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A Brief Review on Grain Refinement In Steel Through Dynamic Strain Induced Transformation

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Abstract

Grain refinement is the only way to increase both strength and toughness in steel. In the last decade, dynamic strain induced transformation (DSIT) shown tremendous capabilities of grain refinement in steel. This method is widely used for production of ultra-fine ferritic steel. The present article reviews dynamic strain induced transformation phenomena in steel. It covers DSIT methodology, mechanism, effect of process parameters, and modeling on the basis of physical metallurgy principles. In each section DSIT phenomena is briefly reviewed to highlights work done in the field of DSIT and the gaps in knowledge.

Introduction

The development of ultra-fine grained ferrite leads to significant improvement in toughness in steel. To produce high toughness steels of high weldability attainment of ultra-fine grained ferritic structure is necessary. This has stimulated interest among researchers to evolve newer and newer techniques to refine ferrite grains to as small a size as possible. The hardening in polycrystalline metals with smaller grain size is first reported by Hall [1] and Petch [2] as:

$$\sigma = \sigma_0 + KD^{-1/2} \qquad (1)$$

Where σ is the flow stress of the polycrystalline material, K is a constant and D is the grain diameter. The principle of the above described hardening effect due to grain refinement has been explained in a review paper by Li and Chou [3]. A gliding dislocation propagating into another grain is blocked by the surrounding grain boundaries; this results in the formation of a dislocation pile-up near the grain boundary. Increasing number of pile-ups near the grain boundary leads to stress concentration. Once a critical stress is reached, other dislocations in the neighboring grains are activated and glide until they meet the grain boundary. With the decreasing size of the grains, the total grain boundary area is substantially increased and more obstructions would be encountered by the dislocations during their propagation. Thus a higher stress will be required for the dislocations to move, thereby giving rise to higher strength. Another interpretation of the hardening effect as per Hall-Petch relationship is due to J.C.M. Li [4]. Instead of explaining the hardening effect by dislocation pile-up mechanism, Li proposed that ledges at the grain boundaries might pump dislocations into the grains during deformation; the yield stress of metal is stated to correspond to the stress required to overcome the stress-field around the dislocations near the ledges or the stress which is needed to activate new ledges. Many studies have reported that dislocations were generated from the grain boundary ledges at the onset of yielding [5-7], and that these provide strong support to the hardening mechanism proposed by Li. Having been a matter of paramount importance in respect of strengthening of alloys, evolution of techniques for effective grain refinement in some high performance steels has been the subject of advanced research.

Different routes for the production of ultrafine grained steels have been explored by a number of workers with the main aim to achieve ultra-fine grains with minimum energy. The evolution of strategies adopted so far to produce an ultra-fine grain structure of steel includes the following with individual merits and demerits.

- Grain refinement through inclusion
- Thermo-mechanical processing
- Severe plastic deformation
- Dynamic strain induced transformation

Dynamic Strain Induced Transformation (DSIT)

Dynamic strain induced transformation of austenite is of particular interest because it can produce ferrite grains much finer than what is achieved by conventional TMCP [6-10]. This is possible through introduction of extensive intra-granular nucleation sites, retarding transformation growth by 3D impingement and finally by continuous dynamic recrystallization of DSIT ferrite.

Microstructure control can be affected by means of suitable design of rolling schedules, so as to be able to produce DSIT ferrite in low carbon steels [11]. Micro-alloying with Nb/Ti is known to insure extra refinement in low carbon steel. When low carbon steel is mechanically worked in (α+ϒ) two phase field, dynamic softening takes place due to both continuous dynamic recrystalization (CDRX) and dynamic strain induced

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transformation (DSIT). However the mechanism capable of describing the DSIT as a whole is yet to be developed.

Deformation

It is known that deformation of steel increase the Ar_3 temperature. Prior austenite grain size, cooling rate and steel composition are known to influence the deformation aided above rise in transformation temperature. If the steel is deformed so much so that the Ar_3 temperature increases to the temperature of deformation, ferrite will be dynamically formed during deformation [12]. Principle and optical micrograph of DSIT grains are shown in figure 1 and figure 2.

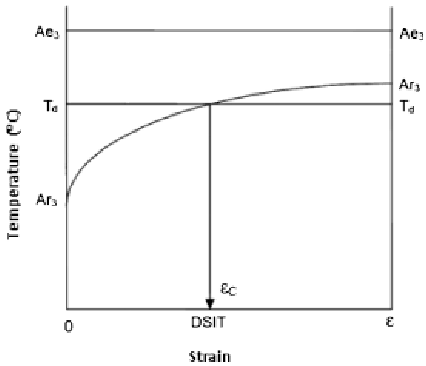


Figure 1: Principles of dynamic strain induced transformation during deformation at constant temperature [13]

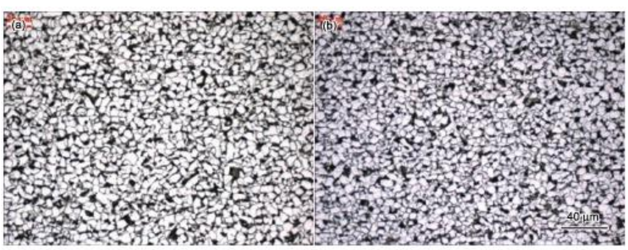


Figure 2: Optical micrographs of DSIT at deformation temperature (a) 850 ^{0}C and (b) 770 ^{0}C for 0.14C-0.64Mn steel [23]

Difference between Static strain induced Transformation (SSIT) and DSIT

R. Priestner et. al. [14] and R. Bengochea et. al [15] have shown that there is a significant difference in post deformation growth of ferrite in DSIT and SSIT; moreover P. J. Hurley et. al in [16] have demonstrated that recovery removes some of the potential nucleation sites formed in austenite before SSIT while this does not occur in DSIT. The summarized difference between the two types of transformations is tabled below.

Table 1: Characteristic difference between SSIT and DSIT

DSIT	SSIT
The austenite to ferrite transformation takes place during the course of deformation.	The austenite to ferrite transformation takes place after deformation.
Numerous nucleation sites are generated	Less nucleation sites are generated.
DSIT provides least time for transformation growth	Comparatively more time is available for growth.
A low under-cooling with high strains yields significant amount of transformation	Higher level of under-cooling is required to achieve a significant transformation.
Ultrafine ferrite of grain size 1 µm is achieved till date. Can we produce DSIT ferrite less than 1 micron?	Achievable grain size is limited to 5-10 µm.

Mechanism of DSIT

Elegant study due to A. Shokouhi and P. D. Hodgson [17] on hot torsion testing of low carbon micro alloyed steel led to a good understanding of the transformation mechanisms of both SSIT and DSIT. These authors reported that the static and the dynamic strain induced transformation had different grain refinement potential due primarily to (a) difference in the number of viable nuclei and (b) the extent of possible coarsening in the above two mechanisms.

The major difference for grain refinement potential of DSIT and SSIT lies in the fact that DSIT envisages a reduction in time difference between nucleation at different sites and consequent growth of ferrite grains, thereby leading to the preservation of a higher portion of effective nuclei in the microstructure. SSIT set up a 2D impingement among the ferrite grains; therefore a harmonious transformation and coarsening occur in this process and this leads to the formation of relatively large equi-axed grains in the final microstructure. However DSIT involves a group of grains in 3D impingement and this type of impingement inhibits the movement of ferrite/ferrite inter-phase boundaries; this gives rise to the formation of grains which maintain their fine sizes throughout the transformation [17-18].
However, different mechanisms are proposed for grain refinement through DSIT. These are:

- Diffusional transformation
- Diffusional transformation of austenite and the subsequent dynamic re-crystallization of ferrite
- Massive transformation to ferrite

Distinguishing the dynamic nature of DSIT process from the static strain assisted transformation achieved by controlled rolling is the key to successful development of a mechanistic model of DSIT.

J. H. Chung et. al [19] has advocated that a massive austenite to ferrite transformation is involved in DSIT because the formation of ultrafine ferrite is insensitive to strain rate. They found that the microstructure of ferrite during hot deformation was of bulky type and from morphological identity it is conjectured that DSIT is a massive transformation. However Beladi et. al. reasoned out massive transformation as it takes place just below T_o temperature (the temperature at which $G^{\Upsilon}=G^{a}$) [12].

Similar observation by Haiwan Leo [20] has led to the conclusion that massive transformation is not possible during DSIT on account of deformation being carried out above Ae_3 and stored energy of austenite being much higher in comparison to what is produced by hot deformation. However J. H. Chung et. al demonstrated massive transformation taking place in DSIT of medium carbon steel [19].

Investigation on the kinetics of ferrite formation as a function of amount of deformation is documented in literature [21]. Accelerated kinetics of ferrite transformation in either case of partioned and partition-less growth behavior of ferrite could be noticed in Fe-C-X alloys with increasing amount of deformation of austenite in (Υ+a) phase field.

The fact that the accelerated transformation at low under-cooling has been more common is seemingly due to a large contribution of stored deformation energy to the driving force for transformation. Precipitation of cementite particles leading to incomplete carbon diffusion during DSIT process was also reported by the same authors [22].

A recent report put forward a mechanism which is different from deformation induced transformation and is described as deformation enhanced process of phase transformation [23]. Since austenite to ferrite transformation is stated to take place both during under-cooling and during straining, the increment in nucleation due to deformation and enhancement in driving force due to under-cooling have to be concurrent. Interaction between deformation enhanced transformation and dynamic recrystalization of ferrite formed by the above process is seen to favor the production of fine grained ferrite and pearlite in the microstructure. Eventually it has been possible by the above workers to secure ferrite grain size in the range of 2-3 µm by means of single rolling process.

Effect of Process Parameters

Strain

It is a known that applied strain generates intra-granular defects which act as potential nucleation sites of ferrite [24-26]. However most of the researchers proposed two types of strain; first, critical strain to start DSIT process, $\varepsilon_{c\ DSIT}$ and another strain which is higher than $\varepsilon_{c\ DSIT}$ is required to complete the UFF formation and is called ε_c. M. Militzer et. al. developed equation to calculate both the strains [27]. A typical stress-strain curve is shown in the figure 3. The effect of equivalent strain is shown in figure 4.

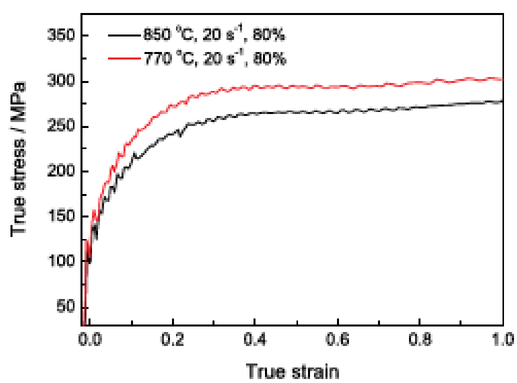
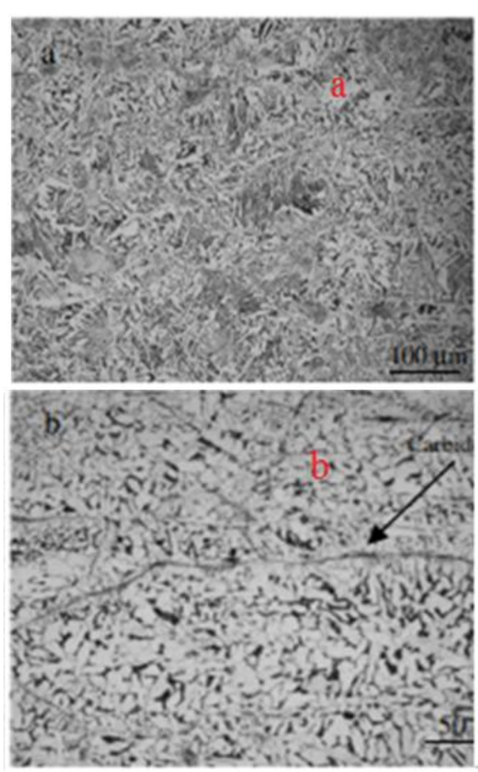


Figure 3: Stress-strain curve at different temperature for 0.14C-0.64Mn steel [23]



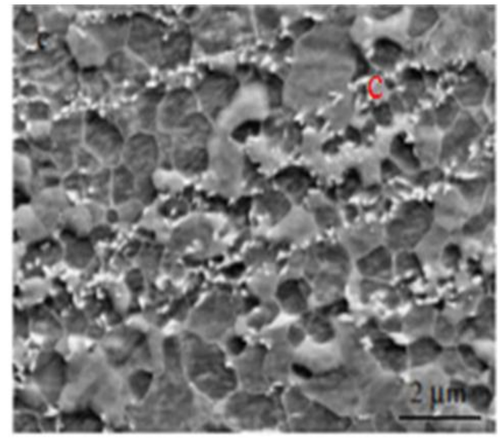


Figure 4: The microstructure of 0.16%C steel at different equivalent strains (a) 0,(b) 0.6,(c) 0.8 [28]

H. Beladi et. al. reported the results of a study on the evolution of dynamic strain induced transformation in steel of composition 0.17C-1.5Mn-0.45Si-0.046Al-0.02V (in wt.%) by way of its deformation in the Ae_3-Ar_3 temperature region. The results of the concerned study led to the findings that [28]:

I. $\varepsilon_{C\ DSIT}$ decreases with decrease in prior austenitic grain size.
II. $\varepsilon_{C\ DSIT}$ decreases with a reduction in the deformation temperature in Ae_3-Ar_3 temperature region.
III. $\varepsilon_{C\ UFF}$ increases with increase in prior austenitic grain size and deformation temperature.
IV. $\varepsilon_{C\ UFF}$ decreases with increase in post deformation cooling.

Strain Rate

The strain rate is found to influence the grain refinement through DSIT process; as increasing strain rate can inhibit the recovery process in austenite grains through DRX and it may produce higher number of dislocations. Equally the distribution of shear bands and slip system in austenite are reported to have been affected by the strain rate. Nevertheless it is admitted that the researchers have so far exhibited difference in opinions [29-31].

The fact that increasing strain rate leads to finer microstructure is reported by H. Beladi et. al. [12]; however Tong et. al. advocated for a detrimental effect of strain rate to achieve a uniform grain structure.

Some authors have recorded their observation on strain rate dependency in the early stage of DSIT process; however they report DSIT ferrite formation is independent of strain rate in later stage of DSIT process; On the other hand, the proposition of Hodgson et. al. is supportive of the fact that increasing strain rate produces deformation heating and ultimately reduced the time available for transformation and that these two factors work against an ultrafine structure being formed. Figure 5 shows the effect of strain rate on microstructure.

Deformation Temperature

It is a fact that a higher level of under-cooling is required to produce UFF ferrite in DSIT process. This implies that the deformation temperature is a parameter of DSIT process. It was Hodgson et. al. who proposed that the temperature of deformation would affect the volume fraction of DSIT ferrite; without affecting the degree of grain refinement. It was also verified that deformation of austenite within A_{e3}-A_{r3} region is quite important for DSIT to occur. Hong et. *al* (2003) has shown temperature insensitivity to grain size, except in micro-alloyed steels where it does appear that Nb offers further refinement [33-36]. It is felt that further investigation is required to understand the role of temperature of deformation on DSIT ferrite.

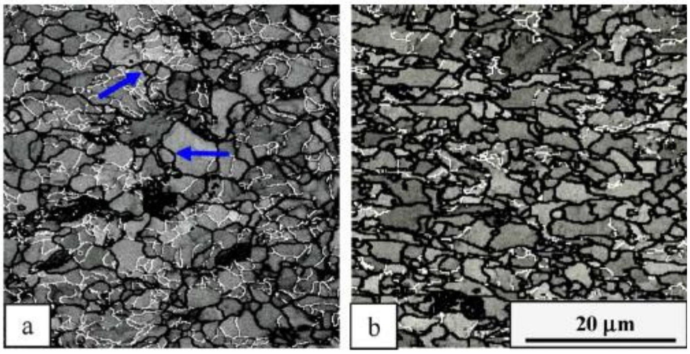


Figure 5: EBSD maps showing the microstructure development at 845 ^{0}C for strain of 0.8 and strain rate of (a) 0.001s^{-1} and (b) 0.1s^{-1} [32]

Grain Size of Deforming Austenite

It is reported by previous worker that larger is the prior austenite grain more intense become the generation of intra-granular crystal defects viz. dislocation [33-34]; It is also found that effect of strain is strong for large austenite grain size. This produces much finer DSIT ferrite; however smaller grain size in early stage of DSIT is stated to produce finer ferrite. In considering pinning effect due to second phase particles, grain growth is retarded.

Effect of Additives on Ferrite Grain Refinement

Addition of Copper is known to lower Ar_3 temperature of steel [37] and this has a positive effect on DSIT. It is suggested that additives like C, Mn, Nb retard the transition of austenite to ferrite grains by DSIT. This is become of the formation of carbide on the grain boundaries of austenite. Rios et.al studied effect of Nb addition on DSIT of C-Mn steel. They showed that Nb addition favors the DSIT phenomenon as shown in figure 6 and figure 7 [38].

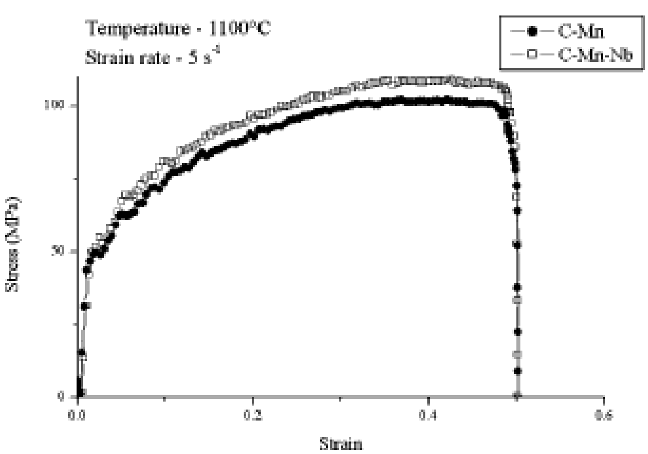


Figure 6: Stress-strain curve obtained for C-Mn and C-Mn-Nb steel after deformation with strain rate of 5 s^{-1} at temperature T=1100 ^{0}C and strain 0.5 [38]

Some amounts of austenite remain untransformed during DSIT. The higher hardness of the austenite as compared to that of the initial austenite is indicative of its carbon enrichment; this opposes DSIT. Information about the effect of minor addition on grain refinement during DSIT is still lacking.

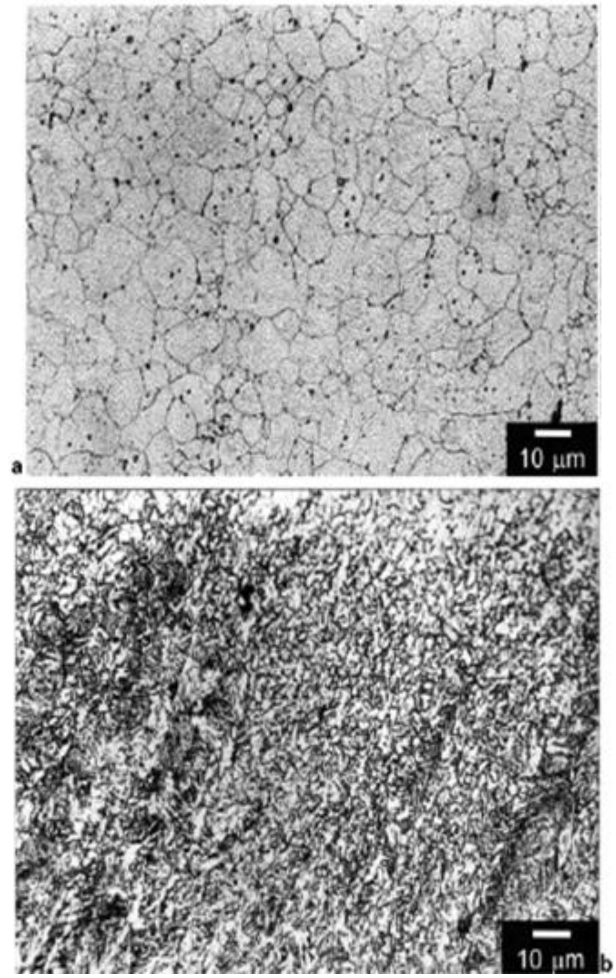


Figure 7: (a) Recrystallized austenite for C-Mn steel and (b) DSIT ferrite for C-Mn-Nb steel after deformation [38]

Modelling

Hodgson et. al. proposed a descriptive model in which they suggest there is a regular spacing of planer defects in austenite (produced by deformation) which acts a potential nucleation sites, the ferrite nucleates from these sites. [12]. Umemoto et. al. developed a mathematical model in which they proposed [39]:

$$Rate\ of\ nucleation = f\ (stored\ energy\ induced\ by\ deformation) \quad (2)$$

However this model has its limitation in controlled rolling; because in controlled rolled rolling some of the strain energy induced by deformation remains stored in austenite.

Recently a cellular automation model by Zheng et. al. [40] has considered that the stored deformation energy E_d is released due to recovery during post dynamic holding. The evolution of the stored energy as a function of soaking time t is calculated. The simulated and experimental microstructures are shown in figure 8.

M. Militzer et. al proposed a phenomenological model in which they describes the conditions under which an ultra-fine ferrite forms in low carbon-steel as a result of deformation induced ferrite transformation [41]. They assume corner points in dislocation cell substructure of microshear bands provide suitable nucleation sites for DSIT ferrite. They proposed:

- UFF ferrite formation is promoted by steel chemistry

- Minimum inter-facial velocity criterion must be fulfill for temperature range for UFF formation.
- Critical strain for initiation of DSIT:

$$\mathcal{E}_c = \frac{w}{d_y}\mathcal{E}_b + \mathcal{E}_0 \quad (3)$$

where w= width of micro-shear band; d_y= austenite grain size; $\mathcal{E}_b$= strain within the micro-shear band; $\mathcal{E}_0$= critical strain after which plastic strain associates micro-shear bands.

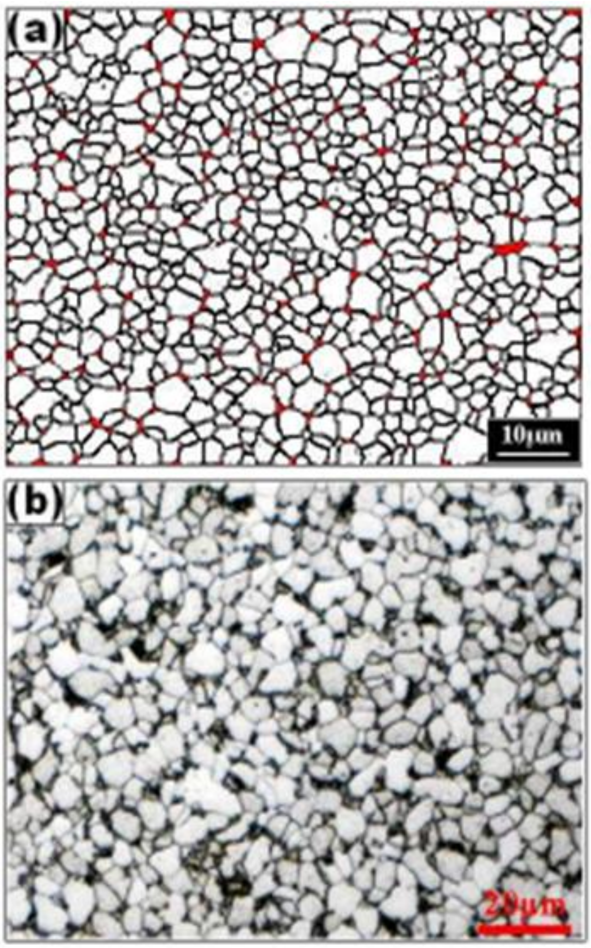


Figure 8: The resultant DSIT microstructure with a dual phase structure (a) simulated and (b) experimentally observed in optical micrograph [40].

Influence of Dynamic Re-crystallization (DRX) on DSIT

Dynamic re-crystallization (DRX) is one of the most efficient methods to achieve ultra-fine ferrite grain in the steel. The DRX associated with the formation of new grains (in hot working condition); the size of grain is expressed as:

$$\frac{\sigma}{G} = AD^n \quad (4)$$

Where A is a constant, G is the shear modulus and n is the grain size exponent, which is about -0.7 for hot working conditions.

The factors influencing the grain size achievable through thermo-mechanical controlled processing are known to be work hardening and softening by dynamic process of recovery. The three mechanisms viz. strain hardening; dynamic recovery and dynamic re-crystallization are different in their softening mechanisms. The point at which the combine effect of strain hardening and recovery are unable to accommodate more immobile dislocation is the starting point of DRX process [42-54]. Fig. 9 show flow curve during deformation.

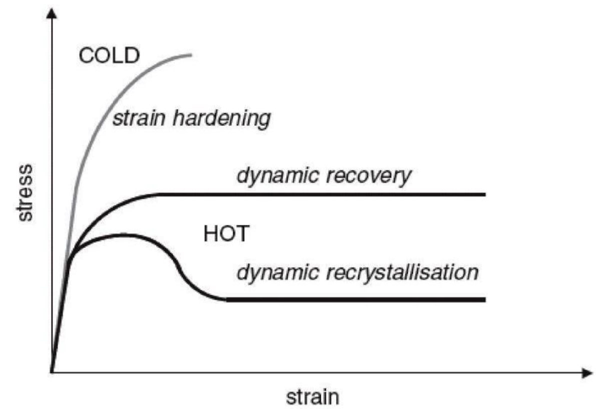


Figure 9: Typical flow curve during cold and hot deformation [55]

We know that austenite to ferrite transformation takes place dynamically if Ar_3 temperature is below the deformation temperature as shown in the fig. 10.

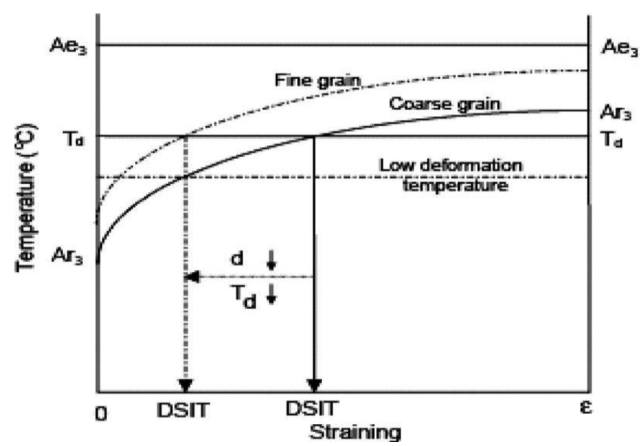


Figure 10: Condition for occurrence of DSIT [56]

As both DSIT and DRX are able to produce ultra-fine grained ferrite [57-59]; therefore the occurrence of DSIT or DRX depends on when critical strain for initiation of DSIT reach first or the critical strain for initiation of DRX will reach first. It also influence volumetric partition of DRX and DSIT grains in the final microstructure.

If deformation is applied

1. Above or below Ae_3; DRX prevail.
2. Close to Ar_3; DSIT will occur.

The fig. 11 shows critical deformation as a function of deformation temperature for DSIT and DRX for C-Mn steel.

Jetson et. *al* studied comparative influence of thermo-mechanical parameters on competition between DSIT and DRX for C-Mn and C-Mn-Nb steel [61]. He showed that at higher deformation temperature but well below to Ae_3; the deformation becomes critical for initiation of DSIT for ferrite; but if micro-alloying element like Nb is present in the austenite it can retard austenitic re-crystallization which leads to increase critical strain for initiation of DRX. Therefore DSIT will take place first and then DRX occurs. Fig. 12 shows temperature dependence of critical strain for occurrence of DSIT and DRX.

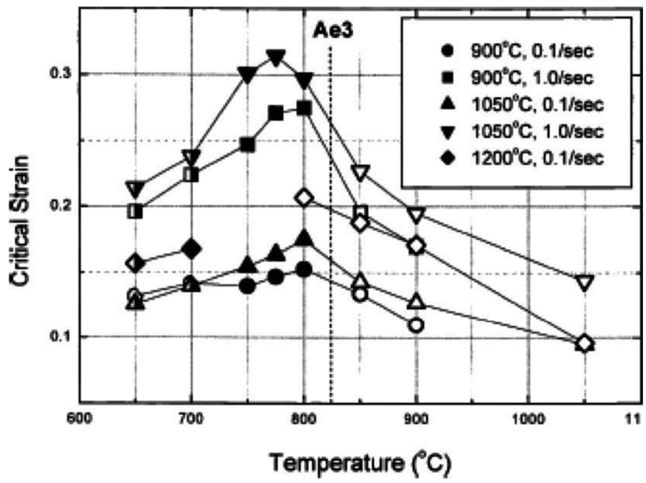


Figure 11: Critical deformation for onset of DSIT (black symbols) and DRX (white symbols) as function of deformation temperature for C–Mn steel [60]

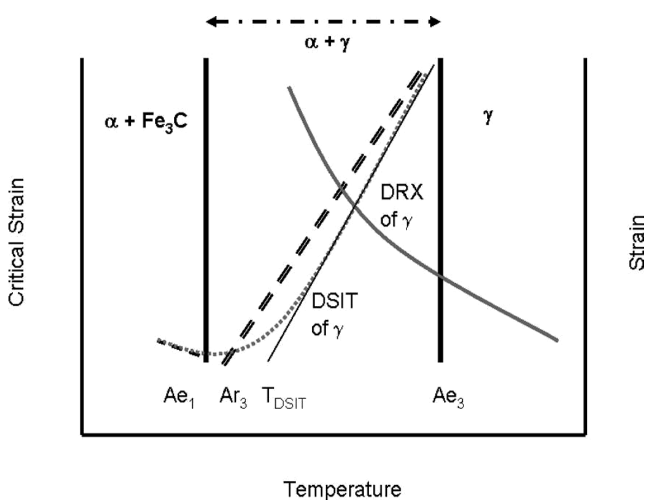


Figure 12: Temperature dependence of critical strain for occurrence of DSIT and DRX [61]

DRX of austenite

It is known that in DSIT, transformation of austenite takes place during its deformation. Also it is known that there is a critical value of strain beyond which DSIT can only occur. This critical strain is obviously a function of temperature and may be of strain rate; but it is a question whether within the limit of critical strain for a particular deformation temperature (T_d) and specific strain rate, austenite undergoes DRX or not. To know if there is any chance of DRX of austenite preceding DSIT for a deformation situation for DSIT ($T,\epsilon,\dot{\epsilon}$) it is required to know if critical strain for DRX of austenite at the temperature of DSIT is less than the critical strain for DSIT. If it is so, a large part of deformation energy will be consumed and thus this DRX of austenite will appreciably influence the subsequent DSIT phenomena.

Effect of Copper in DSIT

It is known that DSIT ferrite nucleates intra-granularly during deformation of austenite; the DSIT ferrite experiences transformation growth till 3D impingement inhibits the growth.

It is further known that solubility of Cu in ferrite is very small as compared to that of austenite, therefore ϒ-α transformation envisages the precipitation of Cu preferably at ferrite grain boundaries. There are reports on possible strain induced precipitation of Cu. Now it is a question if deforming austenite undergoing DSIT may concurrently precipitate out Cu at the DSIT ferrite grain boundaries.

There could be two options:

Either Cu is precipitated at the dislocations within deforming ϒ; or Cu may precipitate at the DSIT ferrite boundaries; we cannot rule out the occurrence of both the events while deforming Cu bearing austenite to realize DSIT; if the deformation energy is first spent for DSIT, then pure solubility constraint will drive the precipitation of Cu on to the ferrite grain boundaries.

This will inhibit the transformation growth in a great way and final ferrite grain size may be less than the 3D impingement limiting situation. In fact, we do not know if the solubility of Cu in deformed austenite is far less than that in un-deformed austenite although one will expect it to be so. Therefore it is a question to answer if precipitation of Cu occurs before DSIT or during DSIT.

In either case there will be extra-impediment of the transformation growth of ferrite and hence finer ferrite grain will be formed. In view of the presence of Cu particles at the boundaries of ferrite; the ferrite grain refinement (so obtained) will be a stable phenomenon.

If there is precipitation of Cu in deformed austenite, there will be significant difference in final grain size of ferrite formed in the two alloys.

If there is precipitation in deformed austenite; there can be two possibilities:

1. Initial Cu to form is normally BCC, the Cu particles themselves can nucleate ferrite; in such case we are likely to see Cu particles at the triple points of ferrite. If it is not, the Cu particles will impede the transformation growth of ferrite; when the moving boundary comes across the particle and we will see them obstructing grain boundary movement.

   There can be another possibility;

2. if the Cu precipitation is limited and the inter-particle distance of Cu is higher than mean free path for 2d impingement, grain refinement of ferrite directly due to Cu is not possible (although copper particles assist in retention of deformation of deformation bands to act as intra-granular nucleation sites for ferrite.

It is known that ferrite undergoes dynamic re-crystallization while austenite is undergoing DSIT. We know that for each temperature of deformation there will be critical DSIT strain. Excess deformation energy if available will deform ferrite which under certain situation of strain, strain rate and temperature may undergo DRX. We do not know whether the magnitude of excess deformation energy has any influence in final DSIT grain size and shape.

Effect of micro-alloying element (Ti) on DSIT

It has been found that the addition of micro-alloying element (Nb/Ti) decreases the stacking fault energy of austenite phase and retards the dynamic recovery process. Therefore strain energy produced by deformation becomes concentrated resulting in generation of high dislocation densities. In literature it is confirmed that high dislocation densities act as nucleation sites for DSIT ferrite. Therefore it is a question if the addition of micro-alloying elements (Nb/Ti) can affect the DSIT phenomena? (like DSIT nucleation kinetics).

Effect of micro-alloying element on DRX peak strain

The peak strain in stress/strain curve is given by:

$$\mathcal{E}_p = AZ^m \quad (5)$$

Where;

Z= Zenner-Hollomon parameter; ε_p+ peak strain; m= power law term; A=constant depends upon material composition and initial grain size of material.

The addition of micro-alloying elements (Nb/Ti) retards DRX kinetics of austenite through solute drag effect, therefore constant A in above equation changes (and we can correlate this change in constant A); with the concentration of micro-alloying elements.

This increase in peak strain compensated by increase in high dislocation densities within austenite; this may ensure more nucleation sites for DSIT ferrite (this may affect the volume fraction of DSIT ferrite).

Conclusions

1. Dynamic strain induced transformation DSIT is conditioned by deformation of austenite during transformation to ferrite; that is within the A_{e3}-A_{r3} temperature.
2. The role of dynamic re-crystallization on DSIT ferrite; the reason of equi-axed morphology of DSIT ferrite grains is to be authenticated.
3. It also feels, difference in mechanism proposed for DSIT by a number of workers; so a general mechanism which can define entirety of DSIT phenomena is yet to be developed.
4. Effect of micro-alloying element like Nb/Ti on DSIT; as these elements tends to retard the DRX process; therefore it can influence the DSIT phenomena.

References

1. E.O. Hall: Proc. Phys. Soc. B64. 747. (1951)
2. N.J. Petch: Iron Steel inst. 74. 25 (1953)
3. J.C.M Li, Y.T. Chou: Metal. Trans. 1145. (1958)
4. J.C.M Li: Trans. TMS-AIME 227. 239. (1963)
5. E. S. Venkatesh, L.E. Murr: Scripta Metall. 10(1976) 477
6. J. H. Beynon, R. Gloss and P. D. Hodgson: Mater. Forum, 1992, 16, 37–42.
7. W.-Y. Choo, K. K. Um, J. S. Lee, D. H. Seo and J. K. Choi: Proc. Int. Symp. on ‘Ultrafine grained steels’, Fukuoka, Japan, September 2001, The Iron and Steel Institute of Japan, 2–9.
8. H. Beladi, G. L. Kelly, A. Shokouhi and P. D. Hodgson: Mater. Sci. Eng. A, 2004, A367, 152–161.
9. P. D. Hodgson, M. R. Hickson and R. K. Gibbs: United State Patent No. 6,027,587, 2000.
10. Y. Adachi and S. Hinotani: Proc. Int. Symp. on ‘Ultrafine grained steels’, Fukuoka, Japan, September 2001, The Iron and Steel Institute of Japan, 84–87.
11. B. Eghbali; Material Science and Engineering A, 527 (2010) 3407-3410
12. H. Beladi, G.L. Kelly, P.D. Hodgson; International Mateials Review; 2007 vol52 No1
13. Shaban, M., S. Gozalzadeh, and B. Eghbali. "Dynamic Strain Induced Transformation of Austenite to Ferrite during High Temperature Extrusion of Low Carbon Steel." *Materials transactions* 52.1 (2011): 8-11.
14. Pristner,R. and de los Rios,E.;1980, Met. Tech; 7,309.
15. Bengochea, R.;Lopez,B. and Gutierrez, I; 1999,ISIJ Int;39,583
16. P.J. Hurley, P.D. Hodgson, B.C. Muddle, Scripta. Mater. 40 (1999) 433
17. A Shokouhi et. al, Effect of transformation mechanism on final grain size, Material Science and Technology, 2009, vol-25
18. A Shokouli et. al Dynamic adjustment of ferrite grains during dynamic strain induced transformation,2007, Material Science and Technology, 2007,vol-23.
19. J. H. Chung, J.K. Park, T.H.Kim,K.H.Kim,S.Y.Ok; Material Science and Engineering A 527 2010 5072-5077
20. Haiwen Luo Material Science and Engineering A 528 2011 8259-8262
21. Vinogradov, A., et al. "Kinetics of deformation processes in high-alloyed cast transformation-induced plasticity/twinning-induced plasticity steels determined by acoustic emission and scanning electron microscopy: Influence of austenite stability on deformation mechanisms." *Acta Materialia*61.7 (2013): 2434-2449.
22. Zhao-Dong Li, Zhi-Gang Yang, Chi Zhang, Zhen-Qing Liu; Material Science and Engineering A, 527 (2010) 4406-4411
23. Luhan Hao, Mingyue Sun,Namin Xiao and Dianzhong Li; J. Mater. Sci. Technol; 2012 28(12), 1095-1101
24. Z. M. Yang, R. Z. Wang, H. Dong and Q. A. Chen: Proc. Int. Symp. on ‘Ultrafine grained steels’, Fukuoka, Japan, September 2001, The Iron and Steel Institute of Japan, 112–115.
25. L. Du, C. Zhang, H. Ding, X. Liu and G. Wang: ISIJ Int., 2002, 42, 1119–1124.
26. H. Yada, Y. Matsumura and T. Senuma: Proc. Conf. Thermec ’88, Tokyo, Japan, June 1988, The Iron and Steel Institute of Japan, Vol. 1, 200–207.
27. M.Militzer, The Minerals, Metals and Material Society and ASM International 2009
28. H. Beladi, G.L. Kelly, A. Shokouhi, and P.D. Hodgson: *Mater Sci Eng A*, Vol.A367 (2004),p.152
29. B. Mintz and J. J. Jonas: Mater. Sci. Technol., 1994, 10, 721– 727.
30. Z. M. Yang, R. Z. Wang, H. Dong and Q. A. Chen: Proc. Int. on ‘Ultrafine grained steels’, Fukuoka, Japan, September 2001, The Iron and Steel Institute of Japan, 112–115.
31. H. Yada, C.-M. Li and H. Yamagata: ISIJ Int., 2000, 40, 200–206.
32. Eghbali, B., and A. Abdollah-Zadeh. "Strain-induced transformation in a low carbon microalloyed steel during hot compression testing." *Scripta materialia*54.6 (2006): 1205-1209
33. Hong, Seung Chan, et al. "Effects of Nb on strain induced ferrite transformation in C–Mn steel." *Materials Science and Engineering: A* 355.1 (2003): 241-248.
34. Hazra, Sujoy S. *Ferrite grain refinement in dual phase steels*. Diss. University of British Columbia, 2006. S.C. Hong, S.H. Lim, K.L. Lee, D.H. Shin, K.S. Lee, ISIJ Int. 43 (2003) 394–399.
35. H.-C. Lee, K.-K. UM, ISIJ Int. 48 (2008) 1050–1055.
36. J.S. Kirkaldy, E.A. Baganis, Metall. Trans. A 9 (1978) 495–501.
37. K. Hase, Y. Hirai, T. Hoshino, A. Matsuzaki, K. Amano, S. Takaki, Testu-to-Hagane 90 (2004) 554–561.
38. P. R. Rios, I. de S. Bott, D. B. Santos, T. M. F. de Melo & J. L. Ferreira (2007) Effect of Nb on dynamic strain induced austenite to ferrite transformation, Materials Science and Technology, 23:4, 417-422
39. Umemoto,M;Hiramatsu, A; Moriya; Watanabe T; 1992, ISIJ Int.; 32, 306
40. Chengwu Zheng,Dierk Raabe,Dianzhong Li; Acta Materialia 60 (2012) 4768-4779
41. Militzer, M., and Y. Brechet. "Phenomenological model for deformation-induced ferrite transformation." *Metallurgical and Materials Transactions A*40.10 (2009): 2273-2282.
42. Shokuhfar, A., S. M. Abbasi, and N. Ehseni. "Dynamic Recrystallization under Hot Deformation of a PH Stainless Steel." *International Journal of Iron & Steel Society of Iran* 3.1 (2006): 8-12.
43. Kentaro IharaYasuhiro Miura. Dynamic recrystallization in Al-Mg-Sc alloys. Materi als Science and Engineering: A, (2004).
44. Tsuji, N, Matsubara, Y, & Saito, Y. Dyanamic recrystallization of ferrite in interstitial free steel. Scripta Materialia, (1997).

45. Glover, G, & Sellars, C. M. Recovery and recrystallization during high temperature deformation of α-Iron. Scripta Materialia, (1973).
46. Glover, G, & Sellars, C. M. Static recrystallization after hot deformation of α-iron. Metallurgical Transactions, (1972).
47. Hongyan WuLinxiu Du, Xianghua Liu. Dynamic recrystallization and precipitation behavior of Mn-Cu-V weathering steel. Journal of Materials Science & Technology, (2011).
48. Smallman, Raymond E., and A. H. W. Ngan. *Physical metallurgy and advanced materials*. Butterworth-Heinemann, 2011.
49. Guo-Zheng QuanYuan-ping Mao, Gui-sheng Li, Wen-quan Lv, Yang Wang, Jie Zhou. A characterization for the dynamic recrystallization kinetics of as-extruded 7075 aluminum alloy based on true stress-strain curves. Computational Materials Sci- ence, (2012).
50. Gourdet, S., and F. Montheillet. "A model of continuous dynamic recrystallization." *Acta Materialia* 51.9 (2003): 2685-2699.
51. Verlinden, Bert, et al. *Thermo-mechanical processing of metallic materials*. Vol. 11. Elsevier, 2007.
52. Quan Guo-zhengTong Ying, Luo Gang, Zhou Jie. A characterization for the flow behavior of 42CrMo steel. Computational Materials Science, (2010).
53. Kumar, Pawan, et al. "Dynamic Re-Crystallization of Low Carbon Steel in Plain Strain Condition." *International Journal of Mechanical Engineering and Robotics Research* 5.2 (2016): 160.
54. Pawan Kumar, Peter Hodgson, *Effect of Temperature and Strain Rate on Dynamic Re-Crystallization of 0.05C-1.52Cu-1.51Mn Steel*, Mechanics, Materials Science & Engineering, Vol. 6 (2016), DOI 10.13140/RG.2.1.4905.2403.
55. Guo-Zheng, Quan. *Characterization for dynamic recrystallization kinetics based on stress-strain curves*. INTECH Open Access Publisher, 2013
56. P. D. Hodgson, H. Beladi and G. L. Kelly: *Can. Metall. Q.*, **44** (2005), 179.
57. Sun, L., et al. "Effect of strain path on dynamic strain-induced transformation in a microalloyed steel." *Acta Materialia* 66 (2014): 132-149.
58. Zhang, Shenghua, et al. "In situ investigation on the deformation-induced phase transformation of metastable austenite in Fe–13% Cr–4% Ni martensitic stainless steel." *Materials Science and Engineering: A* 635 (2015): 129-132.
59. Gong, P., E. J. Palmiere, and W. M. Rainforth. "Thermomechanical processing route to achieve ultrafine grains in low carbon microalloyed steels." *Acta Materialia* 119 (2016): 43-54.
60. J. K. Choi, D. H. Seo, J. S. Lee, K. K. Um and W. Y. Choo: *ISIJ Int.*, **43** (2003), 746
61. Ferreira, Jetson Lemos, et al. "Influence of thermomechanical parameters on the competition between dynamic recrystallization and dynamic strain induced transformation in C-Mn and C-Mn-Nb steels deformed by hot torsion." *ISIJ international* 47.11 (2007): 1638-1646.

