ON SOME ASPECTS OF THE PLASTICITY AND FRACTURE PROPERTIES OF FERRITIC MATERIALS

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Results of previously published analyses of the parameters controlling the plasticity and fracture mode of ferritic steels are summarized and generalized as follows: Fracture mode is controlled by the mechanism of plastic deformation. Fracture mode transitions from transcrystalline ductile to transcrystalline cleavage at low temperatures and to intercrystalline at elevated temperatures are the consequence of deformation twinning and grain boundary sliding, respectively. The actual temperature and strain rate of the fracture mode transitions are affected by the grain size and by the parameters controlling the deformation stress of individual grains. The actual extent and combination of metallurgical strengthening parameters is morphologically manifested as the microstructure of the steel. However, the dominant role of the microstructure as a complex qualitative characteristic of the steel cannot be replaced by quantitative material parameters (strength and grain size), since the relative contribution of different strengthening mechanisms to the strength of the matrix and to the probability of activation of deformation modes, controlling the fracture mode transitions, is different.

K e y w o r d s: fracture mode, transcrystalline cleavage, intercrystalline fracture, grain size, strength, ferritic steel

KONTROLNÉ PARAMETRE PLASTICITY A LOMOVÝCH VLASTNOSTÍ FERITICKÝCH MATERIÁLOV

Sumarizácia a zovšeobecnenie v minulosti publikovaných výsledkov analýzy faktorov riadiacich plasticitu a mechanizmus lomu feritických materiálov: Mechanizmus lomu je určený mechanizmom plastickej deformácie. Zmeny mechanizmu lomu z tvárneho transkryštalického na štiepny pri nízkych teplotách, resp. na interkryštalický pri zvýšených teplotách sú vyvolané aktiváciou deformačného dvojčatenia, resp. poklzov hraníc zŕn.

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Aktuálne podmienky zmeny mechanizmu lomu závisia v prvom rade od veľkosti zrna a parametrov, ktoré riadia deformačné napätie individuálnych zŕn. Vonkajším morfologickým prejavom spevňovacích procesov je mikroštruktúra feritického materiálu. Úlohu mikroštruktúry ako komplexnej kvalitatívnej charakteristiky feritického materiálu však nie je možné nahradiť kvantitatívnymi materiálovými charakteristikami (pevnosť a veľkosť zrna), pretože relatívny príspevok rôznych mechanizmov spevnenia k pevnosti a pravdepodobnosti aktivácie kontrolných mechanizmov plastickej deformácie je rôzny.

1. Introduction

The requirements laid upon the steel as a structural material are usually expressed as conservation of sufficient toughness at required strength. Retention of the balance between the strength and toughness is also a centerpiece of weldability studies. While the mechanical properties of the steel result from a sophisticated and rigorously controlled technological regime, the thermal cycle of welding can arouse a whole range of spontaneous thermally activated processes, resulting in emergence of characteristic microstructures, with significantly changed mechanical properties – usually increased strength and decreased toughness.

The requirement of sufficient toughness implicitly expresses the necessity of ductile transcrystalline fracture, which is the only fracture mode accompanied with a significant plastic strain. The nature of the other two basic fracture modes, i.e. transcrystalline cleavage and intercrystalline, exclude comparable fracture energy levels. The ductile fracture mode can, therefore, be considered an inevitable condition for sufficient toughness. Acquaintance with the basic parameters controlling the fracture mode and fracture properties of structural materials (ductility, toughness) is thus particularly important.

Though the unfavorable impact of increased strength upon the toughness of a structural steel is in general accepted, the fracture properties of ferritic steels are usually analyzed in relation to their microstructure. Universally respected prime influence of microstructure on the fracture properties of ferritic steels reflects a widely known experience that different microstructures of ferritic steels can be accompanied by significantly differing fracture properties even in the case of similar strength.

The results presented below summarize the most important outputs of several research projects, aimed to the study of basic parameters, controlling the fracture mode of different ferritic structural materials in different loading conditions. We believe that, based on the analysis of this wide and rich set of experimental data, the dominant and, from the standpoint of strength, unsystematic impact of microstructure upon the fracture properties can be understood, and the basic material parameters controlling the fracture properties of ferritic materials can be identified.

2. Parameters controlling the plasticity and fracture mode of ferritic steels

2.1 The metallurgical strengthening mechanisms and the microstructure of ferritic steels

The plastic resistance of polycrystalline material at any given state of deformation (e.g. [1, 2]) is controlled by the lattice resistance (Peierls-Nabarro stress) and:

– solid solution strengthening,

– secondary particle strengthening,

– grain boundary strengthening,

– dislocation strengthening.

The above metallurgical strengthening mechanisms thus determine the engineering yield strength as well as the flow stress, regardless whether they occur during the steel manufacture process or the weld cycle. Consequently, the *mechanical properties of the structural material result from the collective influence of the actual combination and extent of different strengthening mechanisms, which in turn are governed by its entire thermal and stress/strain history.*

On the other hand, the mechanical properties of the ferritic steel are usually referred to its microstructure. Depending on the cooling rate from the austenitic temperatures a whole range of morphologically different microstructures can occur in ferritic steels. Classification of the International Institute of Welding [3] distinguishes seven basic microstructural categories (arranged according to increased cooling rate): ferrite, pearlite, acicular ferrite, coarse acicular ferrite, upper bainite, lower bainite and martensite. The morphological differences that enabled the above classification result from:

– different density of dislocations (manifested as different micro-hardness),

– different density, distribution and shape of secondary particles,

– differences in the geometrical parameters of basic microstructural unit (polyhedral or lath microstructures) and the nature of delimiting grain boundaries (high or low angle boundaries).

All of the above differences modify the mobility of dislocations (mean free path, sliding resistance), thus their influence can be directly linked with the basic metallurgical strengthening mechanisms. It means *the microstructure of the ferritic steel can be considered an external morphological manifestation of the current combination of metallurgical strengthening processes.*

2.2 Mechanism of cleavage and ductile-to-brittle transition of ferritic steels

2.2.1 *Mechanism of cleavage*

The mechanism of cleavage in ferritic steels was recently analyzed in detail in [4–7]. It was demonstrated that the initiation of cleavage fracture due to the decreased temperature and/or increased strain rate (that is the DBT of ferritic steels) is connected with the activation of deformation twinning. Deformation twinning was found to be an integral constituent of the plastic deformation at transition and sub-transition temperatures and this even in the growing cleavage crack tip region. Intersections of unfavorably oriented twins with active slip systems ahead the main crack tip acted as nucleation sites of cleavage re-initiation. The re-initiation of cleavage occurred through initiation of microcracks termed pre-cleavage microcracks (PCMC [4, 5, 6]), which grew towards the approaching main crack. Neither PCMCs, nor deformation twins, were found in the ductile fracture region.

2.2.2 *Effect of loading conditions*

The proposed role of deformation twinning in DBT of ferritic steels is not in any contradiction with the literature data dealing with the parameters controlling the DBT. As far as the effect of loading conditions is concerned, deformation twinning is known to be the preferred mode of plastic deformation at low temperatures and high strain rates (e.g. [8]). Since the twinning stress of ferritic materials exceeds their yield stress [8] a limited slip of dislocations always precedes the deformation twinning [9]. It is also known that the decreasing temperature and increasing strain rate tend to restrict the slip of dislocations to primary slip systems [10, 11].

Following the strain compatibility requirement, operation of at least five independent slip systems is necessary for the mutual geometrical adjustment of the grain boundary regions of plastically deformed neighboring grains [12]. In other words, the same five active independent slip systems are necessary to relax the local stress peaks by continuous plastic strain. However, this requirement is beyond the potential of primary slip systems, thus, most probably, it is precisely the termination of the activity of secondary slip systems, which starts up the deformation twinning with decreasing temperature and/or increasing strain rate. Pile-ups of dislocations in primary slip systems at obstacles (usually high angle grain boundaries) seem to provide the necessary high local stress peaks for the dissociation of matrix dislocations to twin dislocations and setting of the pole mechanism of twinning.

The process of deformation twinning is extremely fast. The transonic rate of twin growth was proposed experimentally [13] and by atomistic simulations as well [14, 15, 16]. The results in [16, 27] suggest that the twin growth rate exceeds the rate of brittle crack growth.

Deformation twinning thus fulfils the fundamental requirements for its possible participation in the brittle fracture: increased probability of twinning with decreased temperatures and/or increased strain rate, generation of deformation twins before an extensive slip and this ahead of the rapidly growing main crack tip.

2.2.3 *Effect of material parameters*

The effect of material parameters on the DBT of ferritic steels is again in good accord with the published data about deformation twinning. The principal material parameters affecting the DBT of the ferritic steel were identified e.g. in [18–21] as: the effective grain size (the size of the least microstructural unit delimited by high angle boundary), microstructure, density and configuration of dislocations, and precipitation hardening. The most important results in [18–21] can be summarized as follows:

– The strength increased by secondary hardening and/or increased density of dislocations, decreases the ductility, increases the static and dynamic DBT temperature and decreases the toughness of the ductile fracture.

– The grain size or the size of the least microstructural unit delimited by high angle boundary primarily controls the dynamic DBT temperature.[2]

On the other hand, deformation twinning is favored by large grain size, lack of mobile dislocations and solid solution hardening (e.g. [22]). Obviously, the frequently demonstrated prime influence of the grain size on the DBT temperature is in good agreement with its impact upon the probability of twinning. Since the size of PCMCs is limited by the size of the twins, i.e. the grain size, increased grain size means simultaneously more and larger twins, as well as PCMCs nucleated on them in front of the moving crack tip. Closer spaced and larger PCMCs promote cleavage fracture and thus increase the DBT temperature. Consequently, though increasing the strength of polycrystalline material, grain refinement decreases the DBT.

The enhanced probability of deformation twinning due to lack of mobile dislocations and solid solution hardening [22] is obviously inter-related with the already mentioned fact that the twinning stress of ferritic materials exceeds the yield stress [8]. The number of primary dislocations in the pile-ups, necessary to set off the deformation twinning, will thus decrease with the increasing strength (flow stress). As a consequence, the tendency to deformation twinning increases with the increased strength of ferritic material. Unfavorable effect of the strength upon the DBT [18–21] is thus in good correlation with the known influence of the strength on deformation twinning [22].

[2] Low angle boundaries within the primary austenitic grains are typical for coarse acicular ferrite and upper bainite. The effective grain size delimited by high angle boundary thus significantly exceeds the size of elemental microstructural unit (lath) and explains the low toughness and high DBT temperatures of the both types of microstructure.

One serious objection against the reduction of material parameters controlling the DBT of ferritic steels to effective grain size and strength might be the generally accepted dominant impact of the type of microstructure. However, the role of microstructure becomes more intelligible, once the basic dissimilarities of different ferritic microstructures, used to distinguish between the individual microstructural categories, are inter-related with the basic metallurgical strengthening mechanisms. Since the relative contribution of the above listed metallurgical processes to the strength of material and to the probability of deformation twinning is different (and most probably not plainly additive), different combination of strengthening mechanisms (i.e. different microstructures) can result in comparable strength but significantly different DBT temperature.

2.2.4 *Summary of the results*

The most important conclusions of [4–7, 18–21] can be summarized as follows:

1. The cleavage fracture and the existence of DBT in ferritic steels are both related to the operation of deformation twinning. The main parameters controlling the deformation twinning are the grain size and the strength of the matrix.

2. Amongst the basic strengthening parameters the effective grain size plays an exceptional role, since it enables the increase of strength and simultaneous decrease of DBT. Exceptional influence of effective grain size is in full correlation with the model of cleavage fracture based on deformation twinning.

3. The other strengthening parameters increase the strength on the expense of static plasticity, toughness and increase of DBT. This observation is again in good accord with the proposed role of deformation twinning in cleavage of ferritic steels.

4. The dominant role of microstructure in DBT and cleavage of ferritic steel can be explained via different relative contribution of basic strengthening mechanisms to the resultant strength and to the probability of twinning.

2.3 Mechanism of intercrystalline fracture at elevated temperatures and transcrystalline-to-intercrystalline transition of ferritic steels[3]

2.3.1 *Significance of reheat cracking studies*

The transition from transcrystalline ductile to intercrystalline fracture is a typical creep phenomenon, occurring with a decreasing rate of stationary creep. The mechanism and the conditions of the creep intercrystalline fracture are discussed in

[3] This discussion is restricted to the effect of loading conditions and basic material parameters on the preferred fracture mode of ferritic steel. It follows that intercrystalline fracture due to, e.g., presence of brittle intercrystalline films, heavy segregation of impurities (temper brittleness), corrosion, and other is not concerned.

great detail in many basic textbooks, as well as the dominant role of grain boundary sliding (GBS) in creep intercrystalline fracture (e.g. [23]). Furthermore, nowadays it is generally accepted [23] that intercrystalline creep fracture of high strength steels is at certain loading conditions unavoidable.

However, in the mid 60's a special case of embrittling phenomenon, restricting the exploitation conditions of some structural materials, was reported as Reheat or Stress Relief Cracking (RC). Phenomenon of RC received a lot of attention particularly in 70's and 80's. According to very detailed review articles [24, 25], RC is an intercrystalline cracking of weld metals and the heat-affected zone of welded joints. RC laboratory tensile tests of all susceptible materials manifested a dramatic decrease of plasticity at temperatures above approx. 500 ℃ and strain rates several orders of magnitude higher (up to $10^{-2}s^{-1}$) than creep rates, i.e. at strain rates, significantly suppressing the time dependent component of strain, characteristic for creep[4]. These tests proved that the decrease in plasticity is coupled with the occurrence of intercrystalline fracture and that the observed fracture mode transition is temperature- and strain rate-dependent.

Over the years it has been found that the phenomenon of RC is restricted to coarse grained hard microstructures and that the main metallurgical processes, affecting the susceptibility of the given material to RC, are secondary hardening and embrittlement of grain boundaries due to segregation of impurities [24, 25]. However, none of the models suggested was able to explain the demonstrated tendency to RC of some modern high purity high strength steels, which were prone neither to secondary hardening, nor to intercrystalline embrittlement.

In two such cases we have proved [26, 27, 28] that this type of intercrystalline fracture at intermediate temperatures is, despite the high strain rates, associated with GBS. Though originally suggested by Boniszewski [29], the controlling role of GBS in RC phenomenon was never generally accepted, most probably due to high strain rates of RC tests, which were not compatible with creep strain rates. Moreover, the extent of GBS, leading to intercrystalline fracture at high strain rates is most probably very limited and not easily distinguishable[5].

2.3.2 *Mechanism of grain boundary sliding and intercrystalline fracture at elevated temperatures*

GBS is reported to be controlled by glide and climb of grain boundary extrinsic dislocations [30], produced by a (stress assisted) dissociation of matrix dislocations at the boundary [31], as well as by the diffusion flow believed to be a prerequisite for the accommodation of the interfering steps on the non-planar boundary or at

[4] Time to fracture in the case of RC tests of susceptible materials is usually of the order of tens of seconds.

[5] GBS in [27] was proved by SEM analysis.

grain boundary particles (e.g. [32]). Most probably the re-arrangement of extrinsic grain boundary dislocations (glide and climb) mediates the sliding process, at least at lower temperatures, higher strain rates and corresponding high stresses, while diffusion flow is necessary to retard the evolution of local stress peaks and the initiation of intercrystalline fracture to higher GBS strain levels. It follows that at high strain rates and relatively low temperatures, restricting the accommodation of local stress peaks and the climb of extrinsic dislocations, extremely large local stress peaks are built up at obstacles in the early stages of sliding. Crack-like defects can thus nucleate and extend in the highly stressed grain boundary. Since the glide of extrinsic dislocations is hampered by the imperfections of the grain boundary lattice and the rate of dissociation of matrix dislocations is highly stress-dependent, GBS occurs only when sufficiently high stresses act in the grain boundary region – the reason why RC is restricted to coarse grained high strength steels.

2.3.3 *Parameters controlling the grain boundary sliding and intercrystalline fracture at elevated temperatures*

Probably the most important parameters controlling the extent of GBS on the given boundaries at given loading conditions are the misorientation of the lattices of neighboring grains and the grain size (e.g. [23]). However, the distribution curve of the misorientation of neighboring grains in common polycrystalline materials can be, most likely, considered statistically very similar. From the standpoint of an engineer, the main material parameter controlling the probability and extent of GBS is thus the grain size. The many times experimentally proved increasing extent of GBS with increasing grain size at homologous temperatures above 0.4 is in full accord with the suggested mechanism of RC.

Unfortunately, there is lack of literature data concerning the impact of other material parameters upon the GBS of ferritic steels. However, according to [33] any factor increasing the resistance to shear inside the grains relative to grain boundaries tends to promote intercrystalline fracture. This conclusion is again in good correlation with the suggested role of strength in RC. Furthermore, the temperature and strain rate dependence of the strength of ferritic steels furnishes an explanation for the temperature and strain dependence of the measured reduction in area of RC tests of ferritic steels.

Provided a reasonable decrease in the matrix strength accompanies the increasing temperature, the relative contribution of GBS to overall strain can be reduced due to the decreased rate of their (stress-assisted) generation at the grain boundary. Simultaneously, the increased efficiency of accommodation processes by dislocation creep and diffusion flow in the grain boundary region retards the nucleation of grain boundary defects. The overall plasticity to fracture can thus increase[6], and

[6] The recovery of overall plasticity despite the intercrystalline fracture mode at tem-

intercrystalline voids nucleate rather than crack-like defects. Shallow dimples on the intercrystalline facets manifest the higher activity of dislocations in the grain boundary region and the dimpled intercrystalline fracture morphology resembles the ductile transcrystalline fracture. The above assumption about the relation between the fracture morphology and the fracture stress is in full correlation with the experimental results in [27, 34, 35].

The influence of decreasing strain rate at constant temperature is different. The decrease of the matrix strength within approx. 500–700 ℃ exceeds significantly the drop of strength, occurring with the decrease of strain rate within two orders of magnitude [27, 34]. It follows that neither the rate of dissociation of the matrix dislocations, nor the mobility of extrinsic dislocations, are altered significantly. Since the decreased strain rate favors the thermally activated generation and movement of extrinsic dislocations in the grain boundary, the relative contribution of GBS to the overall plastic strain increases and intercrystalline fracture appears at lower overall strain. On the contrary, increased strain rate can completely suppress the (time-dependent) dissociation of matrix dislocations and initiate a transition to ductile transcrystalline fracture.

GBS thus enables the interpretation of all basic features of RC tests and identifies the mechanism of RC with creep intercrystalline fracture. Often demonstrated influence of secondary hardening and segregation of impurity elements to grain boundaries can be also explained via their effect on the kinetics of GBS [27] and is in good correlation with the model of RC based on GBS.

2.3.4 *Summary of the results*

The most important results of [26–28, 34, 35] can be summarized as follows:

1. The mechanism of intercrystalline fracture of some ferritic materials during reheat cracking tests is, in spite of high strain rates, associated with GBS and can be considered to be identical with standard creep intercrystalline fracture.

2. The main parameters controlling the activation of GBS at high strain rates and thus the transition from ductile to intercrystalline fracture at elevated temperatures are the grain size and the strength (flow stress) of the matrix.

3. The two basic parameters, affecting the probability of intercrystalline fracture of ferritic steel at elevated temperatures that is the grain size and the strength of the matrix, are the same as those, controlling cleavage and DBT at low temperatures[7].

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peratures approaching the A_{c1} temperature of ferritic material is a typical behavior of materials susceptible to RC.

[7] Moreover, current analysis of an extensive set of experimental data indicates [36] in accord with low temperature fracture mode transition (DBT) that the effective grain size has to be used to explain the enhanced susceptibility of upper bainitic structures

2.4 Summary of parameters controlling the fracture mode of ferritic steels

As mentioned earlier, the requirement of sufficient toughness of structural materials can be in general identified with the requirement of ductile transcrystalline fracture mode. The temperature and strain rate region of ductile fracture mode is delimited by the loading conditions of DBT (low temperatures and high strain rates) and TIT (elevated temperatures and moderate to low strain rates). In accord with the results discussed up to now, the sequence of deformation modes and the corresponding fracture modes, as they appear with increasing temperature and/or decreasing strain rate (discussed in more detail in [37]), will then be as follows:

A: Low temperatures and high strain rates

A1: Mechanical twinning, leading to transcrystalline cleavage fracture initiated at the twin-twin or twin-grain boundary intersections.

A2: Mechanical twinning plus glide of dislocations restricted to primary slip systems, leading to transcrystalline cleavage fracture initiated at the intersections of active slip systems with unfavorably oriented twin boundaries.

B: Intermediate temperatures and moderate strain rates

B1: Glide (secondary slip systems activated) or glide and climb of dislocations, leading to transcrystalline ductile fracture initiated by dislocation loops stored at obstacles.

C: Elevated to high temperatures and moderate to low strain rates

C1: GBS and glide of matrix dislocations, leading to intercrystalline fracture by nucleation and extension of crack like submicroscopic defects at obstacles to sliding. Restricted to high strength and coarse-grained ferritic steels and moderate strain rates.

C2: GBS and glide and climb of matrix dislocations (dislocation creep), leading to intercrystalline fracture by nucleation and growth of voids.

It follows that the fracture modes occurring in ferritic structural steels can be directly correlated with the actual deformation mode. Restriction of the deformation mode to glide and glide and climb of grain interior dislocations is an inevitable condition for the ductile transcrystalline fracture.

As discussed in more detail in Sections 2.2 and 2.3, the frequently proved vigorous influence of material parameters (microstructure, grain size) on the actual DBT and TIT temperature and/or strain rate is in good correlation with their influence on the activation conditions of the controlling deformation modes. Thus, it can be summarized that the *both known fracture mode transitions of ferritic steels occurring with the change of loading conditions, i.e. the DBT and TIT, are the result of intrinsic tendency of the material to adjust the operating deformation*

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to intercrystalline fracture at elevated temperatures and this despite their relatively low strength.

mode to external conditions[8]*. The actual temperature and strain rate of the transitions are affected by the actual combination and extent of different metallurgical strengthening processes* (i.e. the microstructure of the matrix and its effective grain size).

3. Discussion

Since the summarized results were discussed in detail in [3–7, 18–21, 26–28, 34, 35, 37], only the common features, linking the presented results from the standpoint of parameters controlling the fracture properties, will be discussed. The most important results can be generalized as follows:

– The fracture mode is controlled by the active deformation mode or the combination of active deformation modes: cleavage fracture is associated with the occurrence of deformation twinning, while intercrystalline fracture is a consequence of grain boundary sliding.

– Modifications of the active deformation mode of the given ferritic material, i.e. activation of deformation twinning or grain boundary sliding, result from the intrinsic tendency of the material to adjust the operating deformation mode to the external loading conditions – the temperature and strain rate (the stress level).

– The principal material parameters affecting the deformation mode at given loading conditions are the grain size and the actual combination of metallurgical strengthening processes, governing the strength of the matrix.

The extent of basic strengthening processes, including the total area of grain boundaries in volume unit (grain boundary strengthening) is governed by the chemical composition of structural material and its entire thermal and stress/strain history, i.e. manufacturing process plus weld cycle (if any) plus operating conditions. The basic aspects of the foregoing discussion of the parameters controlling the fracture properties and the relations between them are schematically summarized in Fig. 1.

Amongst the basic strengthening mechanisms the grain boundary strengthening deserves a special attention. Though increasing the strength, grain refinement decreases the probability of DBT and TIT thus widens the engineering exploitation conditions of the steel. While in the case of dynamic DBT temperature the impact of the effective grain size upon the transition temperature seems to be the far most important, its domination in the case of static DBT measured by tensile tests at cryogenic temperatures and TIT is less pronounced.

Exceptional importance of the effective grain size during dynamic loading at ambient and subzero temperatures is in very good correlation with the proposed

[8] The internal tendency to modify the mechanism of deformation follows from the thermally activated nature of processes participating on the plastic flow: activation of the sources of dislocations in secondary/tertiary slip systems, dissociation of matrix dislocations and generation of extrinsic dislocations etc.

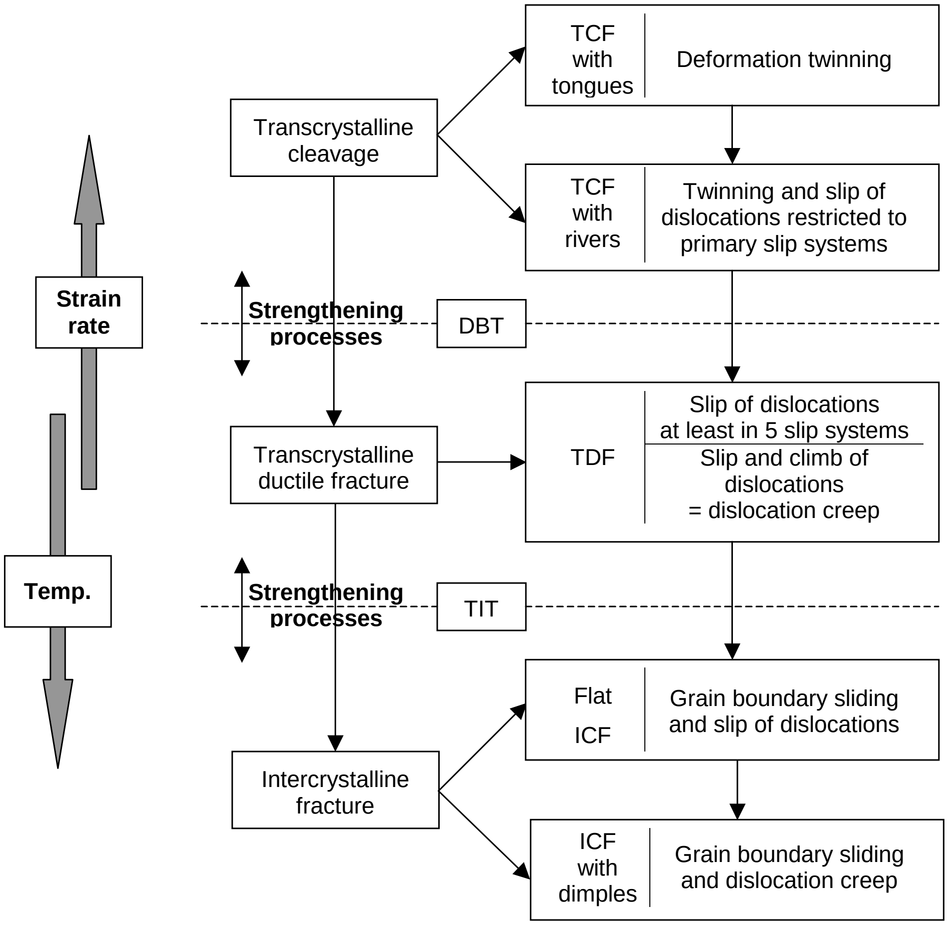

Fig. 1. Schematic representation of the relation between the deformation modes and fracture modes of ferritic steels.

controlling role of deformation twinning in DBT. Since the process of deformation twinning is extremely fast, the strain rate is not the limiting factor of the operation of pole mechanism of twinning. It follows that particularly those parameters acquire an extra importance with increasing strain rate, which directly control the process of deformation twinning, i.e. the grain size. Consequently, parameters controlling the slip of dislocations lose their relative importance.

On the other hand, the strength of the matrix maintains its relative importance in the case of TIT. Increased temperature and decreased strain rate do not restrict the mobility of dislocations. Contrariwise, dislocations acquire a further degree of freedom (climb), facilitating the relaxation of local stress peaks at grain boundaries. Thus, high deformation stress (strength) of the matrix, reducing the energetic barrier for dissociation of the matrix dislocations, retains its importance.

As far as the rest of metallurgical strengthening parameters are concerned, their individual detrimental impact upon the DBT and TIT as well as on the static ductility is not in any contradiction with practical experience. Naturally, since their relative contribution to the resultant strength and to the probability of activation of specific deformation modes differs, formulation of any simple relation between the strength and fracture properties of ferritic steels is currently impossible. Thus, it can be summarized that, though a dominant role of the grain size and the strength of the matrix in the process of fracture of ferritic materials can be manifested in a wide range of loading conditions, quantification of the fracture properties based on measurable mechanical properties is not yet possible. It means that the role of microstructure, as a complex characteristic of ferritic steels, cannot be yet substituted.

On the other hand, it might be important that four basic parameters, i.e. the temperature, strain rate (stress level), strength, and grain size, can most probably furnish a consistent description of the dependence of fracture behavior of ferritic steels on their microstructure and loading conditions. We believe that the presented inferences could simplify the current understanding of the general pattern of fracture of ferritic structural steels.

Another aspect of the presented approach, which might show up to be quite significant, is the fact that the loading conditions terminated by ductile fracture can be defined by the requirement of a single deformation mode being the movement of dislocations. The temperature and strain rate (stress) range of ductile fracture can be thus delimited by loading conditions, leading to stress assisted thermal activation of secondary slip and generation of extrinsic dislocations in the grain boundary. Such loading conditions can be physically defined through their activation energy at given stress levels. The possibility of physical definition of limiting conditions for ductile fracture is promising from the standpoint of the attempt to formulate the phenomenological thermodynamic theory of plastic deformation [38–41]. It might provide the means of including the range of applicability of the theory directly amongst the initial conditions and postulate that within the range of applicability the deformation mode is restricted to single mechanism, i.e. the movement of dislocations. Restriction of possible mechanisms of plastic deformation to a single one significantly simplifies the requirements on the theoretical apparatus.

4. Conclusions

1. The fracture mode of ferritic materials is controlled by the active deformation mode: cleavage fracture is a consequence of the activation of deformation twinning while intercrystalline fracture appears under loading conditions, leading

to grain boundary sliding. Ductile fracture is restricted to temperatures and strain rates at which movement of dislocations is the only mechanism of deformation.

2. Though the principal material parameters, affecting the temperature and strain rate of the activation of deformation twinning and grain boundary sliding, are the strength of the matrix and the effective grain size, the role of microstructure as a complex qualitative characteristic of the ferritic steel cannot yet be replaced by measurable material parameters.

3. The dominant and, from the standpoint of the strength, unsystematic impact of the microstructure upon the fracture properties of the ferritic steels follows from different relative contribution of basic metallurgical strengthening processes to the resultant strength of the matrix and their different relative contribution to the probability of deformation twinning and grain boundary sliding.

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Received: 24.1.2002
Revised: 25.6.2002