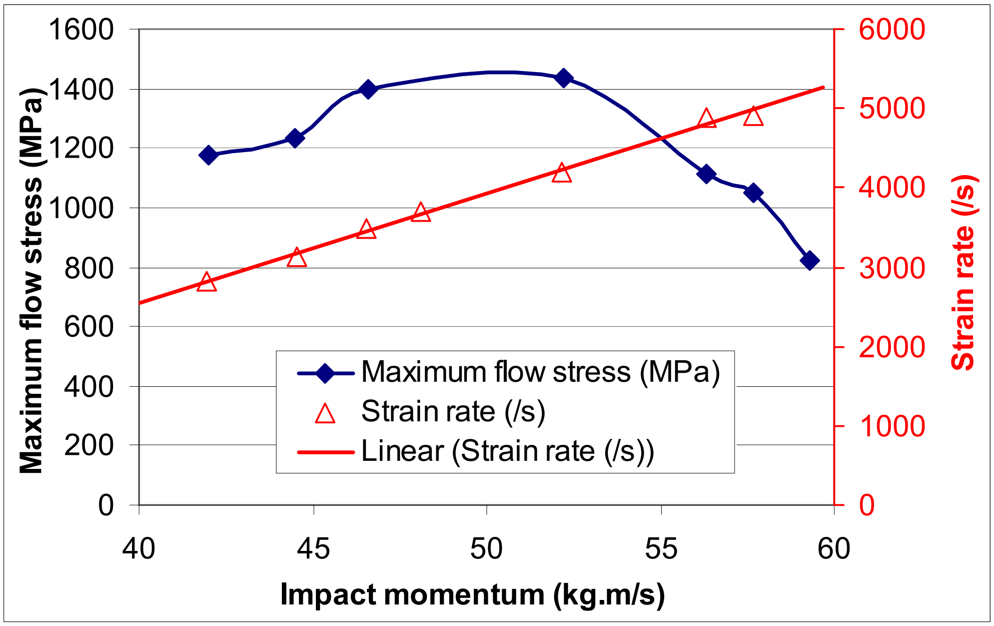

Fig. 2: The effect of impact momentum on maximum flow stress before the onset of stress collapse and adiabatic shear banding

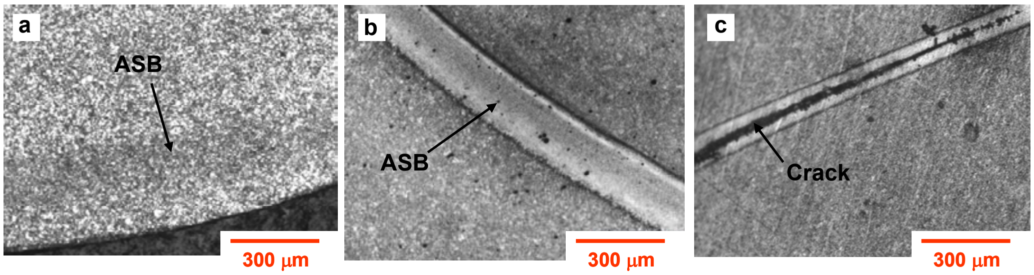

Fig. 3: Optical micrographs showing adiabatic shear bands in RHA steel after impact loading (a) deformed band in a sample impacted at 46.6 kg.m/s and (b) transformed band in a sample impacted at 48.5 kg.m/s and (c) cracking along transformed band in a sample impacted at 59.3 kg.m/s.

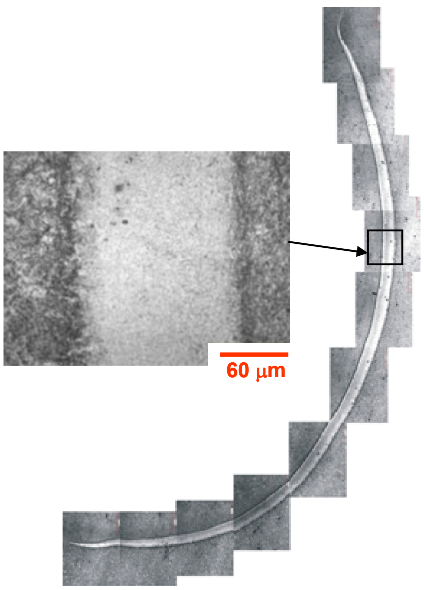

Fig. 4: Optical micrograph showing the overview of a parabolic shaped adiabatic shear band on transverse cross-section of an impacted RHA steel.

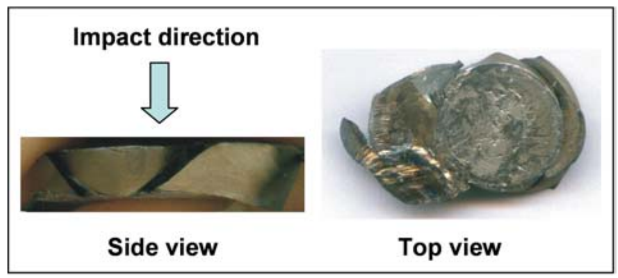

Fig. 5 : Optical macrograph of a sample impacted at 59.3 kg.m/s showing adiabatic shear failure and fusion of fragments along the ASB

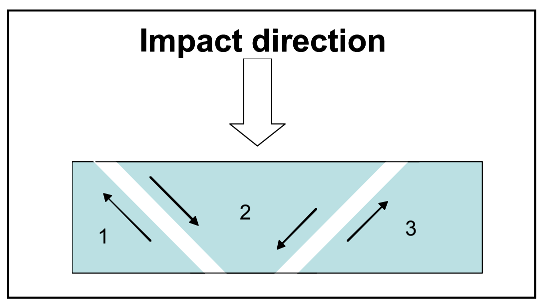

Fig. 6: A schematic representation of the longitudinal section of a failed sample showing three fragments fused together along the shear bands (white strips).

The adiabatic shear band forms a v-shape when observed on the longitudinal cross-section. Figure 5 shows a steel specimen that failed at an impact momentum of 59.3 kg.m/s. Although this material disintegrated into three parts, total fragmentation did not occur as a result of high temperature fusion of the fragments, suggesting a significant temperature rise, along the adiabatic shear bands. A schematic view of fused fragments after impact is shown in Fig. 6. Splashing of the content inside the shear band adjacent to the surface the sample was observed. This suggests a high degree of softening and metal fluidity inside the shear band during deformation. The results of hardness measurement on the steel samples show the adiabatic shear bands to have higher hardness value than the bulk material. The hardness of the shear bands was observed to increase with increasing impact momentum and strain rate as shown in Fig. 7. The transformed bands are much harder than the deformed bands. The thickness of the transformed bands formed was also observed to increase with the intensity of impact.

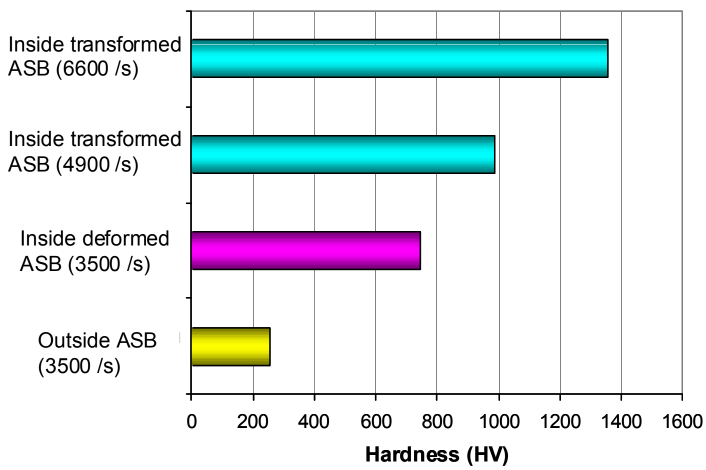

Fig. 7: Effect of strain rate on hardness of adiabatic shear bands formed in RHA steel during impact loading.

4. Discussion

Plastic deformation and failure of the investigated RHA steel at high strain rates is dominated by occurrence of adiabatic shear bands. Adiabatic shear bands occurred when the heat generated during the deformation in the shear bands region was retained causing a local rise in temperature. When the local condition is such that the effect of thermal softening due to the adiabatic heating is greater than the strain-hardening effect of plastic deformation, thermo-mechanical instability resulting in intense shear strain localization occurs. The impact momentum determines the intensity of heat generated inside the shear bands and the associated thermal softening that triggers strain localisation. At low impact momentum, strain hardening dominates and is not easily overshadowed by thermal softening. This explains why no shear bands were formed in the steel at low impact momentums. A previous study has also shown the existence of a threshold impact momentum below which shear band will not occur in steel [16]. The threshold impact momentum required to trigger the formation of deformed and transformed bands in the investigated RHA steel are 44.5 and 48.1 kg.m/s respectively. The transformed bands observed in the steel samples that were impacted at momentums above 46.56 kg.m/s are common in hardened steel and titanium alloys. They are called transformed bands because some researchers consider the transformed bands to be products of a phase transformation occurring due to high temperature increase inside the shear bands during deformation [6,7]. The temperature rise as a result of adiabatic heating during plastic deformation at high strain rates is given by the equation:

$$dT = \frac{\beta}{\rho C_V} \tau d\gamma$$

where C_v is the specific heat and β is the Taylor-Quinney coefficient, i.e the fraction of the plastic work converted into heat that results in temperature rise [17]. Armstrong and Zerilli [18,19] suggested that a local rise in temperature and softening can be produced when a dislocation pile-up pierces through a grain boundary creating a site for shear band initiation. Depending on the plate thickness that is struck by a projectile, an analysis by Chen *et al.* [20] shows that a temperature rise of up to 1527 °C can be attained in the localized zone of a target plate and cause strain localization along narrow bands.

In the present study, a correlation was observed between the dynamic stress-strain curves obtained during impact test and the results of microstructural investigation of the impacted RHA steel samples. For example, increase in impact momentum of the steel led to increase in the maximum flow stress until the impact momentum applied was high enough to trigger the formation of transformed adiabatic shear bands. Beyond this impact momentum, the flow stress was dominated by excessive adiabatic heating, shear strain localization and occurrence of adiabatic shear bands, which cause the observed decrease in the maximum flow stress with further increase in impact momentum. Transformed bands observed in high strength steels after deformation at high strain rates steels have been reported to contain very fine sub-grains of a few hundred nanometers in size [2,21,22]. Meyers and Wittman [23] reported transformed bands in a martensitic steel sample to consist of fine Fe_5C_2 carbides and very fine martensite laths and attributed the white color of the transformed bands to change in etching characteristics of the bands due to dissolution of the carbides inside the shear band. Zurek [24], on the other hand, attributed the white colour of transformed bands to the resolution limit of the optical microscope in resolving the nano-sized subgrains inside the shear bands.

A number of theories have been suggested to explain the nano-sized subgrains that are observed in the white etching bands; Cho et al. [22] and Hawang et al [2] attributed the formation of the very fine cells in transformed bands to elongation and fragmentation of the existing grains along shear band propagation path. Other authors [25-27] have also suggested that microstructural evolution at high strain rates begins with a homogeneous distribution of dislocations that rearrange themselves into dislocation cells which eventually become elongated sub-grains that subsequently break down into equi-axed microcrystalline structure as strain increases. The high hardness observed inside the shear bands, as reported in this study, is attributed to the extreme fine structures that are characteristic of transformed bands. Since other investigators [27,28] have observed high dislocation density inside adiabatic shear bands, higher dislocation density in the shear bands will also contribute to their high hardness values. Likewise, the increase in hardness of shear bands with increasing impact momentum can be explained in terms of increased dislocation generation inside the shear bands due to increasing strain intensity. This is in line with the dislocation avalanche model of adiabatic shear banding proposed by Armstrong et al. [10,11].

5. Conclusion

The dynamic response of a rolled homogeneous armour steel to dynamic impact loading is investigated. Dynamic stress-strain curves are generated to provide relevant information on mechanical properties of the material at high strain rates. Microstructural evolution in the materials during deformation is also investigated. It is evident that the plastic deformation and failure of the materials is controlled by the phenomenon of adiabatic heating leading to thermal softening and strain localization along adiabatic shear bands. Occurrence and the type of adiabatic shear bands are dependent on the impact momentum. Failure at high strain rates is thus caused primarily by these shear bands.

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