The tensile properties of carburized and uncarburized low carbon mild steel

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The properties of a low carbon mild steel in monotonic tension loading were compared in the plain normalized and the carbo-nitrided slowly cooled conditions. The application of a carbo-nitriding process raised the yield strength of the steel to that of the nominal tensile strength in the uncarburized samples, and increased the nominal tensile strength to a value 45% above that of the plain normalized steel, whilst still retaining a good measure of ductility. The fractures for the plain samples were "cup and cone" type whilst those for the reinforced samples revealed "slant mode" fractures.

1. Introduction

Engineers usually require a material with a blend of high yield strength and good elongation, but these properties are often mutually exclusive. It has been shown [1] that the yield strength of a normalized low carbon mild steel can be increased by inducing strain ageing effects in the steel, until the yield stress attains values up to and beyond the ultimate tensile strength, but unfortunately, the elongation is correspondingly reduced as shown in Fig. 1. Furthermore, the onset of yield at this raised stress is associated with plastic instability and thus the material cannot transfer load at stress concentration points in structures.

Many investigators have shown that single crystals can be strengthened by the presence of a thin coating on the surface. For oxide coatings the results are contradictory. Thus bending experiments on oxidized cadmium [2] and tension experiments on gold, silver [3] and zinc [4] have shown that the critical shear stress to initiate glide is approximately twice that for unoxidized materials. Tests on polycrystalline cadmium and zinc [5] have not, however, shown comparable effects. The results for the torsion testing of both single and polycrystalline iron and zinc have shown strengthening effects associated with oxide coatings [6].

The limited results available on the effect of metallic coatings have shown a strengthening effect, in torsion, associated with the application of zinc and chromium coatings to copper wire, and copper and zinc coatings to gold wire [7]. Single crystals of copper coated with chromium and tested in tension have also shown strengthening effects [8]. However, different effects have been reported for single and polycrystalline zinc coated with copper [7] as only the single crystals

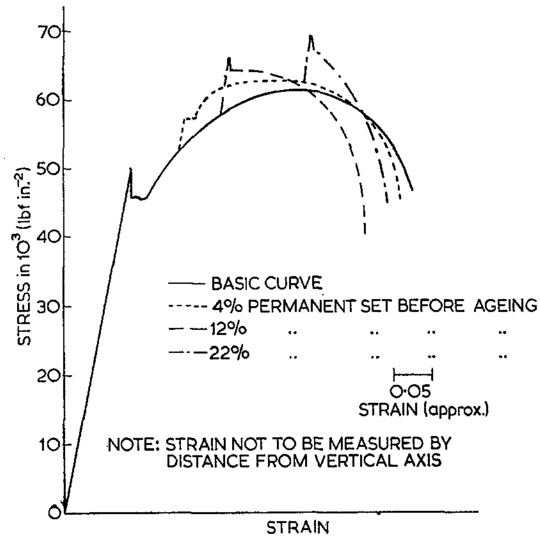

Figure 1 Effect of single ageing treatment on the tensile strength – from [1].

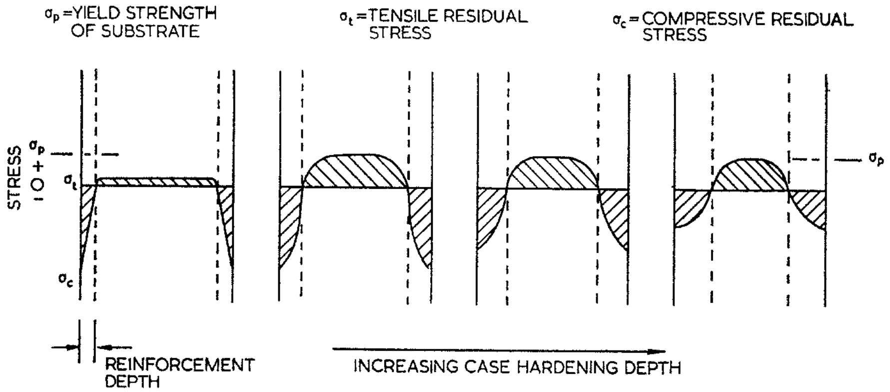

Figure 2 Diagrammatic representation of residual stress pattern with increasing case hardening depth.

showed a strengthening effect. In considering the practical significance of these findings, it must be borne in mind that the strengthening effects reported apply for small diameter wire samples of soft metals. When the effects of coatings on higher strength structural materials are considered, the results available show that a reduction in mechanical strength occurs. Thus, when soft aluminium cladding is applied to a strong alloy to afford corrosion protection [9], a reduction in static strength of up to 12.0% occurs on both 0.1% PS and nominal tensile strengths.

An increase in the yield strength of mild steel can be obtained by applying a carburizing treatment followed by quenching to obtain a martensitic case. The increase in volume associated with the $\gamma - \alpha^1$ transformation causes a residual stress pattern to develop during cooling, the compressive stress at the surface being balanced by a tensile stress at the core [12] and the effect of these residual stresses on the yield strength have to be considered. For a given compressive stress at the surface, any thickening of the martensitic case will result in an increase in the value of the tensile stress in the substrate because of the reduced core area (Fig. 2). The maximum possible value of the tensile residual stress (σ_t) at the core will be governed by the yield strength of the substrate (σ_p) and once this value is attained, the corresponding maximum value of compressive residual stress (σ_c) at the surface will also be reached. When the depth of case exceeds that for which $\sigma_t = \sigma_p$, the value of σ_c will fall, owing to the reduced area of the unhardened substrate, but the value of σ_t will remain unaltered, being equal to σ_p.

Table I shows some residual stress patterns reported for steels of similar carbon contents (approximately 0.18%C) which were developed after carburizing and quenching treatments.

From Table I it can be seen that by increasing the case depth from 5 to 8% of the bar diameter, the residual tensile stress at the core is almost doubled. When, however, the case depth is increased to 20% of the bar diameter, the stress at the core remains at 131.0 MN m^{-2} but the stress in the case drops to 340 MN m^{-2}. Some insight into the levels of the balancing stresses attained between the case and core can be derived from Fig. 2. When the level of the compressive stress at the case induces a tensile stress at the core which attains the value of the yield strength of the steel, the balance of the elastic stresses will be disturbed and plastic deformation of the core should then reduce the

TABLE I Relationship between residual stresses in case and core for various case hardening depths

Bar diameter (mm)	Case depth (mm)	Case depth as % of bar diameter	Residual stress near surface (MN m^{-2}) (compressive)	Residual stress at core (MN m^{-2}) (tensile)
38.0 [10] 8620 steel	1.78	5.0	324.0	70.0
19.0 [11] 8617 steel	1.52	8.0	416.0	131.0
6.3 [11] 8620 steel	1.27	20.0	340.0	131.0

level of the compressive residual stress in the case. The low tensile stress level of 131 MN m^{-2} at the core for case depths of 8 and 20% is considerably below that of the yield strength typical of an 0.18% carbon mild steel in the normalized condition. However, the prolonged soaking treatments within the austenitic range involved in carburizing to case depths of 8 and 20% would provide an opportunity for grain coarsening with a corresponding reduction in yield stress.

The practical importance of the level of the residual tensile stress at the core of a carburized and quenched steel would be particularly important in components subjected to axial-tensile-loadings. The residual tensile stress would be additive to the applied stress and the onset of plastic yielding of the core could occur at relatively low loadings. Campbell and McIntire [10] have measured the residual stresses in carburized and quenched specimens which had been tempered at 425°C and found the tensile stress at the core to be as low as 15.0 MN m^{-2}. Such a treatment would provide a steel with a strengthened case without deleterious tensile stresses at the core. A carburized steel not subjected to a quench treatment should also provide a strengthened surface without large residual stresses due to both the slower cooling required for the $\gamma - \alpha$ transformation and the higher temperatures at which it occurs compared to the $\gamma - \alpha'$ change.

2. Experimental work

Comparative tensile testing of a low carbon mild steel of the En1A type in the plain and carburized conditions was carried out in an Instron machine at a strain-rate of 0.05 min^{-1}. Cylindrical tensile specimens of 4.06 mm diameter were used and the mechanical properties shown in Table II were obtained in the normalized condition.

Carbo-nitriding was carried out in a sodium cyanide bath at 920°C, the bath being maintained at a cyanide content of 22% throughout the process, to give a carbon content of approximately 0.7%. Samples with a range of thickness of carburized layer up to a maximum of 0.49 mm (12% of the diameter) were prepared and to ensure constant grain sizes in both case and core of all samples a "split" carburizing treatment was adopted. This involved removing the samples from the salt bath 6 min before the lapse of the scheduled carburizing time and then reheating to complete the treatment. The recrystallization involved in this interruption of the carburizing soak provided a grain size of approximately 0.03 mm diameter which was equal to that of the normalized unreinforced steel. All the samples were slowly cooled to room temperature after carburizing.

Micro-hardness surveys were carried out at various load levels in the tensile test. Topographical details of the fracture surfaces were examined with a scanning electron microscope.

3. Results

Micro-sections of the carburized specimens revealed a general distribution of carbon in the surface layers in the form of pearlite (Fig. 3) with no evidence of grain-boundary carbide (Fig. 4).

Comparative stress-strain diagrams of the carburized and plain steels are shown in Fig. 5 and reveal that the yield strength of the steel with a carburized layer of depth 0.45 mm has been raised to the level of the nominal tensile strength of the un-carburized plain steel. Also, that the nominal tensile strength of this case carburized steel is approximately 130 MN m^{-2} higher than its yield strength.

In Fig. 6, the influence of varying the depth of the carburized layer on the yield strength and nominal tensile strength of the steel is revealed. The yield strength seems to reach a plateau at a reinforcement depth of about 0.4 mm. All the carburized examples showed a "slant" mode fracture (see Fig. 7) whilst a "cup and cone" fracture was obtained for all of the plain steel samples. Micro-hardness surveys of both the plain and carburized specimens are shown in Figs. 8 and 9.

4. Discussion of results

From the comparative stress-strain diagrams

TABLE II Mechanical properties of En1A steel in the normalized condition, the test pieces being prepared to a fine turned finish

Nominal tensile strength (MN m^{-2})	Upper yield strength (MN m^{-2})	Lower yield strength (MN m^{-2})	El%	RA%	Hardness no. 30 kg
450.0	340.0	306.0	40.0	57.0	127.0

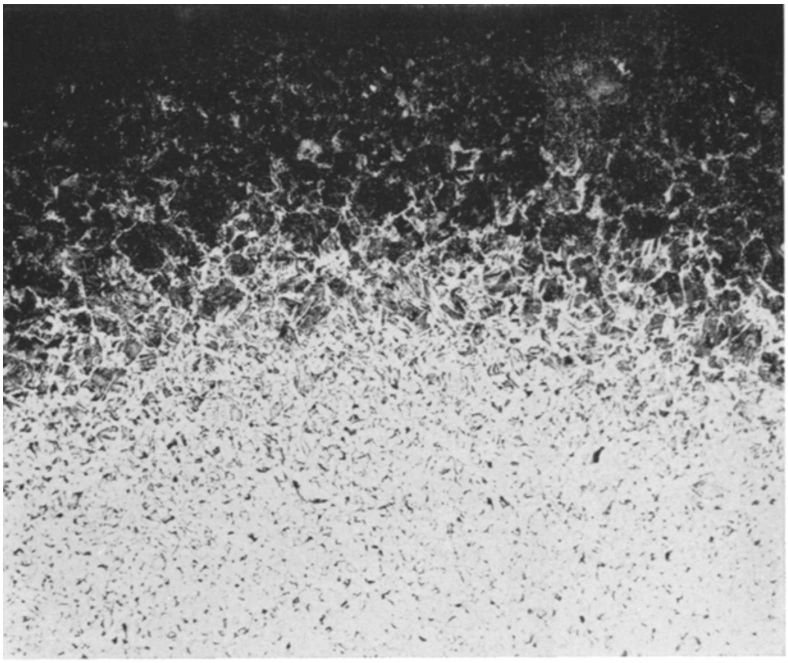

Figure 3 Micro-section of reinforced layer. Nital etch (× 180 approx.)

Figure 4 Micro-section of reinforced layer. Sodium Benzoic etch (× 1500).

shown in Fig. 5 it can be seen that a carbonitriding treatment can raise the yield strength of the steel to the level of the nominal tensile strength of the plain material. Some insight into the distribution of plastic deformation and the extent of strain hardening during tensile loading

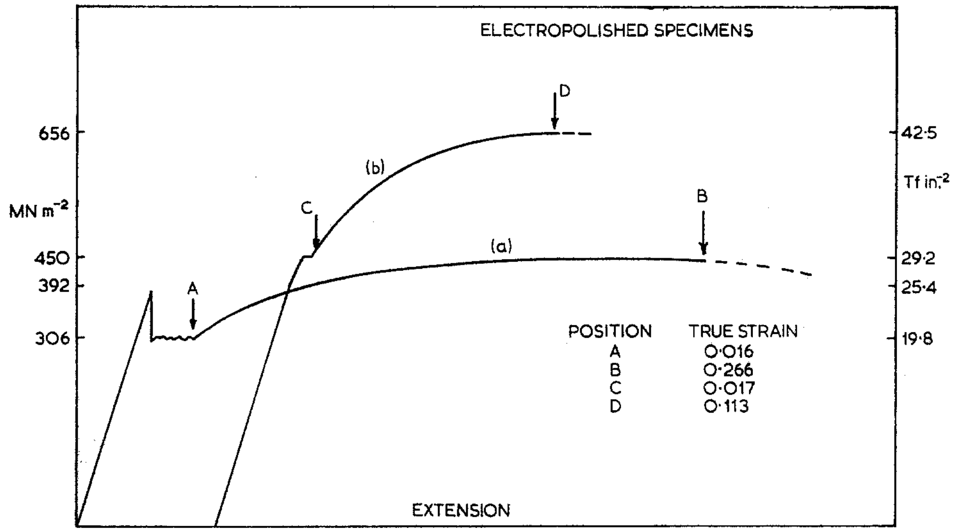

Figure 5 Tensile data for: (a) a normalized parallel specimen; (b) parallel specimen reinforced to a depth of 0.45 mm.

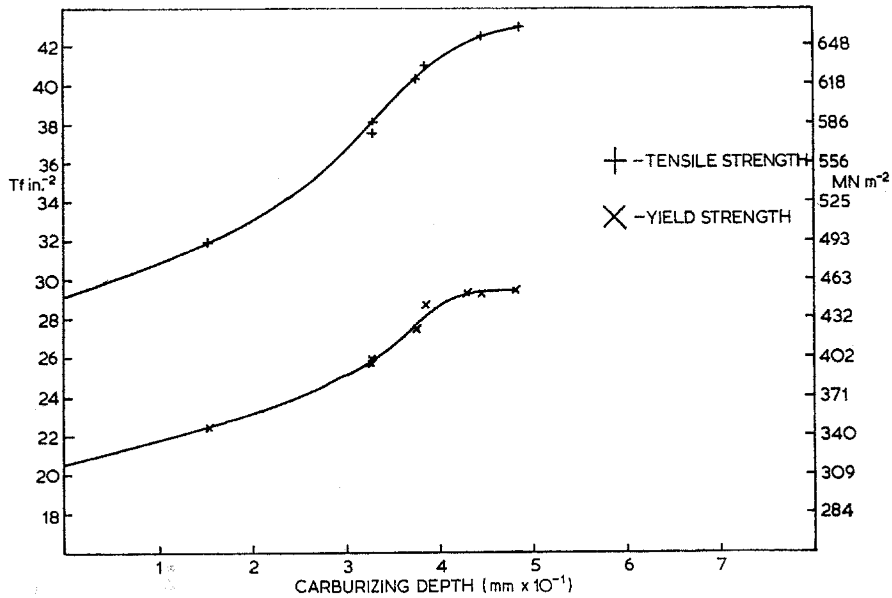

Figure 6 Tensile data for reinforced parallel specimens tested under monotonic tension.

of the two materials can be derived from the micro-hardness data.

The micro-hardness survey of the uncarburized steel (see Fig. 8) reveals that at the completion of the discontinuous yielding in the stress-strain diagram (position A – Fig. 5) some differential strain hardening has occurred, the surface layers increasing in hardness value by 30 units, whereas the core material has only increased by 10 units. When, however, the peak load at the nominal tensile strength is attained (position B – Fig. 5) an outer annulus consisting of approximately 90.0% of the cross-sectional area has a uniform hardness and only the remaining 10.0%

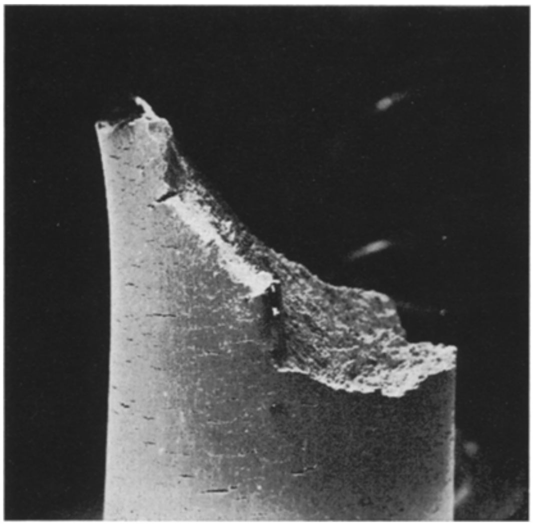

Figure 7 "Slant mode" fracture of reinforced specimen (× 15 approx.)

area at the core gives lower hardness values.

The hardness survey for the carburized material (see Fig. 9) shows that after yielding (position C – Fig. 5) the hardness at the centre of the test piece has increased by approximately 10.0 units and this increase in hardness is distributed uniformly at the core of the material, whereas there is no detectable change in hardness within the carburized case. When the stress level of the nominal tensile stress is attained at position D (Fig. 5) there is evidence of strain hardening in both case and core. It thus appears that the pattern of strain hardening is significantly different in the plain and carburized samples. In the uncarburized steel, strain hardening is initiated at the surface layers and progresses towards the centre of the test piece. When, however, the surface layers are carburized, there is a raising of the yield strength (see Figs. 5 and 6), and at the yield point the core material strain hardens significantly and uniformly (see Fig. 9). It thus appears that the yield strength of a mild steel can be considered under two distinct conditions relating to the core material:

1. the yielding of the core grains associated with a plastic zone initiated at the relatively weak surface grains of the uncarburized steel;
2. the yield of the core in the absence of prior yield at a weak surface, the carburized layer preventing the premature yielding of the surface layers.

The premature yielding of the relatively weak surface grains would entail increased loading of the core compared to the surface layers during subsequent extension of the test piece, as the plastic modulus of the steel is considerably lower than that of its elastic modulus. The yield strength-reinforcement depth plot of Fig. 6 shows a progressive increase in yield strength

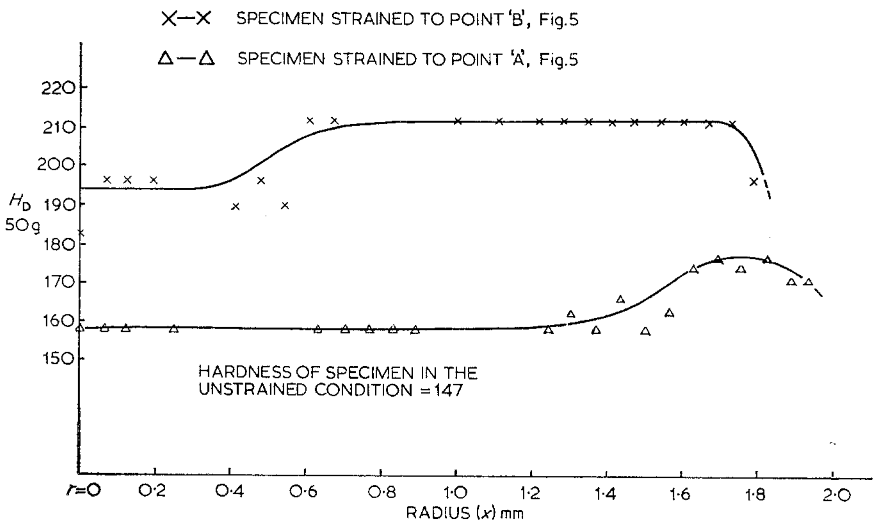

Figure 8 Micro-hardness survey of normalized parallel tensile specimens tested to the plastic instability stress (σ_P) and the yield plateau stress (σ_{YL}).

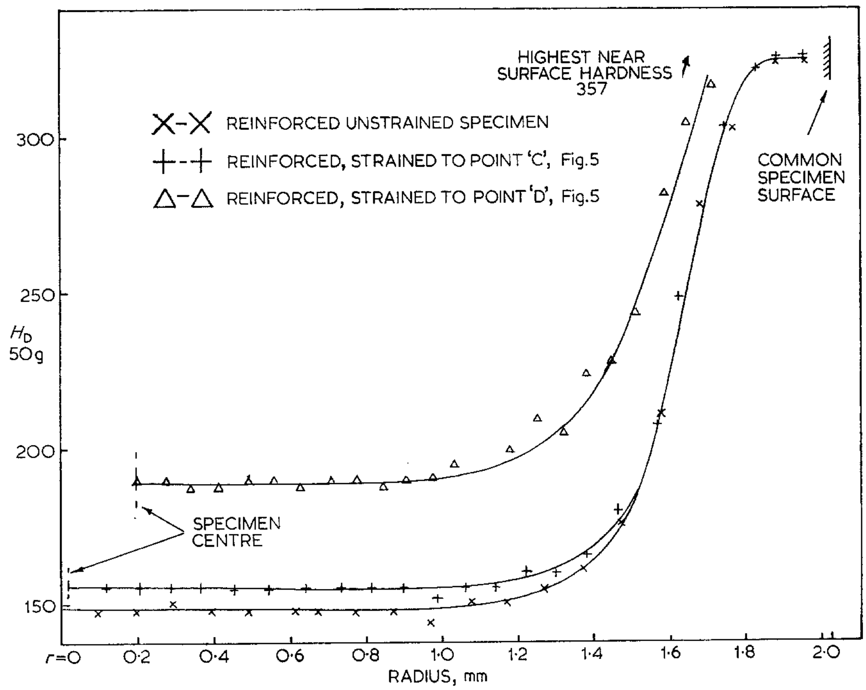

Figure 9 Micro-hardness survey of reinforced unstrained and strained specimens.

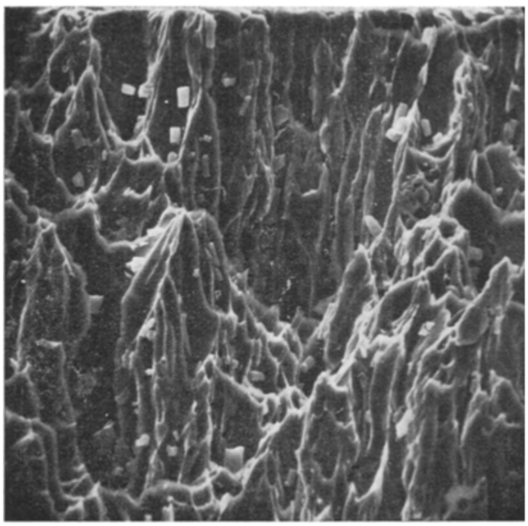

Figure 10 Contours of fracture surface, view taken at the centre of the specimen and normal to its axis (× 900).

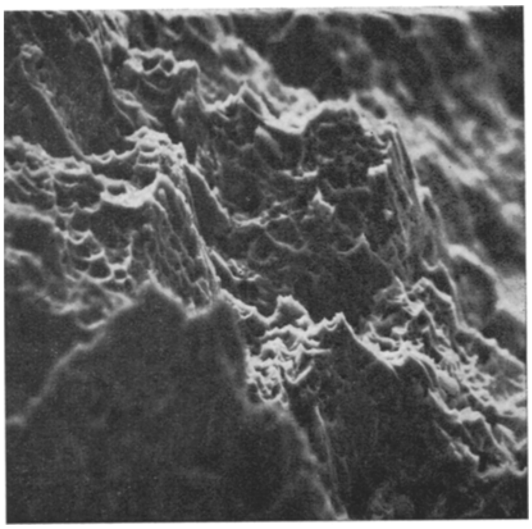

Figure 11 Contours of fracture, view taken of reinforced region approximately parallel to the specimen axis (× 840).

with increasing depth of carburizing until a carburizing depth of 0.4 mm is attained. Beyond this case depth, there is no further increase in yield strength and this plateau in the graph would probably correspond to a transition from type (1) to type (2) yielding of the core material.

The contours of the fractures obtained from the reinforced specimens are shown in Figs. 10 and 11. Fig. 10 reveals the characteristics of the substrate in the carburized material whilst Fig. 11 shows that of the carburized layer. There

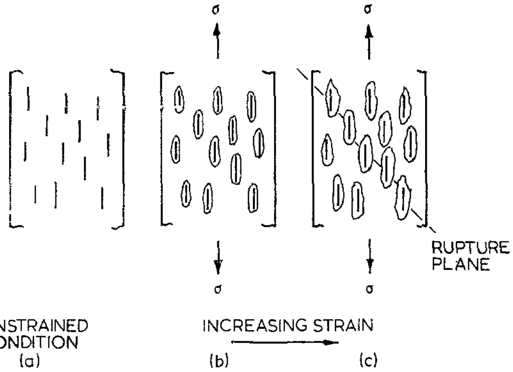

Figure 12 Diagrammatic representation of "slant mode" failure.

is evidence of considerable plastic flow during fracture in both. Final rupture occurred in a manner analogous to that encountered in the tensile necking and "cup and cone" fracture of ductile metals, but the fracture occurred along the plane of maximum shear stress throughout the cross section. It can be inferred, therefore, that triaxial stresses in the material are at a low level, otherwise general crack propagation in the centre of the specimen would have occurred in a direction normal to the axis of straining. Fracture appears to be initiated at the sulphide inclusions. If these inclusions are weakly bonded to the matrix, the applied stress would separate the inclusions from the surrounding metal to form voids. Such voids would elongate in the direction of the applied stress and grow normal to this axis by localized plastic thinning of the ductile membrane (Fig. 12), and this method of plastic deformation appears to conform with the fractographic evidence. The plastic deformation of the membrane approaches ideal ductility, necking down to chisel-edged failures between the voids. Final rupture is caused by shear decohesion as the cavities join up to form elongated dimples on the plane of maximum shear stress. Although Fig. 7 shows a single "slant" mode fracture surface some V-shaped shear fractures were also obtained and the above model will apply to both types of fracture.

Table III shows the relationship between the increase in hardness values and the increase in flow stress attained for the strain hardening range between the yield strength and the nominal tensile strength of the steel.

The increase in hardness for the plain steel is greater despite a smaller increase in flow stress over the strain hardening range. These results emphasize the change in the mode of plastic deformation induced in the steel by a carburizing treatment.

Considering the requirements of the engineer for higher yield strengths in the widely used mild steels, without incurring a substantial loss of ductility and fracture toughness, a carburizing treatment without quenching appears to provide this desirable goal. Furthermore the carburizing treatment would avoid the addition of alloy elements which can contaminate scrap metal and complicate remelting techniques. The elimination of the quench treatment should also avoid distortion problems and quench cracking dangers. The absence of residual tensile stresses in the core would be of special benefit in components subject to tensile-axial-loadings. For the experimental conditions obtaining in this investigation a carburizing depth of 0.4 mm (10% of the diameter) appears to provide the optimum advantage.

5. Conclusions

The application of carburizing without a quenching treatment to a mild steel can raise the yield strength in monotonic tension by up to 30% and the corresponding nominal tensile strength by 45% as compared to the properties of the normalized material.

The improvement in yield and tensile strength induced by carburizing without quenching is accompanied by a reduction in ductility, but even in the highest tensile strength condition the

TABLE III Relationship between increase of yield strength and increase in hardness values for the strain hardening range between yield and nominal tensile strength

Material	Strain hardening range – yield – NTS strength ($MN\ m^{-2}$)	Corresponding increase in hardness at position 0.8 mm from centre 50 g load	Corresponding increase in hardness at centre of test piece 50 g load
Plain steel	144.0	55.0 units	38.0 units
Carburized steel	206.0	33.0 units	33.0 units

steel exhibits a ductility (as measured by a reduction in area) of 12%.

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