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Microstructural categories in ferritic welded joints

T. Šmida*, V. Magula, J. Bošanský

IBOK, a. s., Pionierska 15, 831 02 Bratislava, Slovak Republic

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Abstract

The mechanism of γ-αFe transformation and its impact on the morphological characteristics and basic mechanical properties of the ferritic steel is discussed. It is proposed to merge the categories: Widmanstätten ferrite, coarse acicular ferrite and both upper bainites into the new 'Widmanstätten bainite' category. Change of the category name of acicular ferrite into 'intragranular bainite' is suggested.

Key words: phase transformations, ferritic welded joints, microstructural categories

1. Introduction

The analysis and evaluation of microstructures has more than a 150-years-long tradition. Microstructures were initially described and differentiated exclusively on the basis of the morphological characteristics of metallographic sections, but with the development of physical metallurgy and understanding of the basic mechanisms of transformation of γ-αFe, the current labelling and division into ferrite (F)/pearlite (P), bainite (B) and martensite (M), consistent with the transformation mechanisms, was established in the middle of the last century. Later, the development of welding technology and its metallurgical specifics brought about the introduction of new categories to better reflect the diversity of morphological structures of the welded joints. The occurrence of a large number of specific transitional microstructures and/or microstructures affected by multiple temperature cycles led to a growing terminological disarray between the applied research in the field of welding and weldability and the researchers on campus. The result was that the two groups of researchers felt all too frequently as they were working on different material problems.

The most recent draft classification of welded joints of steel structures was published in Zváranie/Svařování in 2005 [1]. However, with the passage of time, it seems that from the viewpoint of the specific combinations of mechanical properties and morphological features there is a space not only for merging some of the existing microstructural categories, but also for terminological fine-tuning and harmonization with the standard microstructural categories in physical metallurgy.

2. Basic types of Fe transformations

By default, modern physical metallurgy [2] distinguishes three basic mechanisms of polymorphic transformations: ferritic/pearlitic in cases of small undercooling, martensitic in cases of high undercooling, and bainitic, which fills the temperature range between the former two. The bainitic transformation is often described as a mechanism sharing some characteristics with the martensitic as well as with the ferritic transformation. The cross-over and closeness of the individual transformation mechanisms can be analysed very well via characterization of transformation mechanisms by:

– the chemical composition across the interface between the original and new phase,

– the mode of movement of the interface between the original and new phase.

As long as there is no change in the chemical composition across the interface between the original and emerging phase, the term 'non-diffusional transformation' (NoT) is used, otherwise 'diffusional transformation' (DiT) is the case. If the new lattice is created by random jumps of individual atoms and the non-

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*Corresponding author: tel.: +421 907 742 255; fax: +421 249 212 409; e-mail address: t.smida@ibok.sk

Table 1. Mechanisms of phase transformations [3]

	ReT	DsT	DiT	NoT
Ferrite/pearlite	X		X	
Bainite		X	X	
Martensite		X		X

-coherent interface moves without the existence of an orientation relationship between the original and new phase, the transformation is 'reconstructive' (ReT). If the new phase emerges via displacement of entire groups of atoms without exchange of the nearest neighbours, the transformation is displacive (DsT). In DsT, the coherent or semicoherent interface migrates with a coordinated movement of atoms, there is an orientation relationship between the original and new phase and the transformation is accompanied by a change in the shape of the transformed material. The affinity or divergence of the individual mechanisms of transformation of γ-εFe is then as given in Table 1 – the occurrence of diffusion is a common feature of ferritic/pearlitic and bainitic transformations, and bainitic and martensitic transformations both share the coordinated movement of groups of atoms [3]. The bainitic transformation can therefore be considered as transient, whereby its mechanism will share some characteristics with martensitic and ferritic/pearlitic transformation as well.

The bainitic transformation occurs in a relatively wide temperature range. Due to its affinity with ferritic/pearlitic as well as martensitic transformation, it can be expected that the boundaries between the individual types of transformation are not sharply delimited. Widmanstätten ferrite (WF) can serve as a good example. Although the debate on the details of the mechanisms of WF formation is still underway [4], in spite of its name transformation into WF occurs according to [5, 6] with the same mechanism as the bainitic transformation (DsT + DiT) and according to [7] WF is 'structurally and kinetically continuous' with B.

The situation is similar on the opposite end of the bainitic transformation temperature range. The mode of the interface movement indicates that there is no sharp boundary between the B and M [8], which corresponds to the comparison of both mechanisms in Table 2 [9]. The 24 possible correlation relations between the austenite and M, B and WF [10, 11] suggest that something similar to 'structural and kinetic continuity' indeed exists not only between WF and B, but also probably across the entire spectrum of transformation products. This would explain the existence of a high number of transitional phases in the ferritic weld joints and the ongoing debate about their classification.

3. Effects of transformation temperature on the nature of the transformation product

A majority of the key characteristics of the product of γ-αFe transformation is related to the change of specific volume of Fe with a temperature decrease. With increasing undercooling the elastic/plastic stress between the initial phase and the transformation product increases and results in:

– changes of the product shape from polyedric into lath or acicular,

– increase of density of dislocations in the lattice of transformation product.

Other important characteristics are related to the nucleation mode. At high temperatures and low undercooling, heterogeneous nucleation is preferred on large planar heterogeneities like the primary austenite grain boundaries. Such nucleation coupled with DsT prefers formation of agglomerations of lath units separated by the boundaries with a small angle, while the boundaries of agglomerations which grow from the different nuclei are separated by boundaries with a large angle. Increasing undercooling and increasing number of active nuclei cause decrement of the mean diameter of these structural units.

At the highest levels of undercooling, new phase begins to emerge in the less effective sites of heterogeneous nucleation, i.e. the lattice heterogeneities inside the original austenitic grain. This will result in additional decrease in the mean diameter of the new structural units enclosed by the large angle bound-

Table 2. Mechanisms of bainitic and martensitic transformation [9]

	B	M		B	M
Nucleation and growth reaction	x	x	Large shear	x	x
Plate shape	x	x	IPS shape deformation	x	x
Diffusionless nucleation	–	x	Diffusionless growth	x	x
Carbon diffusion during nucleation	x	–	Carbon diffusion during growth	–	–
Substitutional diffusion during nucleation	–	–	Substitutional diffusion during growth	–	–
Confined to austenitic grain	x	x	Glissile interface	x	x

ary and eventually in the formation of isolated laths rather than agglomerations when nucleation starts to occur on smallest structural heterogeneities. Increasing undercooling thus results in gradual emergence of 4 Dubé's morphological categories of the product of γ-εFe transformation (p. 41 in [2]):

- intergranular alotriomorphs,
- WF plates or laths,
- intragranular idiomorphs,
- intragranular plates.

By decreasing the transformation temperature, the diffusion speed and range also decrease, which is necessarily reflected in the redistribution of carbon atoms, the solubility of which will change dramatically with the change in γ-αFe. While at temperatures near the temperature of the ferritic/pearlitic transformation C manages to diffuse (and precipitate) at the boundaries of the emerging laths, at temperatures at the opposite end of the bainitic transformation temperature range C precipitates in the form of carbide inside the laths.

It should be noted that in addition to the cooling rate/degree of undercooling the actual temperature of the individual types of phase transformations depends mainly on the chemical composition, which can suppress the tendency for some types of transformation and trigger others.

4. Key exploitation material properties, their relationship to the microstructure and the requirements for classification of microstructures

Pursuant to Chapter 3 it can be concluded that the mechanism of transformation simultaneously affects the extent of all basic metallurgical strengthening mechanisms[1] as well as the morphological characteristics of the transformation product (microstructure). The microstructure can be thus considered as an external morphological manifestation of the same metallurgical processes, as the processes determining the mechanical properties. Therefore there cannot be any causal relationship between the microstructure and mechanical properties.

On the other hand, any categorization makes sense only if the individual categories represent the typical and unique combinations of the important features, in this case the key mechanical properties and morphology of the elementary microstructural unit. What limit the possibilities of use of any construction material (including the welded joints) from the viewpoint of mechanical properties are particularly the resistance to deformation and resistance against initiation and growth of fracture nuclei. From an engineering viewpoint these are well represented by:

- deformation stress (yield stress),
- transition temperatures delimiting the conditions of ductile fracture[2] (Fig. 1).

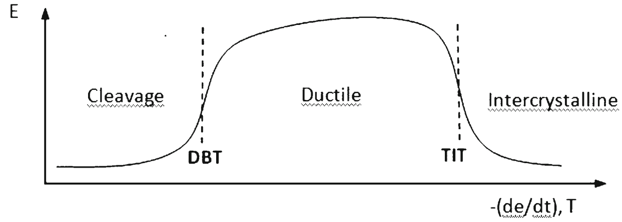

Fig. 1. Schematic representation of the change of toughness with loading condition/fracture mode of ferritic steels.

As discussed in Chapter 3, the deformation stress (yield strength) of a given steel increases with increasing undercooling mainly due to an increase in the dislocation density since the extent of other strengthening mechanisms is considerably less sensitive to the transformation conditions. As discussed in [12, 13], the range of ductile fracture narrows with the increasing deformation stress and, particularly, with the increasing size of the elementary structural unit delimited by the large angle boundary – the ductile to brittle transition temperature increases and the transcrystalline to intercrystalline transition temperature (Fig. 1) decreases. The key exploitation characteristics of the transformation product from mechanical point of view therefore are the deformation stress (well represented by hardness) and the size of the elementary structural unit delimited by the large angle boundary.

5. From the existing classification of welded joint structures

5.1. Bainitic microstructural categories

Apart from the ferrite/pearlite and martensite, the classification of microstructures of welded joints in [1] recognizes 5 basic microstructural categories: coarse acicular ferrite (CAF), upper bainite I and II (UB I and UB II), lower bainite (LB) and acicular ferrite (AF)[3]. According to the density of dislocations (i.e. hardness in Table 3), all of them occur between the temperatures of the ferritic/pearlitic and martensitic transformation. The typical mechanical exploitation properties of the individual bainitic microstructures

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[1] Density of dislocations, status of the secondary phase, shape and size of the elementary structural unit, status of the solid solution.

[2] In general, the mechanism of ductile fracture itself provides sufficient resistance to the initiation and growth of fracture nuclei.

[3] The other two microstructure categories mentioned in [1], the self-tempered martensite and troostite, are a product of repeated thermal influence.

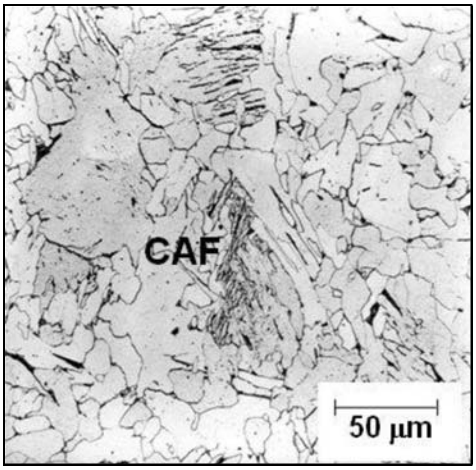

Fig. 2. Coarse acicular ferrite [1].

in relation to the transformation temperature are discussed below.

5.2. Coarse acicular ferrite – CAF

The name 'coarse acicular ferrite' labels all types of ferrites [1] whose longitudinal dimension is significantly longer than the transverse dimension (Fig. 2). The CAF group also includes the WF and the side plate ferrite. CAF nucleates heterogeneously at relatively small undercooling on the prior austenite grain boundary. It grows in the form of laths separated by low-angle boundaries and forms aggregates called packets separated from each other by large angle boundaries. Since CAF grows from the grain boundary into its interior, the largest packet size is limited only by the diameter of the original austenitic grain and thus CAF 'inherits' the primary austenitic grain size.

Due to the lower transition temperatures, the density of dislocations is higher than in ferrite, but the deformation stress (yield strength) remains relatively low. Despite the low yield strength and a relatively high plasticity, depending on the size of the primary austenitic grain it can have a dangerously narrow area of ductile fracture.

5.3. Upper bainite – UB

UB emerges at a transformation temperature lower than CAF so it exhibits higher deformation stress (yield strength) due to higher dislocation densities. The boundaries between the laths in the packet are small-angled; the packets, much like in CAF, grow out of the primary austenite grain boundaries, so that in case of the originally coarse-grained austenitic structure there is an increased likelihood of cleavage or intercrystalline fracture in the UB area.

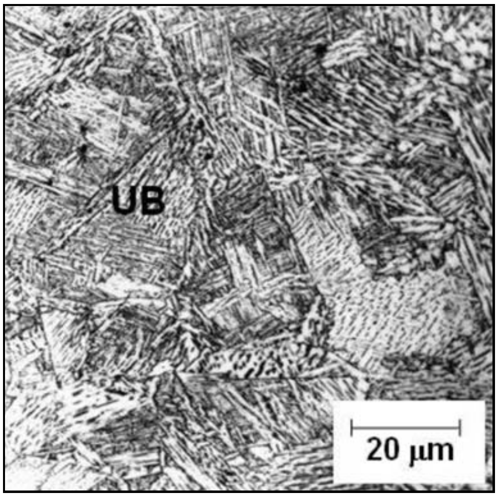

Fig. 3. Upper bainite [1].

Overall, the microstructure of UB is similar to CAF, but it is finer due to the lower transformation temperatures. Depending on the chemical composition [1] distinguishes two modifications – UB I and UB II (Fig. 3).

5.3.1. Upper bainite I

The structural component M-A, partially or completely disintegrated, is found between the ferrite laths. The structural component M-A is found in the weldments of steels alloyed mainly with Mn, Mo, Ni, Cr, and/or Nb, Ti and V microalloyed steels.

5.3.2. Upper bainite II

The UB type II is formed mainly in weldments of carbon steels without significant alloying. Cementite is generated either in the fine or lamellar form along the boundaries of the UB II laths. Compared to UB I, UB II is present quite sporadically in the welded steel joints.

5.4. Lower bainite – LB

LB is formed at temperatures that interface with the temperatures at the beginning of martensitic transformation, i.e. at higher cooling rates than UB. It preferentially nucleates on the boundary of the primary austenite grain, but it is possible that new packets of LB can also nucleate on the packet boundaries because no significant heritability of the primary austenitic grain size is observed in the transformation product [14]. Due to higher undercooling and, consequently, a higher number of active transformation nuclei, the overall packet size is smaller than the one in UB. Unlike UB, due to the shorter diffusion time

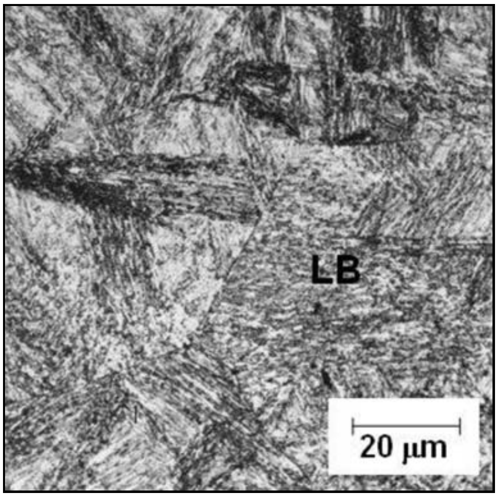

Fig. 4. Lower bainite [1].

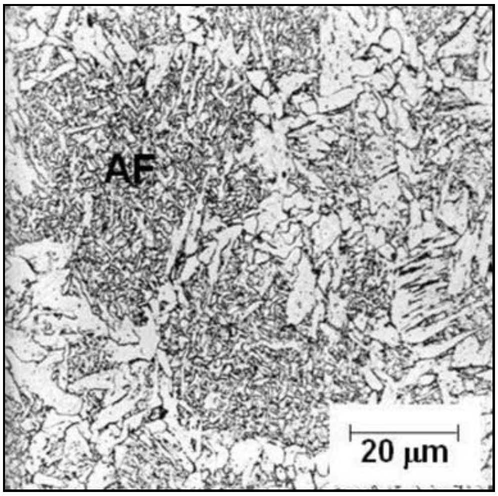

Fig. 5. Acicular ferrite [1].

Table 3. Typical hardness HV10 values of ferritic microstructures [14]

Microstructure	HV10	Microstructure	HV10
F	120–160	AF	260–320
CAF	150–180	LB	280–340
UB	200–260	M	400–700

cementite precipitates inside the laths.

Due to the lower transformation temperatures it has a higher density of dislocations compared to UB and thus a higher deformation stress (yield strength). Taking into account the smaller packet sizes, finer laths and a more homogeneous distribution of the carbide phase, it also has a wider range of ductile fracture than UB (Fig. 4).

5.5. *Acicular ferrite – AF*

AF is described in [1] as a non-polyedric structure, which occurs mainly in the weld metal, but also in the heat affected zone of the ferritic welded joint (Fig. 5). Due to intragranular nucleation on the relatively small crystallographic heterogeneities AF does not form agglomeration of lath units within the packets, but rather randomly oriented laths[4], separated by large-angle boundaries.

Since AF occurs at lower transformation temperatures and higher cooling rate than CAF and UB, due to the higher density of dislocations it has higher strength, but also wider area of ductile fracture due to the large-angle boundaries between the individual ferritic laths.

6. Discussion and proposal for new microstructural categories

In terms of important mechanical properties and morphology, CAF, UB I and UB II in [1] are very similar. According to [5], the lath-like shape of the transformation product is a result of DsT, so CAF forms with the same mechanism as bainite. According to Dubé's morphological classification of the γ-εFe transformation product, all three microstructures are typical representatives of Widmanstätten morphological category. Thus, WF, CAF and UB rather form one single category of microstructures, linked not only by the same mechanism of transformation, but also by the tendency to 'inherit' the primary austenitic grain size resulting in potential problems with transition temperature measured via the Charpy test. Widmanstätten bainite (WB) would therefore be a more logical name for the group of these microstructures. It would reflect their common morphological characteristics and formation mechanism and the influence of the original austenite grain size on the packet size as well[5].

Also AF is a bainitic microstructural category – according to [15] it is an intragranularly nucleated bain-

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[4] This is why the label 'acicular' (needle-like) is not quite correct.

[5] It is worth noting that under static loading, the practical significance of the effects of grain size on the transition temperatures is probably not as dramatic as indicated by Charpy V-notch test. The strain rate during Charpy test is extremely high and overestimates the effects of grain size at the expense of strength. Moreover, unlike some exceptions, it does not match the operational loading conditions of welded structures/industrial equipment. These are better simulated in the static fracture toughness tests where, however, due to lower strain rate the influence of grain size is not that predominant and the measured transition temperatures are lower.

ite. Intragranular bainite (IB) and LB differ significantly from WB – they do not 'inherit' the original austenitic grain size, i.e. transformation refines the original austenitic grain. Since no packets but variously oriented laths, isolated by boundaries with a large angle are created in case of IB, the IB grain size is finer than that of LB. From the morphological viewpoint both structures are therefore well-defined and distinguishable categories with a set of mechanical properties that bridge the gap between the characteristics of M and WB.

To summarize, based on the requirement for a unique combination of key properties and morphological characteristics, it seems logical to introduce new subcategories in the bainitic microstructure, consistent with the morphological terminology and mechanisms of polymorphic transformations of γ-αFe:

- Widmanstätten bainite (originally WF, CAF, UB I and UB II),
- intragranular bainite (originally AF),
- lower bainite,

bridging the temperature interval between ferritic/pearlitic and martensitic transformation.

7. Conclusion

In harmony with the theory of phase transformations, a revision and simplification of the existing classification of the basic structures of ferritic welded joints is proposed as follows:

- ferrite/pearlite,
- bainite,
  - Widmanstätten bainite,
  - lower bainite,
  - intragranular bainite,
- martensite.

Each of the proposed microstructural categories represents a unique combination of mechanical properties, morphological characteristics and mechanisms of phase transformation.

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