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Promoting the Coalescence of Bainite Platelets

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Abstract

An experiment is presented which succeeds for the first time in stimulating the formation of coarse plates of bainite by the coalescence of identically oriented individual platelets. Transformation under the influence of a tensile stress dramatically promotes the formation of the coalesced bainite by increasing the probability of growing parallel platelets in close proximity. Whereas the coarse plates are detrimental to toughness, the result serves to validate the mechanism of coalescence which has been discussed extensively in the literature.

Key words: Coalesced bainite, mechanism of coalescence, stress affected transformation, bimodal plate size

It is now known that in appropriate circumstances, thin–platelets of martensite or bainite can coalesce to produce much coarser plates that are detrimental to mechanical properties [1, 2]; the subject has been reviewed [3]. The consequences of this coarser microstructure with a bimodal distribution of plate sizes, on toughness, continue to be revealed since the original work [4]; some recent studies on strong steels include [5–10]. One of the criteria necessary to obtain such coalescence is that the driving force for transformation must exceed the increase in strain energy associated with the coalescence process, and another that the platelets that combine must form on parallel habit planes [1]. This latter condition necessarily means that the platelets must have the same crystallographic orientation in space, since the orientation relationship with austenite, the habit plane and shape deformation are mathematically connected [11, 12]. The purpose of the present work was to see whether an increase in the probability of finding parallel platelets, by imposing an external stress during the course of transformation, can promote the coalescence process. Such an observation would not only strengthen the concept as a whole, but there are many circumstances where transformations occur during cooling in components which are constrained, and hence stressed. Stress favours the growth of specific crystallographic variants whose transformation strains comply [13].

1 Experimental method

The alloy composition is Fe–0.084C–1.53Si–1.97Mn–0.71Cr–0.031Nb–0.23Al wt%, provided by POSCO and selected because preliminary work indicated a propensity for the coalescence of platelets. It was machined into cylindrical samples 3 mm in diameter and 10 mm in length for dilatometry; additionally, cylindrical Gleeble 3500 tensile samples with a gauge length and diameter of 12 mm and 6 mm respectively, and 10 mm diameter threaded grips, were prepared to study transformation under the influence of stress. The microstructure was observed using 2% nital etchant by optical and field emission gun scanning electron microscopy. After delicate polishing of the sample using colloidal–silica electron backscattered diffraction data were analysed to find evidence for variant selection.

2 Results

Fig. 1 shows the progress of isothermal transformation to bainite at 455°C following austenitisation at 1250°C for 3 min. The reaction was repeated using the Gleeble simulator but applying a tensile stress of 50 MPa when the sample reached the isothermal transformation temperature, and the stress was maintained during the course of transformation. This level of stress should be less than the yield strength of the austenite at 455°C, estimated as 64 MPa using an empirical equation [14].

Scanning electron microscopy revealed a remarkable change in the microstructure as shown in Fig. 2. The sample transformed under the influence of stress revealed strong variant selection, together with numerous regions of coalesced bainite in the same morphology as has been reported in many previous investigations [3]. Furthermore, there was a strong tendency for the bainite to form at approximately 45° to the tensile stress axis, as would be expected from the interaction of the shape deformation [15] of bainite with the stress [13, 16]. It is known that there exist only minor orientation gradients within individual regions of coalesced bainite [17], and this is consistent with the image quality map presented in Fig. 3a where bright contrast implies homogeneous crystallography. This high quality is associated with the fact that boundaries between the participating platelets are eliminated as coalescence occurs. The reduction in the number of variants, from the 24 possible, during stress–affected transformation is confirmed by the $\{100\}$ pole figures shown in Fig. 2b,c; each pole figure comes from just one austenite grain.

Fig. 2b seems to show all coalesced bainite plates pointing essentially in one direction. However, it is possible to obtain different variants which have approximately common habit–plane *traces* on the metallographic plane of observation and yet have different crystallography relative to the austenite. There is considerable work in the literature to show this in the context of lath packets, where laths appearing to grow in the same direction have different crystallographic orientations, for example, [18]. Of course, the individual coalesced plates in the present work are not like these packets, but are essentially single–crystals. This was proven by a further experiment, in which electron back scattered diffraction was obtained from points within *individual* coalesced bainite plates within a single grain of austenite, in the specimen transformed under stress. Some 69 separate measurements were done and it is clear from Fig. 4, first that the plates are single–crystals, and second that one orientation is dominant, presumably because it shows the greatest compliance with the applied stress. A detailed analysis of the kind presented elsewhere [19] to show that the dominant orientation and the two subsidiary orientations are the most favoured, is not possible because of the absence of retained austenite. The austenite is needed in order to define the mathematical set consisting of the habit plane, orientation relation and shape deformation. But it remains the case that the mere observation that the coalesced plates form at about 45° to the stress axis (i.e., close to planes of maximum shear stress) shows that the plates are those which comply best with the applied stress.

3 Conclusions

There are many studies on coarse plates of bainite that have been characterised using a variety of techniques, to come to the conclusion that given the right circumstances, they form by the coalescence of individual platelets which are in the same crystallographic orientation with parallel habit planes. Therefore, anything that encourages the growth of parallel plates in adjacent regions will stimulate their coalescence. The experiments presented here prove that the propensity to form coalesced bainite is dramatically increased when the bainite reaction is forced to occur under the influence of stress. This is because the number of crystallographic variants is then reduced so that the probability of plates forming in the same (favoured) orientation is increased.

It is known that the coarse plates are detrimental to toughness. It follows that there should be a deterioration in properties if the transformation occurs during the cooling of a constrained component, because stresses generated due to thermal contraction are likely to promote the formation of coalesced bainite. This suggests a topic for further investigation since coalesced bainite has now been reported in many different alloys and components.

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References

[1] L. C. Chang, H. K. D. H. Bhadeshia: Mat. Sci. Tech. 12 (1996) 233.

[2] S. K. Liu, G. Y. Zhang: Metall. Transactions A 21 (1990) 1509.

[3] H. K. D. H. Bhadeshia, E. Keehan, L. Karlsson, H. O. Andrén: Trans. Indian Inst. of Met. 59 (2006) 689.

[4] M. Murugananth, H. K. D. H. Bhadeshia, E. Keehan, H. O. Andrén, L. Karlsson: Strong and tough steel welds: in: H. Cerjak, H. K. D. H. Bhadeshia (Eds.), Math. Modelling of Weld Phenomena 6: (2002) 205.

[5] F. G. Caballero, J. Chao, J. Cornide, C. Garcia-Mateo, M. J. Santofimia, C. Capdevila: Mat. Sci. & Eng. A 525 (2009) 87–95.

[6] L.-E. Svensson: Mat. Sci. Forum 539–543 (2007) 3937–3942.

[7] A. Guo, R. D. K. Misra, J. Xu, B. Guo, S. G. Jansto: Mat. Sci. & Eng. A 527 (2010) 3886–3892.

[8] F. G. Caballero, J. Chao, J. Cornide, C. Garcia-Mateo, M. J. Santofimia, C. Capdevila: Mat. Sci. Forum 638–642 (2010) 118.

[9] C. C. P. Mazzaferro, F. D. Ramos, J. A. E. Mazzaferro, T. S. Rosendo, M. A. D. Tier, A. M. Silva, J. F. dos Santos, A. Reguly: Welding Int. 25 (2011) 630.

[10] L. Karlsson, H. K. D. H. Bhadeshia: J. Japan Welding Soc. 80 (2011) 110.

[11] M. S. Wechsler, D. S. Lieberman, T. A. Read: Trans. AIME J. of Metals 197 (1953) 1503.

[12] J. K. Mackenzie, J. S. Bowles: Acta Metall. 2 (1954) 138.

[13] J. R. Patel, M. Cohen: Acta Metall. 1 (1953) 531.

[14] C. H. Young, H. K. D. H. Bhadeshia: Mat. Sci. Tech. 10 (1994) 209.

[15] E. Swallow, H. K. D. H. Bhadeshia: Mat. Sci. Tech. 12 (1996) 121.

[16] H. K. D. H. Bhadeshia: ISIJ Int. 42 (2002) 1059.

[17] E. Keehan, L. Karlsson, H. K. D. H. Bhadeshia, M. Thuvander: Mat. Sci. Tech. 24 (2008) 1183.

[18] S. Morito, H. Tanaka, R. Konishi, T. Furuhara, T. Maki: Acta Mat. 51 (2003) 1789.

[19] S. Kundu, K. Hase, H. K. D. H. Bhadeshia: Proc. Roy. Soc. A 463 (2007) 2309.

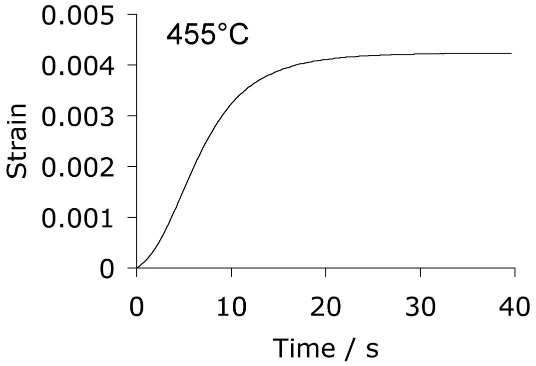

Fig. 1. Dilatometer data for isothermal transformation to bainite at the temperature indicated.

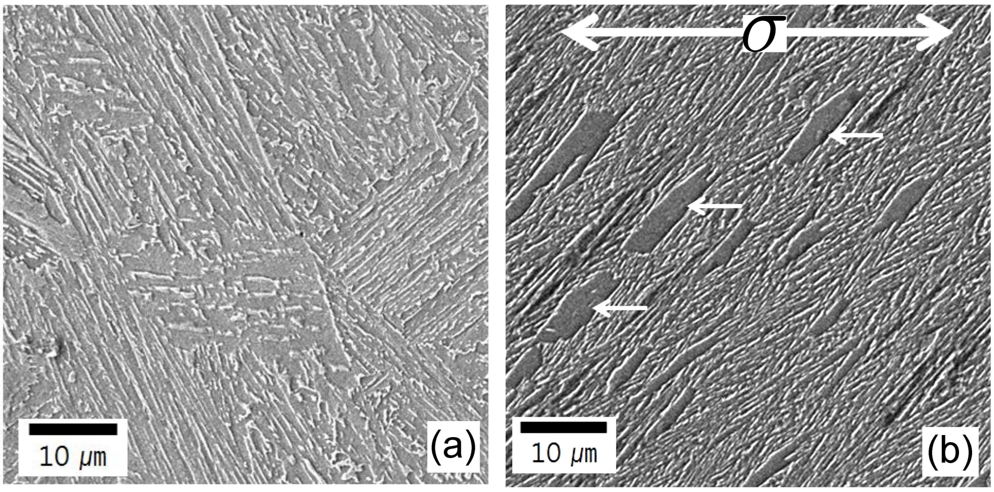

Fig. 2. (a) Stress–free transformation. (b) Transformation under the influence of a tensile stress σ along the orientation indicated. The short arrows show the coalesced bainite.

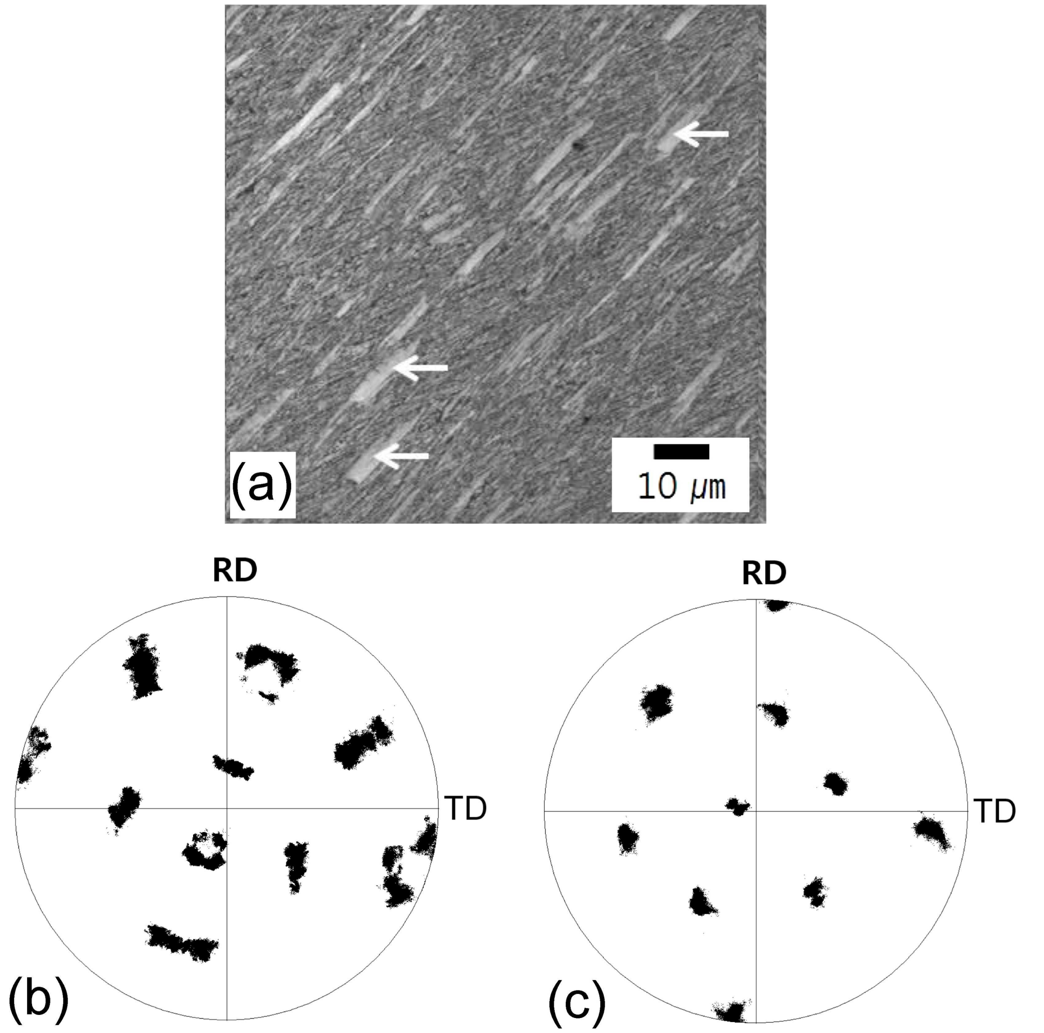

Fig. 3. (a) Image quality map of stressed sample, the orientation of the stress is identical to Fig. 2b. (b) {001} pole figure from a single grain of unstressed austenite, showing intensity from a large number of variants. (c) Corresponding pole figure from stressed austenite, with the tensile axis along 'RD'

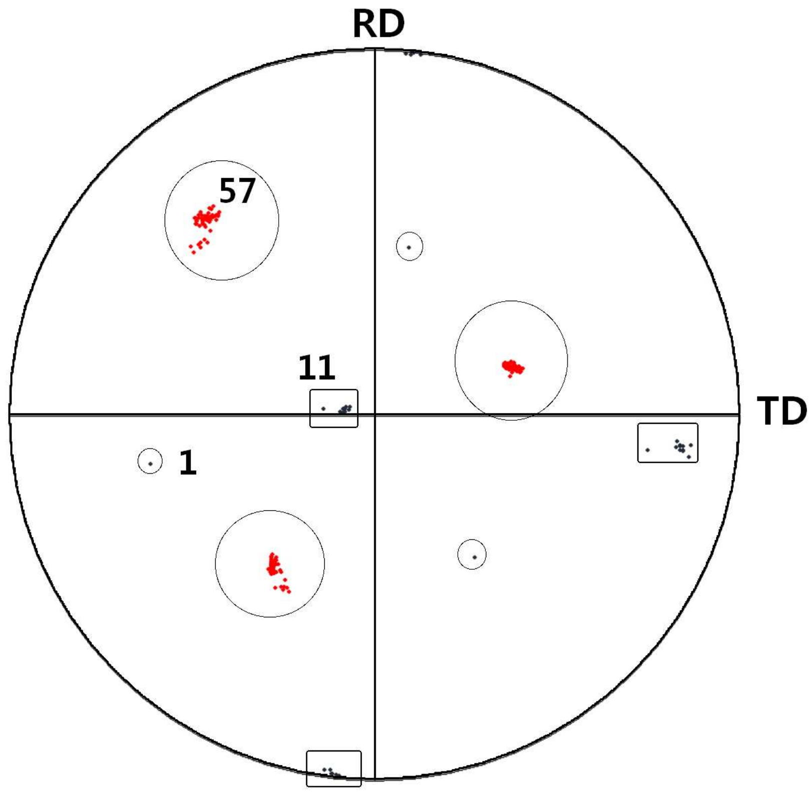

Fig. 4. {001} pole figure showing the orientations of 69 separate coalesced bainite regions, where RD represents the tensile direction. The number of observations for each orientation is indicated by the figures 1, 11 and 57.