

Study on the Mechanism of Strengthening and Toughening Effect of Titanium Addition on HSLA Steel

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Abstract: Based on the determination of load variation against deflection by means of Instrumented Charpy Impact testing, the impact energy distribution of the High Strength Low Alloy (HSLA) steel containing Nb, Ni and Ti for pressure vessels at low temperature has been quantitatively studied. The total impact energy E_t could be divided into two parts, E_i and E_p . E_i is related to the base strength of the material in terms of the grain size and alloy addition, which is also found to be less influenced by the holding time of normalization process at 910°C. Whereas, E_p of Ni-Nb-Ti HSLA steel is strongly linked to the period of holding time. Thermodynamic kinetic investigation was carried out to study the strengthening mechanism with metallurgical microstructure analysis.

Key Words: Instrumented Charpy Impact Testing, Normalization, Thermodynamics

1. Introduction

Impact Toughness is of importance for the evaluation of the resistance capability of structural steel against the crack initiation and rupture under high strain rate loading conditions. In general, It is of significant evidences that the addition of low alloy element (such as V, Ti and Ni etc) and distinct heating treatment process may cause the influence on the impact toughness of High-Strength Low-Alloy (HSLA) steel^[1,2].

In the paper, impact toughness property of HSLA used at the low temperature is studied by determination of the impact energy distribution, dynamic crack growth derived from the Instrumented Charpy Impact testing. In addition, Transmission Electron Microscope (TEM) is also contributed to study the predominant precipitation strengthening mechanism for the improvement of impact toughness as to secondary phase particles such as TiN, Ti(NC).

2. Experimental and principles

2.1 Material preparation

Table 1 Chemical composition of the steel

%	C	Si	Mn	P	S	Al	Ni	Nb	Ti
A	0.137	0.220	1.326	0.011	<0.005	0.015	0.500	0.026	—
B	0.115	0.172	1.333	0.011	<0.005	0.017	0.494	0.022	0.013

The material investigated in the paper is a Nb-Ni-Ti containing microalloyed HSLA steel. The steel is prepared after TMCP process and normalized at 910°C. Two batches of standard V-notch Charpy specimens (10mm×10mm×55mm, notch depth 2mm) are sampled from the middle part of the as-normalized steel plates corresponding to the different normalization holding time for 15 and 40 minutes relatively. As to investigate the influence of the Titanium addition on the impact toughness, reference batches of specimens from the Nb-Ni steel without Ti are prepared in coincidence with the same treatment process as above. (Note: A-15 or A-40 means the batch A specimens normalized for 15 or 40 minutes)

2.2 Impact toughness testing

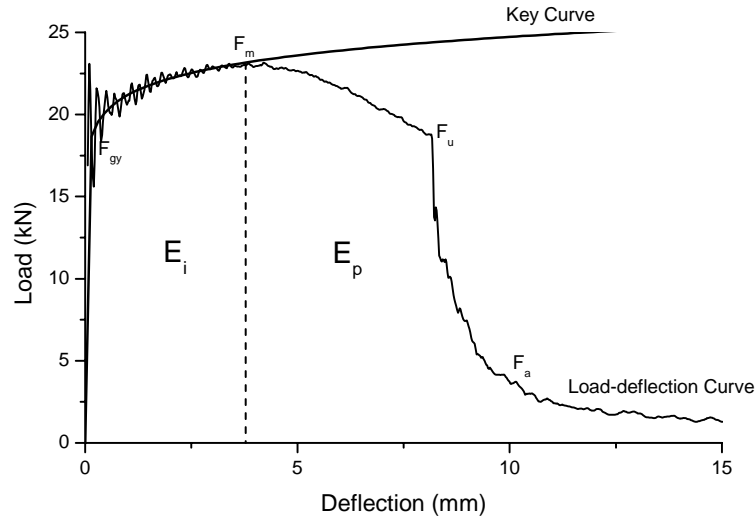


Fig. 1 Curve of load-deflection recorded by instrumentation method with fitted Key Curve and the illustration of the distribution of absorbed impact energy

Fig. 1 shows a typical load-deflection curve recorded by Amsler/RKP 450 instrumented impact testing machine. The impact energy, area beneath the load against deflection, can be subdivided by integration over the relevant range of deflection. The meaning of the subscripts are, *gy*: beginning of total yielding in the ligament or, alternatively, end of the linear load range, *m*: maximum load value, *u*: beginning of unstable crack propagation, *a*: end of unstable crack growth. Key Curve (KC) method is adopted in the study to describe the crack extension behavior after the crack initiation^[3].

After impact testing, broken specimens are collected for the microstructure observation and chemical composition for precipitates by using TEM and EDX.

3. Results and Discussion

3.1 Instrumented Impact Testing

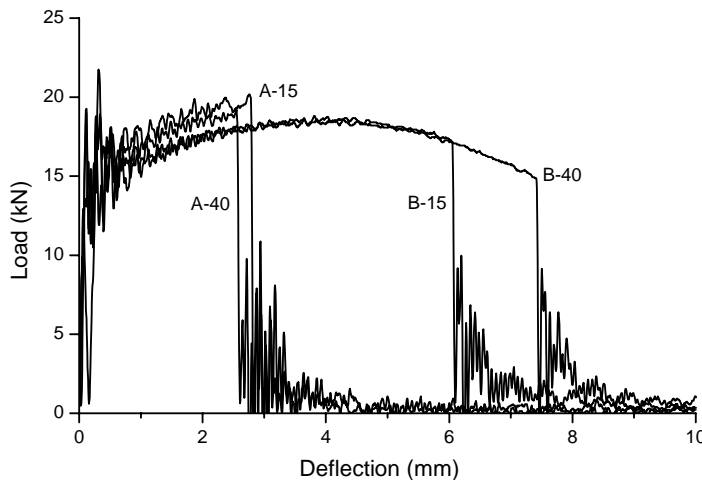


Fig. 2 Curves of load against deflection for the HSLA steels after different normalization treatment.

Fig. 2 shows obvious features on the load-deflection curves for Nb-Ni and Ni-Nb-Ti steels after different normalization holding periods. For all the studied HSLA steels, steep drop of load signals occurs at the F_u point, corresponding to the starting of the unstable cracking. In comparison of batch B which shows a longer and more smooth period of stable crack propagation intervening between F_m and F_u points, Batch A is found to be a quasi cleavage fracture, implied by the unstable cracking

initiating immediately after F_m point. From above, A-15 and A-40 are quite similar, as a contrast the difference between B-15 and B-40 is embodied by the length of stable crack period and the height of the interval from F_m to F_u .

Table 2 Characteristic components of impact energy and parameters for Key Curve from instrumentation method.

	E_t (J)	E_i (J)	E_p (J)	n	k (N/mm)
A-15	53.8	48.7	5.1	0.110	3556.6
A-40	48.0	43.4	4.6	0.126	3539.2
B-15	110.3	68.5	41.8	0.127	3311.9
B-40	134.3	67.9	66.4	0.117	3286.4

In Table 2, energy distribution and the controlling parameters of n and k values for the KC, fitted the load-deflection within the interval from F_{gy} up to F_m are also listed.

From the Fig. 2 and Table 2, the impact toughness of Ni-Nb steel at low temperature is improved by the Ti addition. Crack extension behavior is found significantly influenced by the holding period of normalization, while it seems to be independent of E_i on the variation of normalization holding period for batch B specimens.

3.2 Microstructures and Precipitates

The microstructures of batch A and B are primarily constituted by the ferrite and few pearlite, as shown in Fig. 3.

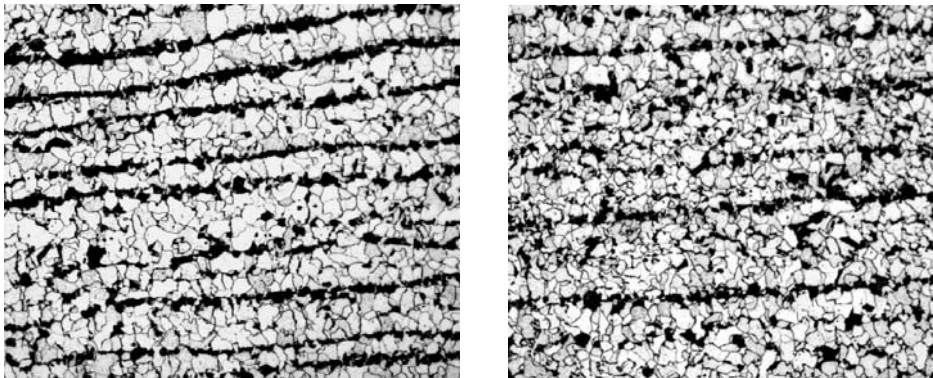


Fig.3 Metallurgical photos for batch A and B showing the ferrite and pearlite, Left for A and Right for B.

The grains size of ferrite of B is obviously refined due to the Ti addition after TMCP process and normalization, which implies the increase of the impact toughness listed in Table 2. TEM observation for batch B is shown in Fig. 4, which indicates that nucleation of the precipitates is confined to heterogeneity sites and the precipitation occurs in austenite or ferrite on grain boundary, dislocation, sub grain boundary during austenite to ferrite (A-F) transformation. The EDX analysis about the chemical composition of the particles detects the abundance of Titanium, shown in Fig. 4.

Electron Diffraction Analysis verifies that these precipitates have the regular crystal structure of the FCC NaCl type. As we known, Carbide or Nitride is early initiated due to the thermodynamical stability by Ti, Nb addition combined with the C, N in steels. Since TiN has the lowest solubility and highest fluxing temperature point, secondary phase particles which precipitate during 1220°C hot rolling and post-normalization holding at 910°C is predominated by TiN. Therefore, the

addition of Titanium and nucleation of TiN particles provide large quantities of heterogeneity sites which transfer to the boundary of austenite and restrain its growth during A-F transformation, resulting in the refinement of grains and improving the impact toughness of batch B in contrast with batch A.

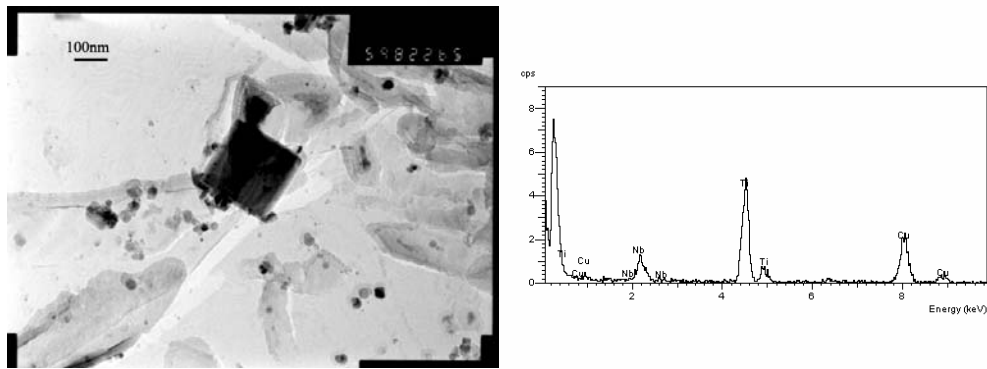


Fig.4 TEM micrograph of B-40 and the EDX analysis of the chemical composition for the precipitates.

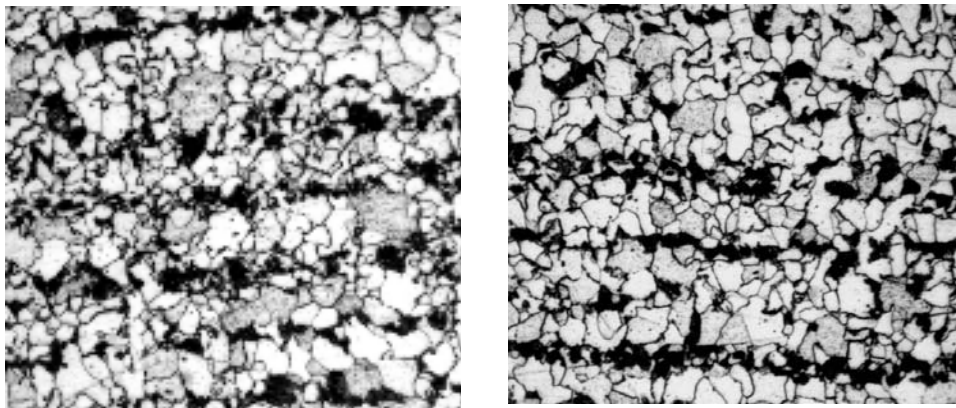


Fig.5 Metallurgical photos for B-15 and B-40 showing the distribution and grain size of ferrite, Left for B-15 and Right for B-40.

For Batch B, the crack initiation energy, E_i of both specimens retains constant, independent of the normalization holding period. B-15 and B-40 are also found to have the close impact working hardening capability (n value) and impact strengthening capability (k value) by KC method, which implies both of two specimens maybe have the same mechanical properties of basal structure. The base yield strength (in MPa) of the steel can be estimated in terms of the grain size and alloy addition from empirical relationships such as Choquet equation^[4] for plain low carbon steel.

$$\sigma_{base} = \sigma_0 + (15.4 - 30C + 6.094 / (0.8 + Mn)) d_a^{-1/2} \quad (1)$$

Where the concentrations are in weight percent and the ferrite grain size, d_a , is in millimeters.

From Fig. 5, it maybe owe to the longer period of normalization treatment, which refines the arrangement homogeneity of the ferrite and removes the partial pearlite of B-40 in comparison with B-15. Nevertheless from optical metallorgaphy, the ferrite grain size is quantified to be identical by using image analysis system, which implies the indistinguishable difference of basal body mechanical properties between two samples, considering the same chemical composition as well.

In general, during the normalization, secondary phase particles precipitate in the

thermomechanical rolling process, including partial numbers of TiN and most of all the TiC will be remelted and transformed to austenite, equilibrium microstructure such as ferrite and pearlite will be also austenized due to the high temperature. Longer period the normalization holds, the more sufficient the austenization will be deserved and the more quantities of secondary particles will be liquated. Adequate holding period is also hoped to provide the preconditions for the dispersing precipitation of TiN and others particles simultaneously with the A-F transformation during the later air cooling.

Shown in Fig. 5, the influence of adequate normalization on the impact toughness is characterized on the better distribution of ferrite microstructure of B-40, compared with B-15. Fig. 4 shows, except that only one of the particle appears in the sight field with the dimension of 200nm, most of the dispersing particles after adequate normalization are all as small as tens of nanometers.

Pinning effect interacting between particles and ferrite boundary will be enhanced by means of increasing the quantities, decreasing the dimension of dispersing particles, which are the key kinetics for strengthening the toughness under impact loading. Once the stable spreading crack meets with the strengthened boundary, the maximum stress level in front of the crack will decrease so as to bypass these nailing particles instead of the unstable propagation along the grain boundary causing fast brittle fracture.

4. Conclusions

By instrumented impact testing, E_t can be subdivided into E_i and E_p , providing abundant information about the brittle and ductile fracture properties. As regards the HSLA steels studied here, the addition of Titanium improves the impact toughness by refining the grain size of ferrite. E_i seems to be no obvious relation with normalization holding period, which is believed as a basal strength parameter inherently linked to the grain size and chemical composition. While, secondary phase particles containing Ti, Nb, etc. formed during the TMCP process are remelted and secondarily precipitated during austenization and later A-F transformation. These particles dispersing and absorbing onto the active sites such as dislocation, boundary dominates the strengthening and toughening mechanism, strongly improving the contribution of E_p to E_t .

References

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