Shear-band structure in ballistically tested carbide-free bainitic steels

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Abstract

Adiabatic shear bands represent intense plastic deformation that is localised because the rate at which the heat generated by deformation is greater than that at which it is dissipated. The structure of such bands generated by ballistic testing is examined in order to reveal the governing mechanisms. We attempt to distinguish in particular whether local reaustenitisation occurs, or if the microstructural change are a reflection simply of intense deformation.

1. Introduction

An adiabatic shear band is a narrow layer of intensely sheared material [1]. Such localisation of deformation occurs when the heat generated by the irreversible consequences of rapid deformation cannot be dissipated fast enough by diffusion. The resulting rise in temperature leads to localised softening and hence a focusing of plasticity into bands, which are typically 10-100 μm in width [2]. The phenomenon is therefore associated with high strain-rate deformation (for example during machining, or ballistic impact [3, 4]) and has been speculated to be the reason for damage accumulation in bearings [5, 6] although the evidence for this is incomplete [7]. The bands can reduce the ability of armour to resist projectiles since plugs of material can then detach relatively easily from the armour [8].

The mechanisms responsible for shear localisation are well understood, but in steels there is an additional complication that phase transformation can occur during the localised heating. There are observations that austenite can form during the adiabatic heating leading to 'transformed bands' that

are essentially fine martensite, but also others that indicate only intense plasticity: the 'deformation bands' [1]. Distinctions have been attempted on the basis of etching characteristics and hardness measurements [9] but the conclusions reached are uncertain [10, 11]. Recent work suggests a transition from deformed to transformed bands takes place as the strain rate is increased [12].

A new armour concept has recently been commercialised, with the steel structure consisting of carbide-free, nanostructured bainitic ferrite and enriched retained austenite [13]. Whereas this particular armour is for severe threats, a range of less potent projectiles can, in principle, be accommodated using coarser variants of the carbide-free mixtures of bainitic ferrite and retained austenite. It is with this in mind that bainitic alloys developed originally developed for use in gun barrels [14, 15] have been evaluated for their ballistic performance. The purpose of the present work was, therefore, to assess the shear bands generated in these steels as a consequence of being fired at during ballistic tests.

2. Materials and experimental procedure

The alloys studied are listed in Table 1; their microstructures and mechanical properties have been reported thoroughly in the original work reported more than a decade ago [14, 15]. The phase fractions, consisting of bainitic ferrite (α_b), carbon-enriched retained austenite (γ_r) and some martensite (α') from that work are also listed in Table 1. The material was produced by a vacuum melting process with the ingots homogenised at 1200°C for 2 days, followed by vermiculite cooling to avoid cracking and facilitate sawing. The plate material from the top of each ingot was trimmed off and discarded, and the remainder was sawn in half for further processing. After heating to 1200°C, the two pieces were rolled in six passes to $\approx 12\,\mathrm{mm}$ thick plate with finish-rolling temperatures in the range 905–937°C, followed by air cooling. The ballistic testing details are confidential, but the projectiles penetrated the steel with sufficient velocity to cause the formation of shear bands; Fig. 1 illustrates the coordinate axes.

Thin foil samples for transmission electron microscopy (beginning with $0.3\,\mathrm{mm}$ thickness) were prepared from each alloy specimen, and discs of $3\,\mathrm{mm}$ diameter were cut using spark erosion techniques. The discs were ground

Table 1: Chemical compositions of alloys, wt%. The volume fractions of the microstructural constituents are quoted from the original work [14, 15].

	C	Si	Mn	Ni	Cr	Mo	V	
Alloy-Mn	0.305	1.42	2.09	0.03	1.32	0.24	0.10	
Alloy-Ni	0.295	1.46	0.02	3.54	1.42	0.25	0.10	

	Al	Cu	Nb	Sn	Ti	N	P	S
Alloy-Mn	0.015	0.009	0.002	0.001	0.0016	0.001	0.002	0.0018
Alloy-Ni	0.011	0.009	0.001	0.001	0.001	0.001	0.002	0.0014

	V_{α_b}	V_{γ_r}	$V_{\alpha'}$
Alloy-Mn	0.26 ± 0.01	0.07 ± 0.01	0.67 ± 0.02
Alloy-Ni	0.62 ± 0.05	0.12 ± 0.01	0.26 ± 0.04

down to $\approx 50\,\mu$m thickness and then electropolished at 7.5°C using a twin jet electropolisher set to a voltage of 26 V. The electrolyte consisted of 15% perchloric acid and 85% ethanol by volume. Samples specifically from the shear bands were extracted using a Helios NanoLab focused ion beam microscope, and mounted on a copper grid.

For quantitative X-ray analysis, the samples were prepared metallographically and then etched using 2% nital to remove any deformed layers. Analysis involved step-scanning on a Philips PW150 X-ray diffractometer using unfiltered Cu K_α radiation with a 2θ scanning speed of $0.1\,^\circ\mathrm{min}^{-1}$.

To help understand whether the structure within the shear bands was transformed or deformed, a set of samples was austenitised for 30 min at $Ae_3 + 10$°C, with Ae_3 calculated using MTDATA and the TCFE6 database [16], before water quenching.

3. Results and Discussion

In the discussion that follows, the term *uniform-shear strain* is used to distinguish ordinary deformation which is fairly homogeneously distributed over macroscopic dimensions, from the highly localised strain *inside* a shear band.

3.1. Metallography

Fig. 2 shows chemical segregation-induced bands that are more prominent in the manganese-rich alloy, because this solute is well-known to par-

tition during solidification. The depleted regions transform into a predominantly bainitic structure whereas the light-etching regions contain untempered martensite. The bands lie in the $x - y$ plane with y corresponding to the rolling direction of the plates. They are useful in the present work as markers of strains caused by impact.

Fig. 3 shows extensive shear banding at the entry-point of the projectile, extending to some 6 mm along y from the hole. The bands are thicker towards the surface of the plate where the deformation of the region in the immediate vicinity of the projectile is intense, as shown in Fig. 3b. The pattern formed by the segregation bands shows that in both samples, the extent of plastic deformation of the material beyond the hole increases with depth of penetration, consistent with the expected reduction of the projectile velocity (Fig. 4). Indeed, the amount of shear banding also decreased with the depth of penetration. The projectile creates a plug that eventually is detached from the armour; these observations indicate that adiabatic shear has the greatest role in the vicinity of the impact, followed by less localised deformation as the kinetic energy is dissipated during the process of penetration.

Using the segregation bands as guides, it was possible to obtain quantitative measurements for the shear strain along the inner surface of the hole. The results are presented in Fig. 5. In both cases, the shear strain at the surface remains roughly constant for most of the penetration — what changes is the extent of material that undergoes uniform shear. While shear bands are visible reaching a penetration depth of 6 mm, the region of constant uniform-strain extends twice as far as this. Towards the entry point of the material, the segregation bands are less clear and so it is difficult to assess the uniform-shear strain early on in penetration. In Alloy-Mn, which has clearer segregation bands, there appears to be hardly any measurable uniform-shear strain at the surface in the early stages of penetration. This indicates that virtually all of the initial deformation is accommodated in the shear bands. The increase in uniform-shear strain towards the exit region in both alloys may be due to this section of material not being constrained. These results indicate that the projectile slows down with penetration, and it is expected that adiabatic shear is most intense at the initial entry point. As the projectile penetrates and slows, ordinary deformation, spread out over a larger region, occurs.

Measurements of the shear strain within a shear band in Alloy-Mn (Fig.

6) are consistent with the assumption of high adiabatic shear in the early stages of penetration. Due to the large shear strains involved, the accuracy of the results is limited, however the data indicate that there is an extremely high degree of shear strain within the shear band.

3.2. Transmission Electron Microscopy

Consistent with previous work [14, 15] and the quantitative details listed in Table 1, the structure of the as-received material in both alloys consisted predominantly of bainitic ferrite and retained austenite, with some twinned martensite observed in Alloy-Mn, as illustrated in Fig. 7. Electron diffraction analysis occasionally revealed faint reflections from cementite[1], but the volume fraction must be sufficiently small to make the particles difficult to detect amongst the contrast from dislocations and other features within the microstructure.

In contrast, the structure within the shear bands (Figs. 8, 9) indicates deformation leading to the formation of irregular, cell-like structures, although electron diffraction shows that the cells do not represent a large spread in orientation. The images are not reminiscent of a structure which has been austenitised due to adiabatic heating followed by quenching to martensite, where neat plates or laths of martensite would be expected.

The mere plastic deformation of the plate-like structure of bainite or martensite on its own does not seem to produce the kinds of structures illustrated in Fig. 8. Ordinary deformation experiments either by tensile testing or using rolling deformation indicate that for significant strains, the plate-like features remain easily discernible after deformation; however, annealing after such cold-deformation leads to micrographs similar to those illustrated in Fig. 8 [17–19]. It might therefore be concluded that the structures illustrated here are generated by warm deformation during the adiabatic heating. Notice also the presence of retained austenite within the bands as detected using electron diffraction. This retained austenite is probably a vestige of the carbon-enriched austenite that is stabilised by the bainite reaction, and although some of it is expected to decompose into martensite during deformation, the remainder will be mechanically stabilised [20–25].

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[1]Interpreted patterns are presented as supplemental data.

These ideas were tested further in two respects. First, a sample from Alloy-Mn was austenitised at 810°C and from Alloy-Ni at 775°C, for 30 min periods; both these temperatures are just 10°C above the respective calculated Ae3 temperatures. The goal was to produce as small an austenite grain size as possible because it is assumed that during adiabatic heating, any austenite grains would have a small grain size due to the rapidity of the process. X-ray analysis (Fig. 10) showed that both alloys contain negligible quantities of austenite upon quenching, so that they are effectively 100% martensitic. The presence of austenite in the shear bands therefore is inconsistent with these being 'transformed bands'. Secondly, the structure illustrated in Fig. 11 has clear martensite plates, inconsistent with the transmission electron micrographs of the shear bands.

The totality of the evidence seems to suggest that for the circumstances of the present work, the shear bands represent plastically warm-deformed regions of the original mixtures of bainitic ferrite, retained austenite and untempered martensite. It is speculated, therefore, that shear banding as a phenomenon could be mitigated by introducing a high density of precipitate particles that would resist the softening of the allotropic lattices of iron.

4. Conclusions

Shear bands that form during the ballistic testing of microstructures consisting of a mixture of bainitic ferrite, carbon-enriched retained austenite and untempered martensite have been characterised using a variety of metallographic and X-ray diffraction techniques. It appears from these observations that the bands consist of deformed layers in which the original structure becomes mechanically mixed, and resembles a warm-worked microstructure that is still in an unrecrystallised state. The observations show that for the circumstances of the present work, the bands are unlikely to represent phase transformation from austenite that forms during adiabatic heating and transforms subsequently into martensite.

By observing the deflection of segregation bands as a function of the depth below the impact surface, it is found that the plasticity spreads laterally as the projectile penetrates, thus reducing the possibility of shear bands. The shear strain within the shear-bands is estimated to be between 2 and 6.

Finally, it is speculated that the introduction of a large density of fine

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carbide particles may help reduce the tendency to localise plastic deformation by making the structure more resistant to softening at high temperatures.

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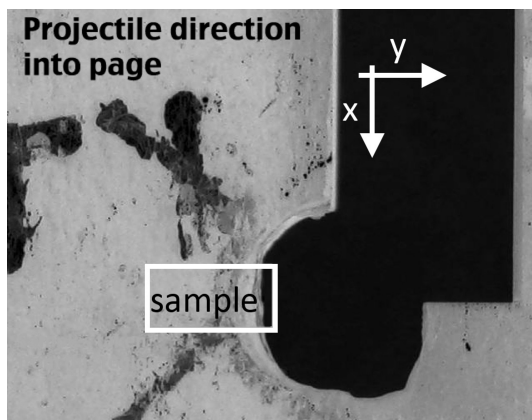
Figure 1: The hole at the bottom is created by the projectile; the location from which samples were extracted is delineated by the rectangle. The coordinates defined are used throughout the paper, with the projectively propagating along $-z$.

(a)   (b)
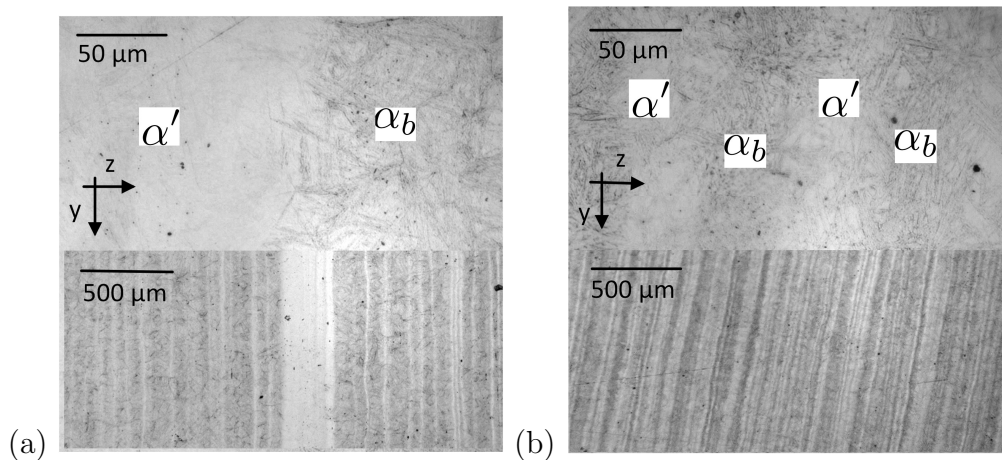
Figure 2: Micrographs illustrating banding, as a function of depth within the steel plate. (a) Alloy-Mn ; (b) Alloy-Ni. The terms α_b and α' refer to regions that are predominantly bainitic or martensitic.
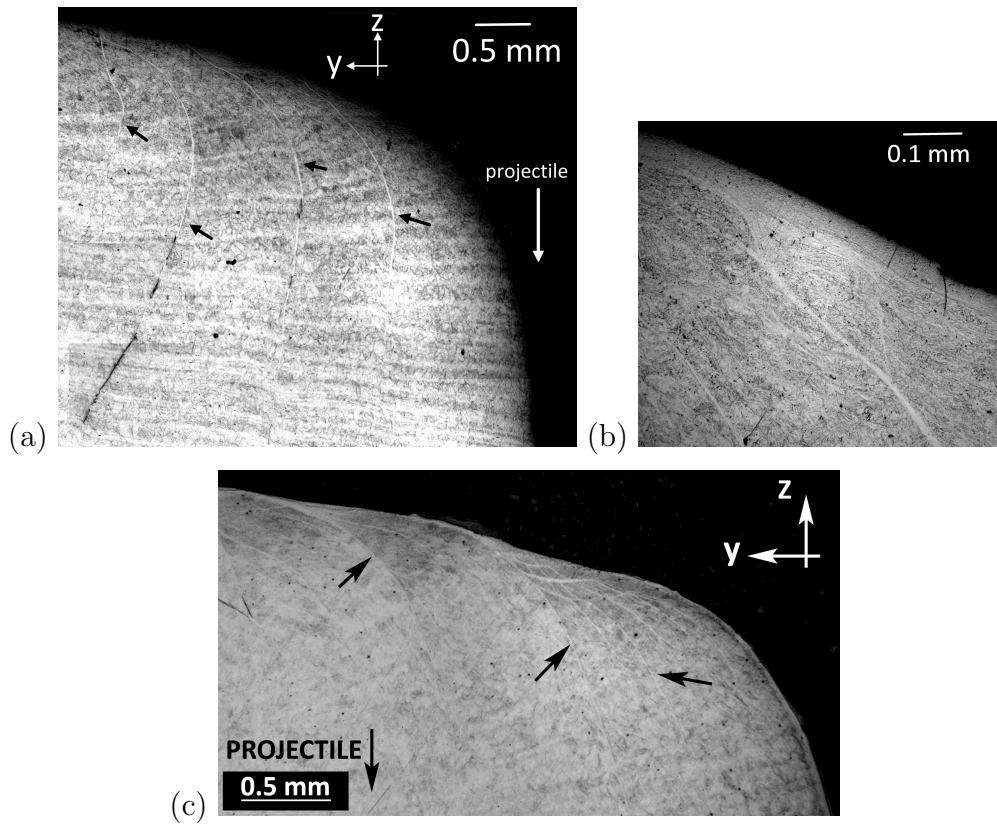
Figure 3: Fine shear bands due to ballistic impact, some of which are indicated by the black arrows. (a,b) Alloy-Mn . (c) Alloy-Ni.
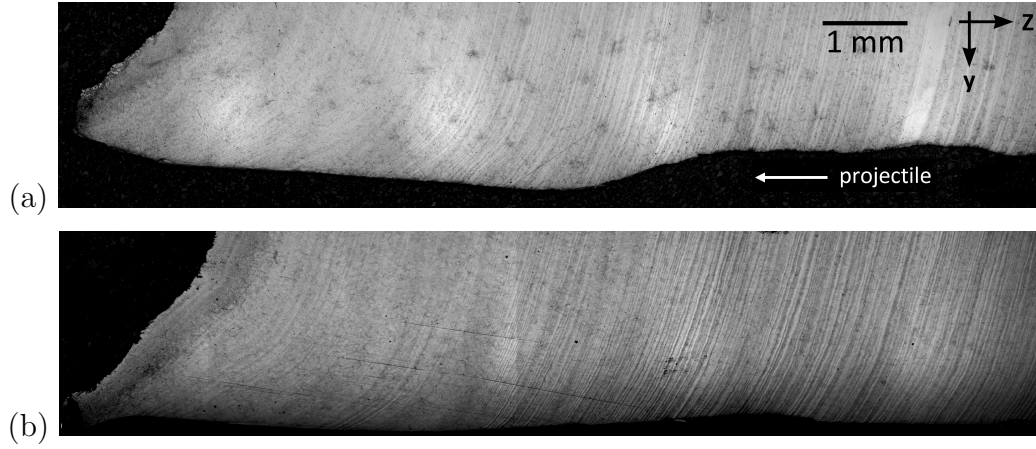
Figure 4: Bullet hole through the depth of the plate, with segregation bands showing the pattern of deformation. (a) Alloy-Mn. (b) Alloy-Ni.
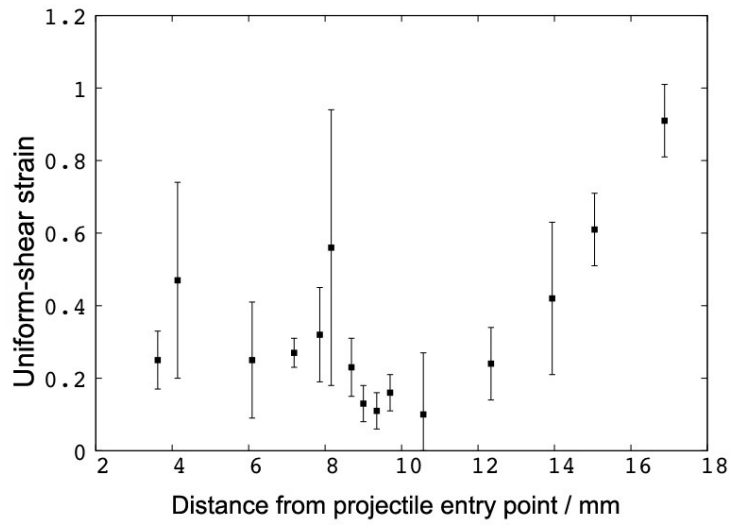
(a)

(b)
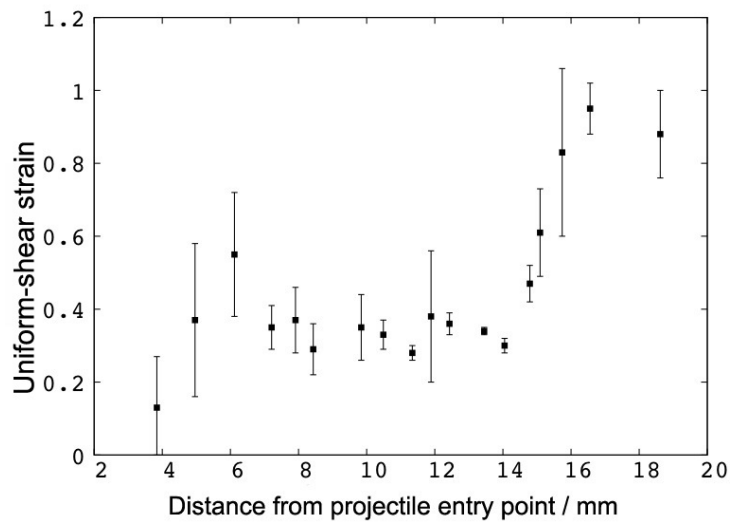
Figure 5: Graphs showing the degree of uniform-shear strain at the surface of the hole as a function of depth of penetration. (a) Alloy-Mn (b) Alloy-Ni
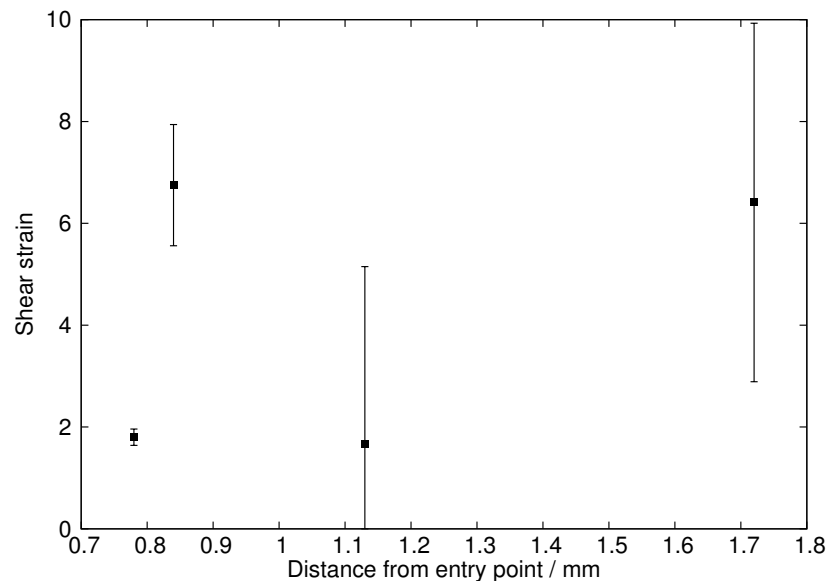
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Figure 6: Graph showing the degree of shear strain within a shear band present in Alloy-Mn, as a function of depth of penetration.
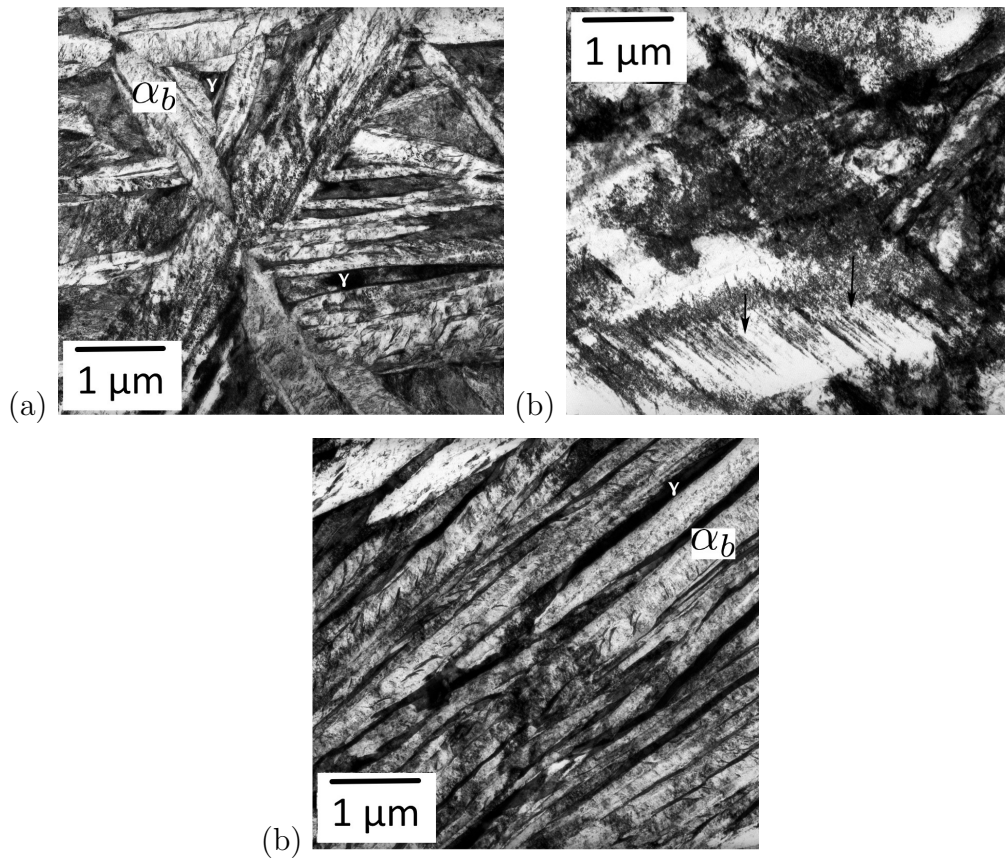
Figure 7: The microstructure in the as-received condition. (a,b) Alloy-Mn. (b) Alloy-Ni.
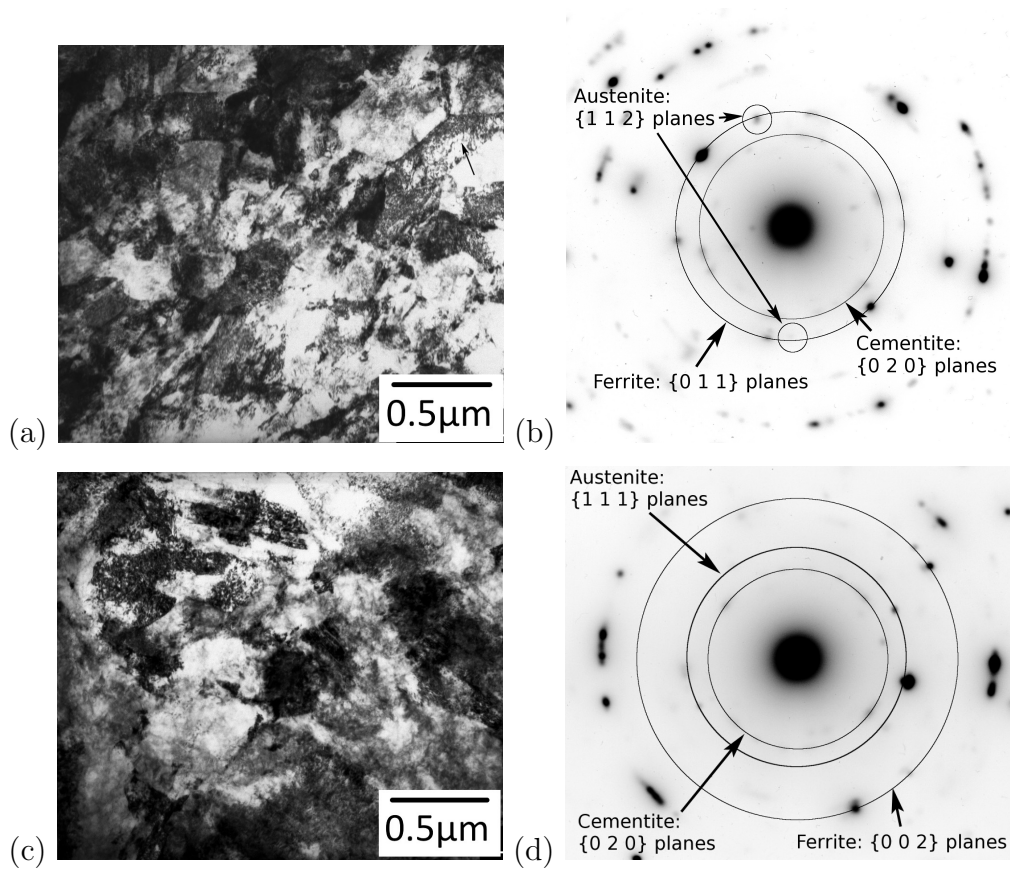
Figure 8: Micrographs of samples extracted from shear bands using focused ion beam milling. (a,b) Alloy-Mn. (c,d) Alloy-Ni.
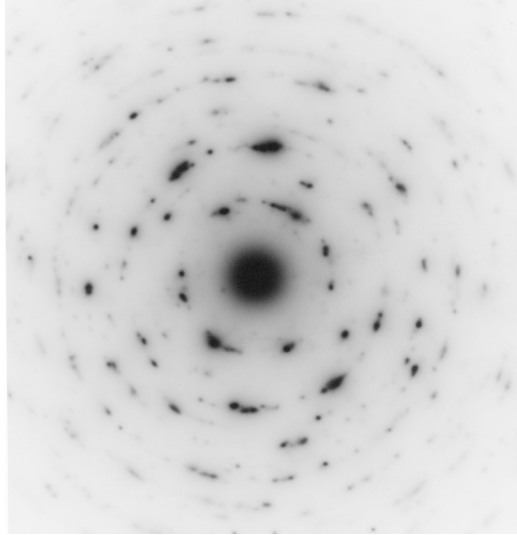
Figure 9: Electron diffraction pattern taken with wide aperture, showing the limited spread of orientations found in the shear band.
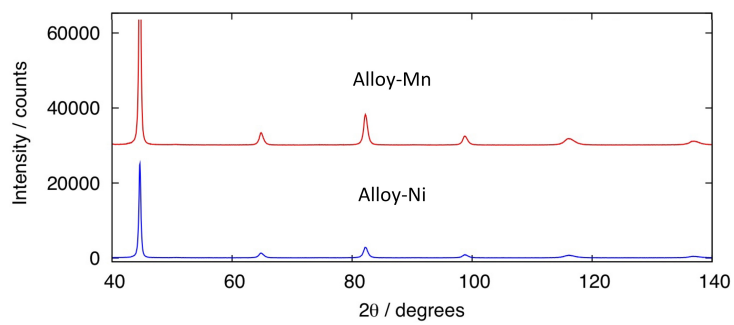

Figure 10: X-ray diffraction spectra of austenitised and quenched martensitic samples, with diffraction peaks visible only from the martensite.
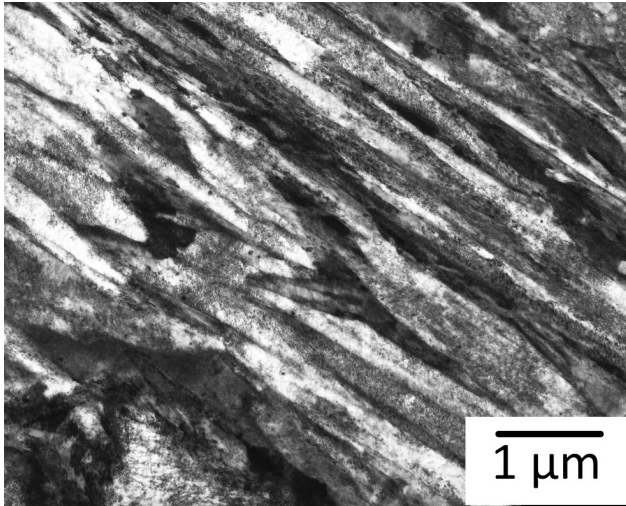
Figure 11: Alloy-Mn in an austenitised and quenched condition showing fine plates of martensite.