

Experiments to Separate the Effect of Texture on Anisotropy of Pipeline Steel

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Abstract

Many linepipe steels exhibit a variation in mechanical properties as a function of the orientation of the test sample relative to the rolling and transverse directions of the steel plate. Such anisotropy limits the optimum design and exploitation of the steel, and its occurrence has been attributed to effects such as microstructural banding and the associated delamination during fracture, and unfavourably oriented ferrite cleavage-planes. It is often difficult to separate the factors, but an experiment has been designed and implemented to study the role of crystallographic texture in isolation. It is demonstrated that the texture plays a major role in influencing the anisotropy of Charpy test energy.

Keywords: pipeline steel, anisotropy, crystallographic texture, memory effect

1. Introduction

The anisotropy in the mechanical properties of hot-rolled steel which is subsequently made into pipes compromises the optimum design of pipes [1, 2]. In the case of spiral-welded pipes, the circumferential direction lies at 45° to that in which the steel is rolled, an orientation which has the lowest toughness and yet is exposed to the highest loading from hoop stress [2–5].

Factors such as aligned inclusions, elongated grains and crystallographic texture all influence the orientation dependence of mechanical properties; there is an extensive literature on the subject, for example, [6–23]. Crystallographic

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texture can influence anisotropy by increasing the probability of cleavage planes being parallel to the fracture plane of Charpy specimens [12, 19, 24], or by biasing the slip systems available for ductile fracture [19]. However, the role of crystallography is not well-established. Some studies indicate a lack of correlation between the texture and the orientation dependence of Charpy properties [11, 13, 25, 26].

It is in practice difficult to separate the roles of the individual causes of anisotropy, partly because most studies of linepipe steels are conducted on the steel supplied in its final state, with a determined microscopic and crystallographic structure. In a recent study on a specific X80 steel where inclusion alignment is absent [27, 28], it was established that the anisotropy of Charpy properties can be attributed to a combination of delamination (caused by microstructural banding and variations in crystallography between adjacent bands) and by crystallographic texture. The latter cause was considered to be secondary in importance, a conclusion reached by testing unconventional notch orientations. However, the purpose here was to obtain further supporting evidence by designing two experiments in which microstructural banding is eliminated but the crystallographic texture retained.

2. Method

Many of the experimental details have been published previously [27] and hence only new procedures and repeated information which adds to clarity are presented here. The X80 steel chemical composition and processing parameters are listed in Table 1.

A heat treatment was designed with the purpose of eliminating microstructural banding while preserving the crystallographic texture. Banding arises because of chemical segregation during solidification, particularly of manganese. The concentration variations inherited from solidification then spread out into layers during the deformation used to shape the cast form into steel plates. The transformation of austenite into ferrite then occurs first in the manganese-depleted regions, and as a result carbon is partitioned into the manganese-enriched regions, when then transforms in harder products. It is well known that such banding can be avoided by rapid cooling since transformation is suppressed to greater undercooling so that nucleation then occurs in all locations, thus avoiding the segregation of carbon [29]. The heat treatment selected was therefore to quench the samples from the austenitisation temperature.

The austenitisation treatment clearly must be above the $Ae3$ temperature which was calculated to be 840°C using MTDATA [30] and the TCFE4 database (allowing austenite, ferrite, cementite and alloy carbides to exist, and the components Fe, C, Mn, Si, P, S, Nb, Ni, Mo, Ti, Al, N). Dilatometric experiments revealed an $Ac3$ temperature of 860°C for heating at 5°C s^{-1} [28] so the austenitisation temperature was chosen to be 890°C and the austenitisation time, 10 min. The temperature needs to be as low as possible so that significant austenite grain growth is prevented, and hence the original ferrite transformation texture is retained on quenching, through what is known as a *texture memory effect* [31, 32].

Orientation distribution functions (ODFs) were measured using $\text{Co-K}\alpha$ X-ray diffraction. The samples for this purpose were prepared using $6\ \mu\text{m}$ diamond paste for the final polish, and the distributions of the $\{110\}$, $\{200\}$, $\{211\}$ and $\{311\}$ poles were used to generate the ODFs. Samples for electron backscatter diffraction (EBSD) were mechanically polished using colloidal silica in the final stage of preparation.

3. Results and discussion

One of the most important anisotropies present in linepipe steels is that of Charpy impact toughness as a function of the orientation of the notch with respect to the plate axes. It has been shown [27] that the sharp minima observed in toughness within the ductile–brittle transition temperature range (≈ -40 to -60°C) as a function of orientation is related to two factors, the lack of delamination during fracture, and a propensity for the cleavage planes in the banded microstructure to align with the macroscopic fracture plane of the Charpy specimen. Supporting information, including microstructure, orientation maps and mechanical properties have already been reported [27]. Fig. 1 summarises the observations and much more detail is available in the original publication [27].

Similar experiments were repeated after reaustenitising and quenching the as-received steel. The resulting microstructure is illustrated in Fig. 2 as a function of orientation relative to the plate axes including the rolling direction. The essential point from the comparison against the banded structure illustrated in Fig. 2a is that the heat treatment has eliminated the microstructural anisotropy in the form of banding. As a consequence, the set of Charpy impact fractographs shown in Fig. 3 shows the absence of delamination or fissuring as it is sometimes called (*cf.* Fig. 1d).

In spite of the elimination of banding and delamination, the variation in Charpy toughness in the impact transition region, as a function of sample orientation is still very strong. The raw data are shown in Fig. 4a. The data are also shown in the form of plots where the radial distance from centre corresponds to the energy absorbed, so that energies recorded from an isotropic sample would follow the quadrant of a circle. Figs 4b,c show that the anisotropies of the as-received and heat-treated samples are similar. This is because the crystallographic texture has not changed much as a consequence of the heat-treatment given to the as-received steel, Figs 5,6. The figures are represented using identical colour scales, and while there are differences in the strength of the textures, both the as-received and quenched samples show similar patterns of behaviour in each of the sections of the orientation distribution maps.

This is a remarkable result given that the dramatic nature of the austenitisation and quenching heat treatment, but can be explained on the basis of a well-known memory effect [31, 32]. There are strong orientation relationships generated when austenite transforms into ferrite. This applies also to the formation of austenite during heating from a fully ferritic structure. As a result, the original texture generated in the pipeline steel which arises because of the existence of strong orientation relationships between the nucleating phase (austenite during heating) and the existing ferrite. This relationship persists during both forward and reverse transformation, unless significant austenite grain growth occurs during prolonged heat-treatment or due to austenitisation at a very high temperature. For the present purposes, this observation provides a unique way of proving the large effect of texture in the absence of overlap of information with phenomena such as microstructural anisotropy or banding.

The role of texture is in terms of the alignment of $\{100\}_\alpha$ planes in the polycrystalline steel, along specific directions relative to the rolling direction. The propensity of such cleavage-planes along a particular orientation must make for easy fracture. Fig. 7 show that the distributions of these planes relative to the rolling direction are comparable for the as-received and heat-treated steels.

The totality of the results from our previous work [27] and the new experiments have been summarised in Fig. 8 using an index defined as follows:

$$\text{Anisotropy index} = (J_{\text{maximum}} - J_{\text{minimum}}) / J_{\text{overall maximum}}$$

where J represents the energy absorbed during a Charpy test and the subscripts ‘maximum’ and ‘minimum’ represent the values of J at a given test temperature.

Comparison of anisotropy index of as-received steel with the heat treated one without the influence of delamination shows with clarity that crystallographic texture has a profound influence on the Charpy anisotropy in the X80 steel studied here.

The density of high-misorientation grain boundaries ($> 15^\circ$) did not vary significantly with orientation relative to the plate axes; these results are not reported here for brevity but are available in [28].

Finally, it is noted that the general reduction in Charpy toughness in the quenched samples relative to the as-received pipe is because the former is much harder at 296 ± 6 HV when compared with the thermomechanically processed pipe which has a hardness of 220 ± 4 HV.

3.1. Isothermal Transformation

An independent experiment was conducted in which X80 steel similar to that described in Table 1 was austenitised at 900°C for 20 min and then isothermally transformed at 400°C for 10 min followed by air cooling, to generate the bainitic microstructure illustrated in Fig. 9a; microstructural banding is absent. A full texture evaluation was carried out [33] but the $\phi_2 = 45^\circ$ sections of the orientation distribution functions, for the samples before and after heat-treatment are also illustrated in Fig. 9b,c. It is evident that the texture is weakened by the heat treatment, more so than in when the steel was transformed into martensite. The Charpy tests (Fig. 10) confirm that toughness-anisotropy in the impact transition regions remains but is reduced, consistent with the change in texture.

4. Conclusions

Unique experiments have been designed to retain the crystallographic texture of X80 linepipe steel whilst eliminating microstructural banding and delamination during fracture. As a consequence, it is possible to reach the following conclusions:

- (a) There exists a memory effect which reproduces the crystallographic texture of processed X80 steel after austenitisation under conditions which avoid significant austenite grain growth, followed by quenching to room temperature.

- (b) The role of the texture is uniquely established as a major cause of Charpy toughness anisotropy, without clouding the interpretation with the possible influence of delamination or microstructural banding. The anisotropy is particularly pronounced in the temperature range where there is a ductile to brittle transition in the mode of fracture.

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Table 1: Chemical composition (wt%) and thermomechanical processing conditions. A_{r3} represents the temperature at which austenite begins to decompose during cooling. Please note that the exact chemical composition and processing is proprietary information.

C	Mn	Si	P+S	Nb+Ni+Mo	Ti+Al	N
< 0.08	< 2.0	0.21	< 0.013	< 0.8	0.03	< 0.0036
Reheating temperature				1100–1180°C		
Cooling start-temperature				Above A_{r3}		
Finish rolling temperature				Above A_{r3}		
Coiling temperature				> 500°C		

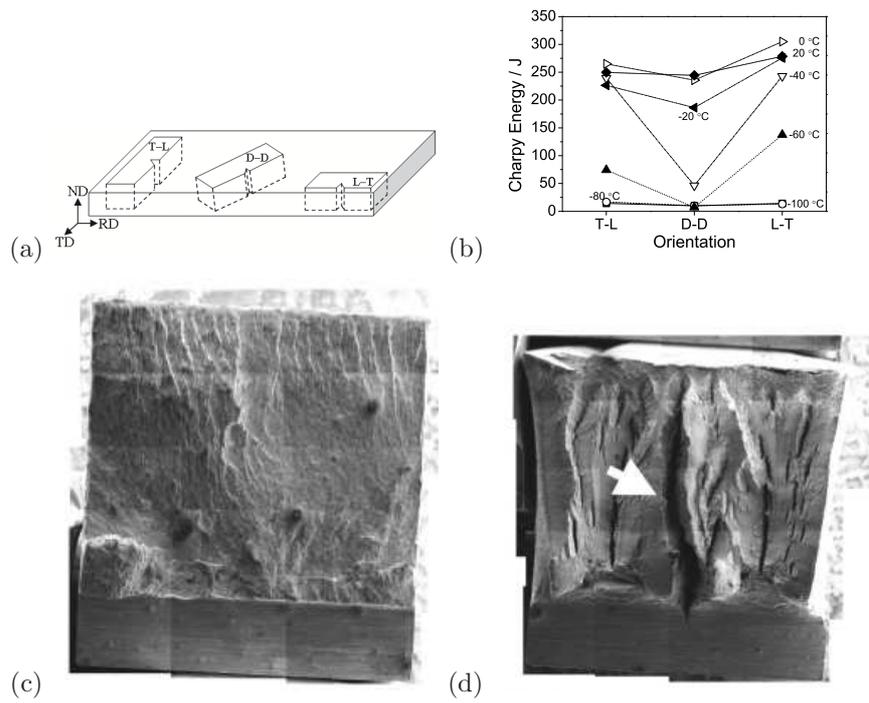


Figure 1: As-received X80 steel. (a) Orientations of Charpy test samples relative to steel plate, where ‘RD’, ‘TD’ and ‘ND’ stand for the rolling, transverse and normal directions. (b) Measured variation in Charpy toughness with notch orientation. (c) Lack of delamination in sample tested in the D-D orientation at -60°C . (d) Heavy delamination in sample tested in the L-T orientation at -60°C . All the data illustrated here are from [27].

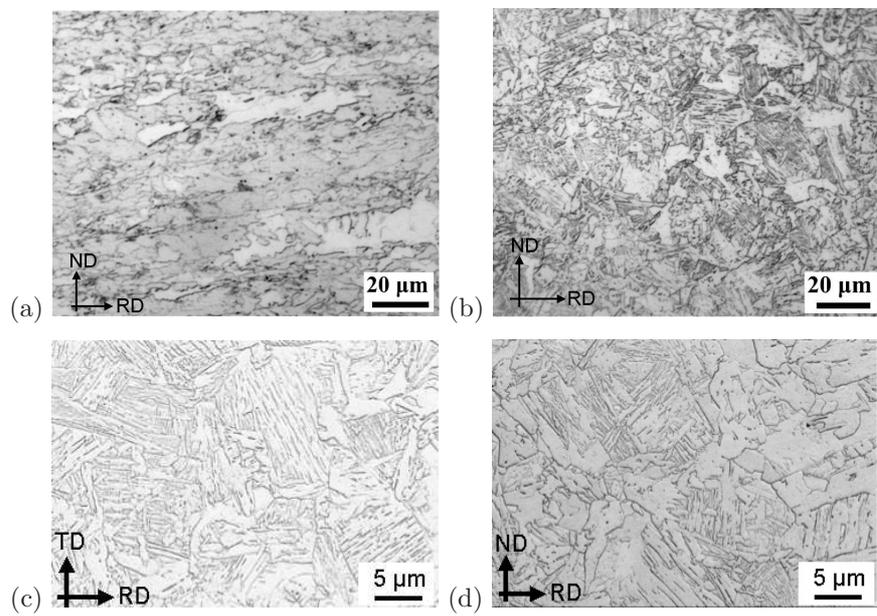


Figure 2: X80 steel. (a) In the as-received condition to illustrate the banding [27]. (b) The corresponding structure following heat treatment. (c,d) Higher magnification images of the heat-treated microstructure.

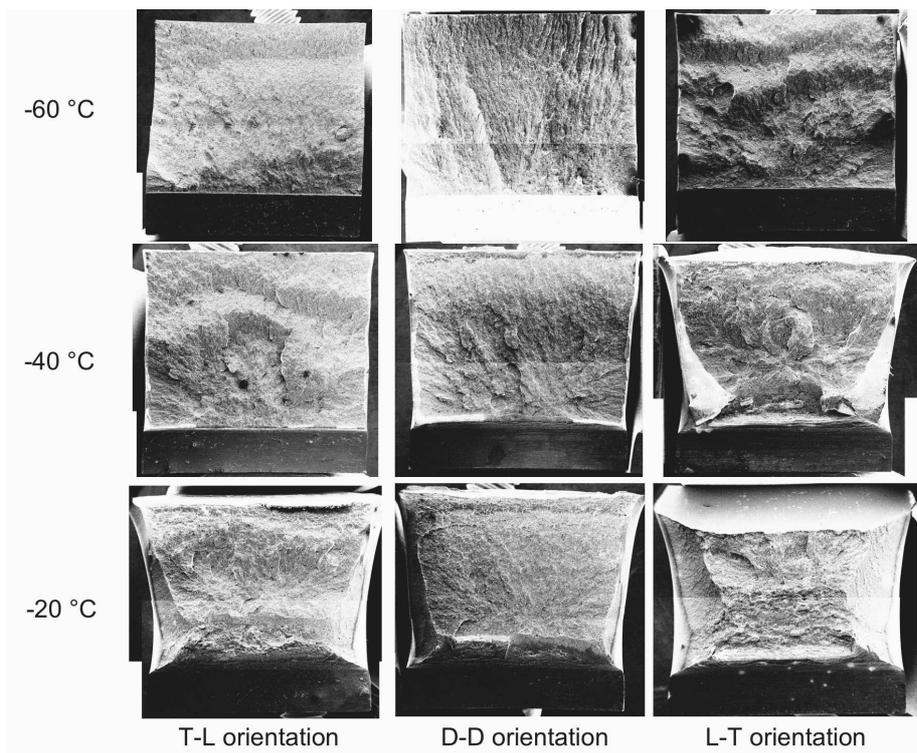
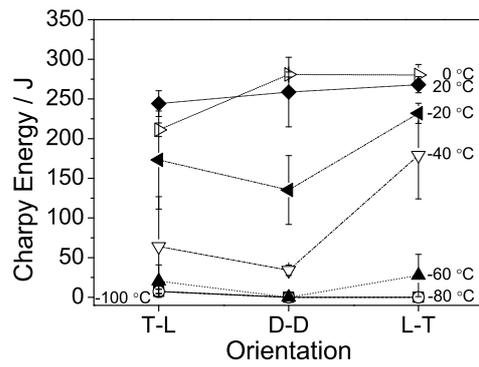
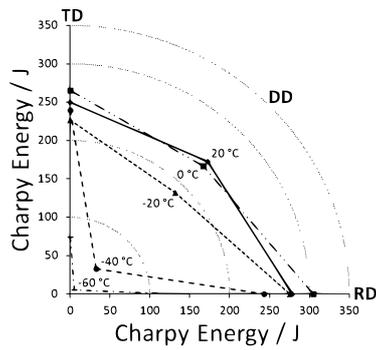


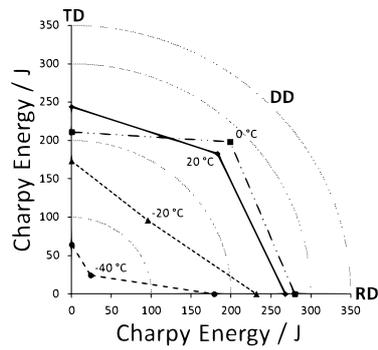
Figure 3: Fracture surfaces of Charpy specimens from heat-treated samples.



(a)



(b)



(c)

Figure 4: Charpy toughness data. (a) Raw data for heat-treated sample. (b) Anisotropy of as-received steel on a radial plot. (c) Anisotropy of heat-treated steel on a radial plot.

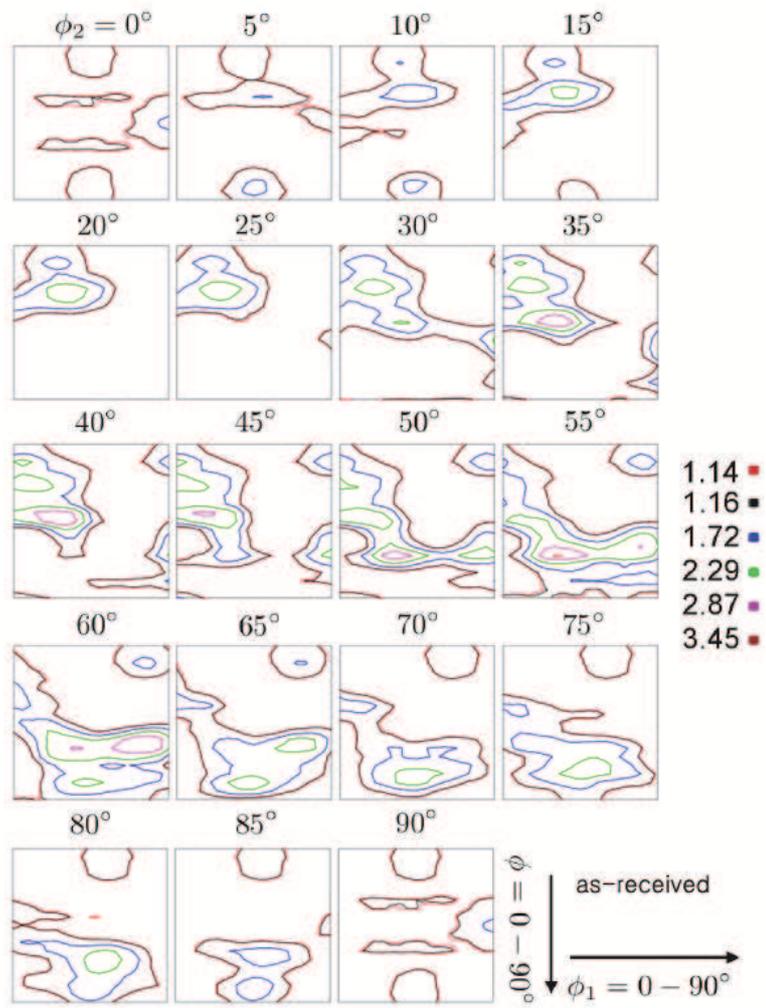


Figure 5: Orientation distribution for as-received steel.

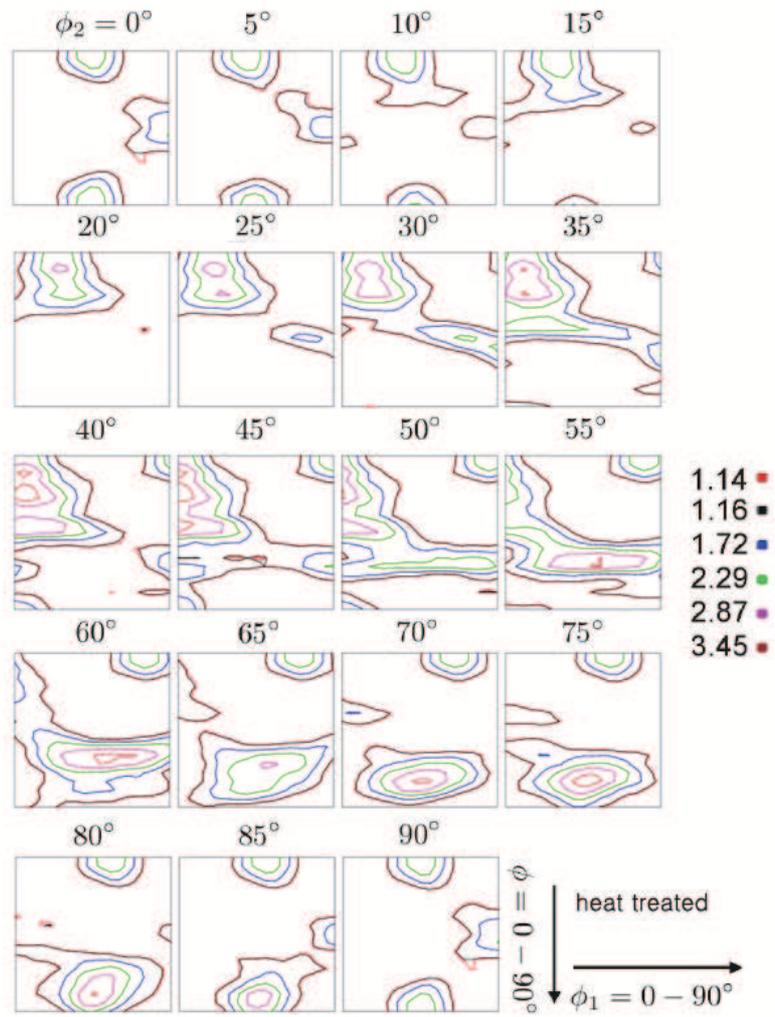


Figure 6: Orientation distribution for heat-treated steel.

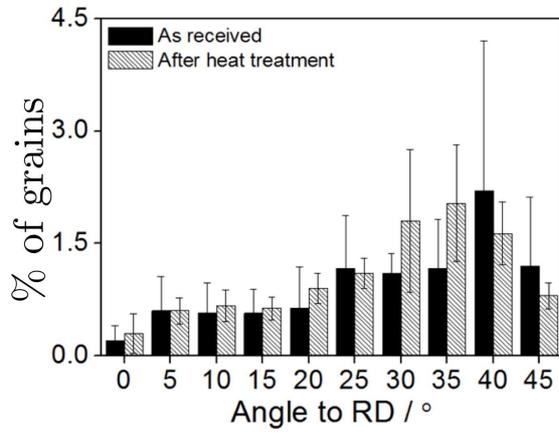


Figure 7: Percent of grains as a function of the angle between $\{100\}$ plane normals and the rolling direction, with a tolerance angle of 2.5° .

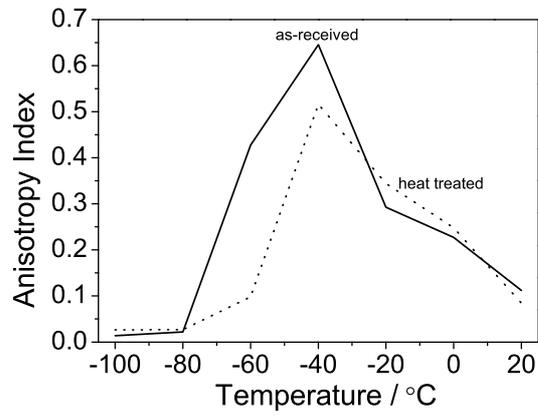
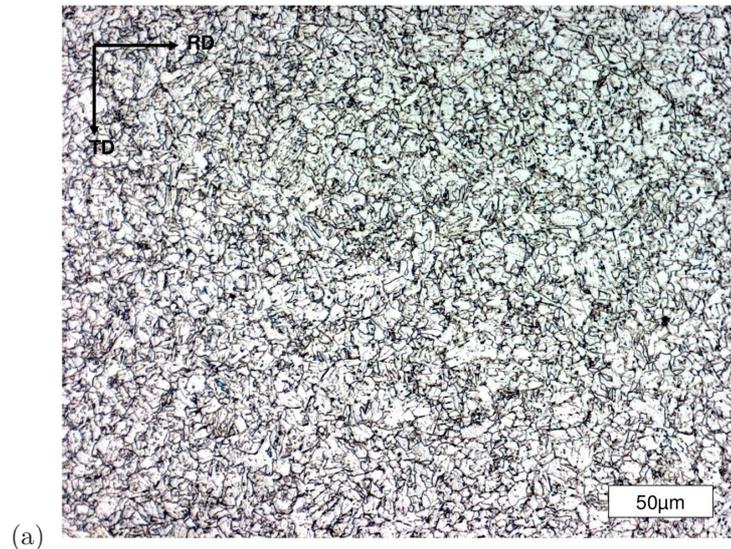


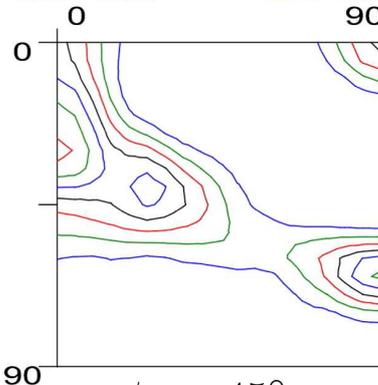
Figure 8: A comparison of the anisotropy indices for the as-received and heat-treated samples.



(a)

1.00 2.00 3.00 4.00 5.00

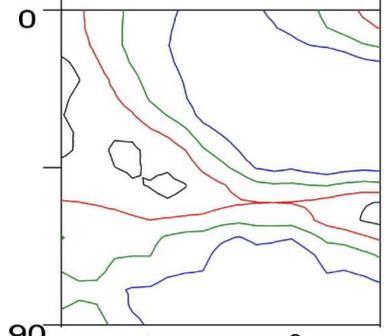
6.00 7.00 8.00 9.00 10.0



(b) $\phi_2 = 45^\circ$

1.00 1.50 2.00 2.50 3.00

0 90



(c) $\phi_2 = 45^\circ$

Figure 9: (a) Optical micrograph of sample heat-treated to produce bainite. (b) ODF ($\phi_2 = 45^\circ$) of the bulk texture of the as-received steel. (c) ODF ($\phi_2 = 45^\circ$) of the bulk texture of the heat-treated sample.

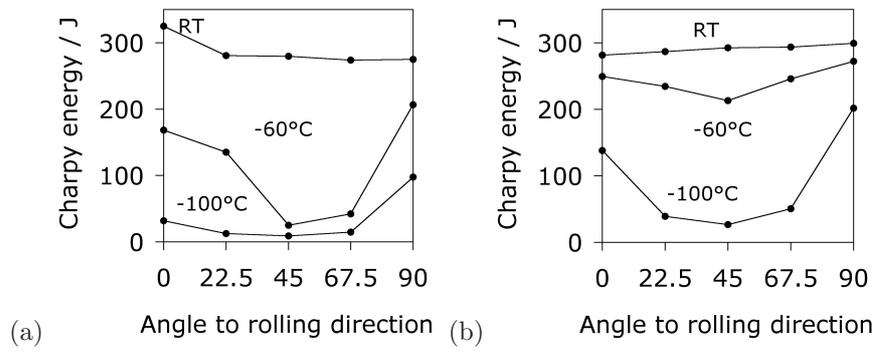


Figure 10: A comparison of the orientation dependence of the Charpy toughness for the as-received (X80-A3) and regenerated bainitic samples.