The influence of microstructural anisotropy on the mode of plate failure during projectile impact

P. W. LEACH, R. L. WOODWARD
Materials Research Laboratory, Department of Defence, P O Box 50, Ascot Vale, Victoria 3032, Australia

Changes in the failure mode of rolled steel plate during projectile impact were examined in terms of the angle between the planes of microstructural inhomogenieties in the steel and the plane of the target. Two failure modes were identified: (1) discing failure involving multiple shear band formation in the rolling plane with separation along the shear bands to form a disc segment, and (2) tensile star cracking with the propagation of a tensile tear through the rear surface of the plate. Both the ballistic resistance and the predominant mode of failure were critically dependent on the orientation of the microstructural banding in the plate.

1. Introduction

An inherent feature of rolled steel products is a marked anistropy in mechanical properties which derives from the directionality of the microstructure in rolled plate. Chemical segregation produced during casting frequently persists in rolled steel plate in the form of longitudinal banding while many types of non-metallic inclusions are deformed by the rolling process into elongated "stringers" aligned in the rolling direction. These microstructural defects seriously reduce the notch toughness and tensile ductility in the through thickness direction [1, 2], the magnitude of the reduction depending on inclusion volume fraction, morphology and size [3, 4].

While interest in the through thickness ductility of steel plate has mainly been associated with the incidence of lamellar tearing during welding [5], these properties are also considered important in the fracture of armour plate by projectile impact [6]. In particular, the mode of failure classified as discing [7] or scabbing [8], which is evident in medium to high hardness wrought materials, occurs by single or multiple crack propagation along planes parallel to the rolling direction with separation of material along these planes.

The present study was designed to examine the details of discing failure in steels in terms of the directionality of microstructure in rolled steel plate. By the use of thick plate sections, it was possible to cut targets at several angles to the original surface and thereby examine the failure mode and ballistic performance in relation to the microstructural directionality in the sample plate.

2. Experimental procedure

The material used in this study was a 0.29% C–3.2% Ni–1.3% Cr armour steel, quenched and tempered to a hardness of 415 HV with details of composition and heat treatment described previously [9]. Prior to this heat treatment, the steel was cross rolled in order to produce uniform mechanical properties in both transverse and longitudinal directions in the plane of the plate (see directions A and B in Table I), although the usual low ductility was exhibited in the through thickness direction (direction C in Table I).

Target specimens for projectile impact (of thickness 7.3 mm) were prepared by machining the rolled surface of the plate to provide an impact surface either parallel or at an angle of 10°, 20°, or 30° to the rolling plane; the targets were thereby oriented at various controlled angles to the planes of inhomogenities of structure in the rolled plate

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TABLE I Tensile test results in directions A (the rolling direction) and B (transverse to the rolling direction) in the plane of the plate and C, the through thickness direction. All results refer to steel in the heat-treated condition

Direction	0.2% proof stress (MPa)	UTS (MPa)	Fracture stress (MPa)	Reduction area (%)	Elongation (%)
A	1147	1323	1937	48	14
B	1155	1325	1913	47	13.5
C	1115	1136	1170	3	1

as shown in Fig. 1. Targets were impacted at normal incidence by an ogive shaped projectile (0.30 caliber APM2) with a hardened steel core. The projectile velocity, which was measured immediately prior to impact, was adjusted to give either perforation of the plate or no perforation, a condition referred to as the critical velocity. Perforation was evident as the ejection of material from the rear of the target, whether in the form of the projectile and/or fragments of target material. Impacted specimens were later sectioned and metallographically examined.

3. Results and discussion

The measured values of critical velocity are plotted in Fig. 2 as a function of the angle between the target specimens and the rolling plane. Fig. 2 shows a decrease in the critical velocity as the angle was increased away from 0°, followed by a rise as the angle was further increased, such that a minimum occurred within the range 10° to 20°.

Two principal modes of failure were observed; both are shown schematically in Figs. 3 and 4 with examples of major features in Fig. 5. At 0°, 10° and 20° to the original rolled plate, a discing mode of failure was evident as illustrated in Fig. 3. Target bending at the rear of the plate by the nose of the projectile was accompanied by the formation of intense shear bands approximately parallel to the rear surface. The development of the shear bands is shown in a partly penetrated sample in Fig. 5a, with the adiabatic nature of the bands evident at higher magnification (Fig. 5b. Previous studies of adiabatic shear in martensitic steels have shown a strong effect of increasing carbon content on the intensification of shear band initiation [10]. However, attempts to determine from metallographic sections whether the planes on which the shear bands propagated were associated with the microstructural banding or stringer-type inclusions were inconclusive. While the shear bands and accompanying crack propagation generally followed the microstructural banding evident in the material, specimens in which both shear bands and cracks crossed the banding were observed.

With the discing mode of failure, the formation of parallel shear bands was observed to occur preferentially on one side of the perforation (as, for example, in Fig. 5a). Such asymmetry is attributed to the differing response of the microstructure in the zone of bending deformation ahead of the advancing projectile. A tilt of either 10° or 20° given to the microstructure in the initial plate was evidently sufficient to cause differing reorientation effects during bending deformation, resulting in uneven conditions for shear band initiation.

Tilting of the initial microstructure can similarly account for the observed tendency for tensile cracking on one side of the perforation. As shown schematically in Fig. 1, forward movement of the projectile resulted in deformation of microstructural banding on the right-hand side until reoriented to become parallel with the plane of the plate; an orientation favourable for the opening up of tensile cracks along previously existing shear bands. Fig. 5c shows an example of a fully perforated plate in which separation of some of the disc sections is evident.

The other mode of failure, petal separation after tensile fracture [11], principally occurred

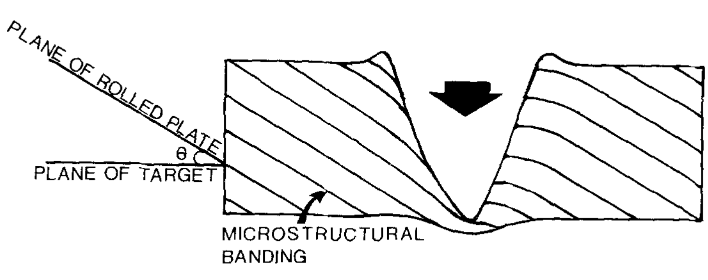

Figure 1 Schematic diagram showing the relation of microstructural banding in the rolled plate to the plane of the target and the deformation of the banded structure due to projectile impact.

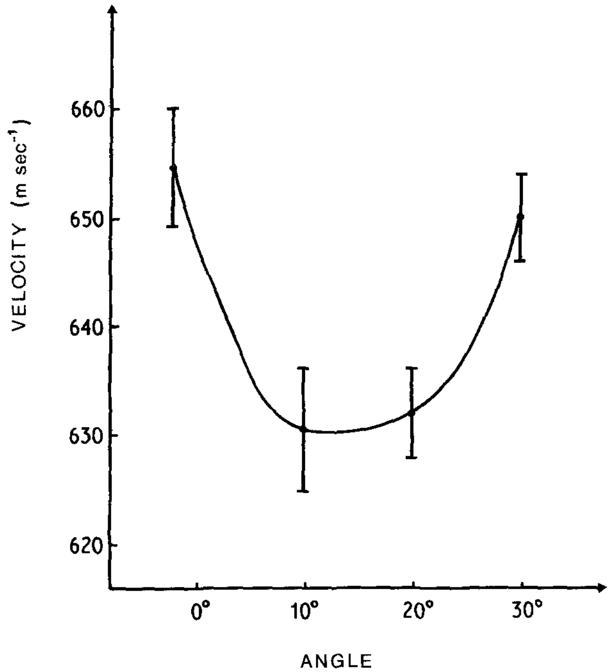

Figure 2 Variation in the critical velocity as a function of the angle between the rolling plane and target plane. The upper limit of the critical velocity is the minimum velocity for plate perforation and the lower limit is the maximum velocity for no perforation.

when the angle between the rolling plane and the target surface, θ, was 30° but was also observed at 0°. As illustrated in Fig. 4, the target material is essentially pushed forward by the projectile, causing tensile tearing to develop in the rear surface of the plate. Once perforation had occurred, the "petals" of displaced material were pushed forward either shearing off along a localized band as in Fig. 5d or becoming folded back while remaining attached to the target.

The two failure modes differed essentially due to the presence or absence of multiple parallel shear bands in the plane of the plate thickness when the rear part of the target was bent away by the projectile. The formation of these shear bands is likely to reduce the work required in bending of the plate [5], an effect which is consistent with the minimum in the critical velocity plot of Fig. 2 at angles of 10° and 20°. However, the major factor controlling penetration resistance by either

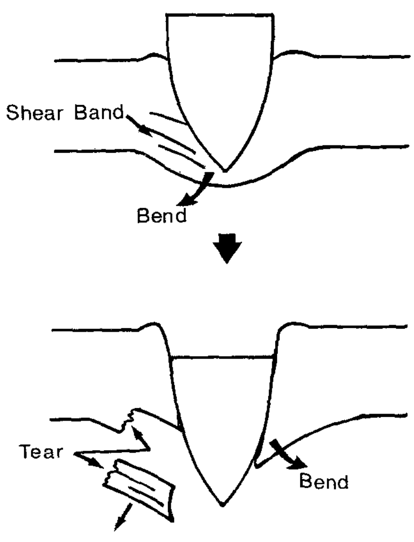

Figure 3 Schematic representation of deformation and fracture during discing failure.

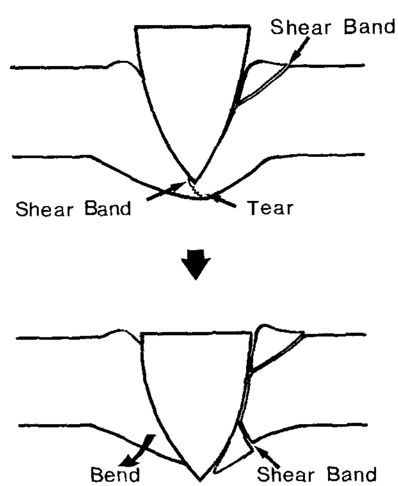

Figure 4 Schematic representation of the tensile star fracture mode of failure showing the initial formation of a tensile tear crack and subsequent deformation.

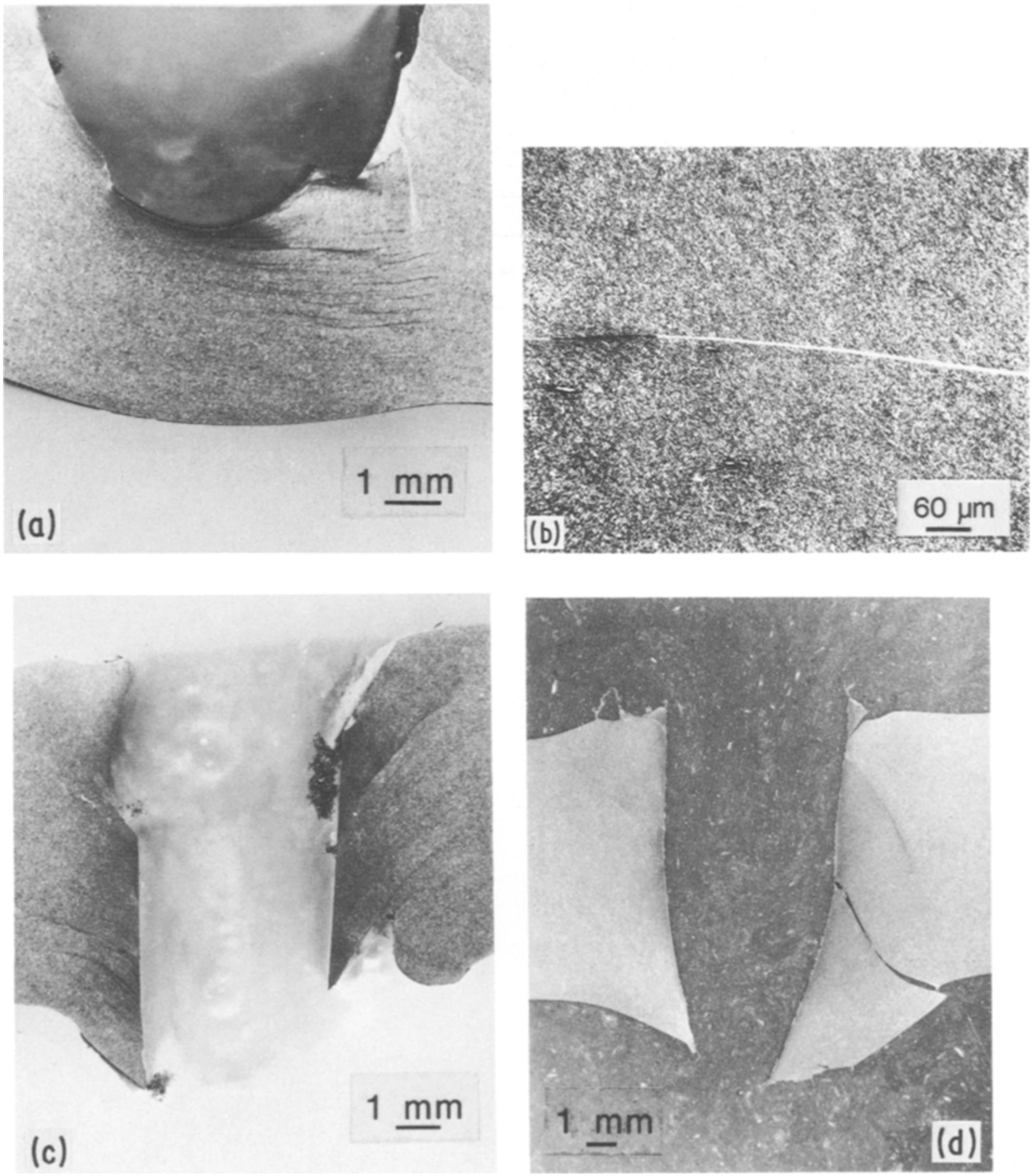

Figure 5 (a) Multiple parallel shear bands evident in a partly penetrated specimen with plate directionality of 10°. (b) Detail of a shear band in Fig. 3a showing white etching character and crack propagation within the band. (c) Fully penetrated specimen showing loss of disc segments on right side. (d) Plate failure by tensile star fracture showing petal separation by shear across the plate.

failure mode is the strength of the metal. This is due to the high proportion of the energy of penetration absorbed by the substantial plastic flow of the target material which precedes fracture of the rear surface [12]. Changes in the mechanism of final breakout, therefore, represent a secondary contribution to the total work done.

4. Conclusions

1. The discing mode of failure in steels was associated with multiple shear band formation in the thickness of the plate with the initiation of shear bands strongly dependent on the orientation of the original rolled structure.

2. The incidence of discing failure at angles of

10° and 20° (the angle between the planes of microstructural homogenieties in the steel and the plane of the target) corresponds to a minimum in the critical velocity for plate perforation.

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