Influences of Volume Fraction, Shape of Martensite Islands on Mechanical Properties of 1Cr17Ni1 Stainless Steel

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Abstract: The paper deals with the fracture analysis of 1Cr17Ni1 after tensile (quasistatic fracture) and impact testing (Dynamic fracture) at room temperature. The temperatures of solution are 900°C, 950°C, 1000°C, 1050°C, 1100°C and 1150°C, respectively. The influence of thermal expositions on tensile properties is found to be obscure. On the other hand, remarkable effects of solution temperatures on room temperature impact toughness are observed. Dynamic and quasistatic fracture behaviour of the 1Cr17Ni1 stainless steel is strongly affected by Volume Fraction, shape of Martensite Islands. In this paper, quasistatic fracture and dynamic fracture behavior of granular structure steels is predicted by Eshelby equivalent inclusion model incorporating the plastic deformation of martensite islands. According to the above laws, we establish the relationship between volume fraction/shape of Martensite Islands and mechanical properties in order to provide technical support for improving the dynamic mechanical properties of the material.

1.Introduction
The 1Cr17Ni1 stainless steel belongs to the group of advanced materials that are used for thick section components of nuclear generators. Applicability of the stainless steels in nuclear generation industry is due to their high magnetic permeability and high resistivity. However, during engineering practice dynamic fracture behaviour of the 1Cr17Ni1 is more difference than quasistatic fracture behaviour. Some authors had discussed other material about this contradiction in their papers[1~6]. In order to study the effect of martensite on the mechanical properties of the dual phase steel, the author put forward strength expressions of the duplex steels from different angles by Shen Xianpu, Lei Tingquan[7], Tomota[8] and other. The micromechanical models of the duplex steels are established by Al_Abbas and Nemse[17], and the effects of martensite content and the size of martensite island on the mechanical properties of the duplex steels are discussed. Pahl, Uthaisangaksul[9] established a micromechanical model of multiphase structure by using stochastic algorithm and discussed the effect...
of the properties of the constituent phases on the fracture properties of dual phase steels. Xia Yuanming\cite{10} assumed that the martensite islands are spherical and always elastic deformed. The effect of the content of martensite on the mechanics of dual phase steels is discussed by using the Eshelby equivalent inclusion model. However, the influence of the shape and strength of martensite islands on the mechanical properties of dual-phase steels is still not quantitatively studied. At the same time, the influence of the shape and strength of martensite islands on the mechanical properties of dual-phase steels is often combined with other factors, which is difficult to be studied by systematic experiments. Based on the Eshelby equivalent inclusion model, the mechanism of plastic deformation of ferrite matrix and martensite island during deformation of dual-phase steel is explained. According to the Eshelby equivalent inclusion model and considering the yield behavior of martensite island, a self-consistent model of granular microstructure steel is established.

The influence of the content, shape and strength of martensite island on the mechanical properties of granular steel is discussed. This contradiction is up to volume fraction, shape of martensite islands.In nuclear generation industry dynamic mechanical is essential. The experiment results indicate that impact energy increases with the content of martensite increasing and the content of ferrite decreasing. The variation of content is effected by the temperature of solution treatment increasing.

2. Experimental

The 1Cr17Ni1 steel is produced by vacuum induction melting and vacuum arc refining routes with proper selection of raw material and strict control of the trace elements. The chemical composition of the investigated material is given in Table 1. The as-received state of the 1Cr17Ni1 stainless steel from forge piece is solution hardening\(900°C, 950°C, 1000°C, 1050°C, 1100°C\text{and} 1150°C\text{oil cooling}) and tempered\(620°C, \text{air cooling})). After the thermal exposures the specimens for tensile and impact testing are machined. Round tensile specimens with 10 mm in diameter and 120 mm gauge length are used. For Charpy impact tests the standardised prismatic specimens (\(10×10×55\) mm\(^3\) with central U-shaped notch \(2 mm in depth) are employed. For each material state three independent tests at room temperature are carried out. In order to characterise the microstructure in the investigated steel, the metallographic observations are performed by optical microscopy (OM). Using Matlab software to process metallographic photos, martensite area is calculated. The fracture surfaces of specimens after tensile and impact testing at room temperature are characterised by scanning electron microscopy (SEM) with EDS used for identification of precipitates. Variation in hardness of the steel on thermal ageing is measured using HRB hardness tester using with a load of 10 kg for 15 s.

![Fig 1. tensile specimens drawing](image)

Fig 1. tensile specimens drawing
### Table 1 Chemical composition of the investigated 1Cr17Ni1 stainless steel

| Element | C   | Cr  | Ni  | Si  | Mn | Fe  |
|---------|-----|-----|-----|-----|----|-----|
| (wt.%)  | 0.11| 16.80| 1.30| 2.00| 1.00| 78.80 |

#### 3. Results and discussion

**3.1. Microstructure**

The structure of 1Cr17Ni1 is the martensite which translates into tempered sorbite\[11\] after tempered at high temperature and ferritic after solution treatment.

Fig 3. shows representative light optical microstructure of the experimental 1Cr17Ni1 stainless steel after thermal exposition. The microstructure typically consists of the tempered martensite and highly ferritic structure. When the solid solution temperature is 900°C, the martensite content is 8.76%. When the solid solution temperature is 950°C, the martensite content is 14.7%. When the solid solution temperature is 1000°C, the martensite content is 17.36%. When the solid solution temperature is 1050°C, the martensite content is 25.26%. When the solid solution temperature is 1100°C, the martensite content is 32.96%. When the solid solution temperature is 1150°C, the martensite content is 24.87%. Obviously, the content of the martensite increases with the temperature of solution treatment raising but the content of the ferrite reversing. However, the content of the martensite descends when the temperature of solution treatment is greater than 1100°C. The reason is that more and more elements which can enlarge the austenite zone are dissolve into the austenite zone with the temperature of solution treatment raising. It leads to increase of the martensite content. The austenite decomposes when the temperature of solution treatment is greater than 1100°C. It leads to reduction of the martensite content\[11\].

In Fig 3.a and b, martensite is a punctate shape, which is distributed uniformly on ferrite structure. This is the morphology of martensite at quenching temperature of 900 and 950 degrees. As the temperature rises to 1000 degrees, Martensite began to form islands and coexisted with punctate martensite. With the increase of temperature to 1050 degrees, the martensite of point shape basically disappeared, only island martensite. At 1100 degrees, the martensite island content is the highest.
(a) 900°C × 1 h Oil quenching, 620°C × 2 h Air cooling, 200× $f_M\% = 8.76\%$ (After Matlab treatment)

(b) 950°C × 1 h Oil quenching, 620°C × 2 h Air cooling, 200× $f_M\% = 14.70\%$ (After Matlab treatment)

(c) 1000°C × 1 h Oil quenching, 620°C × 2 h Air cooling, 200× $f_M\% = 17.36\%$ (After Matlab treatment)

(d) 1050°C × 1 h Oil quenching, 620°C × 2 h Air cooling, 200× $f_M\% = 25.26\%$ (After Matlab treatment)
Tensile properties

In Table 2 the results of the room temperature mechanical tests of the thermally exposed samples are summarised. It is obvious that performed thermal exposure had high influence of on tensile properties, such as yield stress (Rp0.2), ultimate tensile strength (Rm). Variations of yield stress (Rp0.2) and ultimate tensile strength (Rm) with test temperature of the steel in both heat-treatment conditions are shown in Table 2. With the increase of solution temperature, the strength increased first and reached 872 MPa. As the temperature continues to rise, the tensile strength decreases. The change rule of elongation (A) and reduction in area (Z) is opposite to tensile strength respectively. The maximum elongation is 19.95 at solution temperature 950°C. At the same time, the maximum reduction in area (Z) is 60.44%. The change law of yield strength is consistent with tensile strength.

3.3. Rockwell hardness
As the solution temperature changes, the rockwell hardness (HRB) changes little. The change law of rockwell hardness is consistent with tensile strength.

3.4. Impact properties
Impact properties of 1Cr17Ni1 and thermally exposure conditions are studied by carrying out impact tests using full size Charpy U-notch specimens. The specimens are prepared in a way that its orientation with respect to plate is such as to ensure crack propagation along the rolling direction of the plate, which provides most conservative Charpy. As the solution temperature increases, the impact toughness increases. Maximum value is 28.8J at solution temperature 1050°C. As the temperature continues to rise, the tensile strength decreases.

3.5. Electrical resistivity and permeability
As the solution temperature changes, the Electrical resistivity and permeability change little. Electrical conductivity and permeability value has no effect on mechanical properties.

In summary the heat treatment temperature affects the mechanical properties through affecting the microstructure. The strength and impact toughness increase with the increase of martensite content due to the increase of solution temperature. Impact toughness is a dynamic mechanical property index. The change rule of elongation (A) and reduction in area (Z) is opposite to tensile strength respectively. The reduction in area (Z), total elongation (A) are static mechanical properties. Electrical resistivity and magnetic permeability is negligible. However, the difference of the mechanical property of the dynamic state (impact ductility $\alpha_k$) and the quasistatic state (Z, A) is obvious when the temperature is below 1100°C. The mechanical property of the dynamic state is more lower than he quasistatic state.

3.6. Fracture observations

Fig. 4 The curve of $\delta$(%),$\psi$(%),$\alpha_k$(J/cm²) at different solution temperatures.
$\delta$(%),$\psi$(%) are the index mark of quasistatic mechanics which is negligible with the solution temperature increasing. $\alpha_k$(J/cm²) is dynamic mechanics index but which is uniform to the solution temperature increasing. From the upper analysis on the structure, content of the martensite is concordance to the increase of the solution temperature. so the result is that $\alpha_k$(J/cm²) is concordance to the content of the martensite. However dynamic mechanics performance are lower than quasistatic mechanics.
3.6.1. Fracture characteristics after tensile testing

Fig 3. a represents metallographic longitudinal section with profile-view on the fracture with occurrence of splitting after the thermal exposure. Crack expansion proceeds along the boundaries between the martensite and ferrite in which stress concentration occur by the extrusion pressure of phase transition[2]. Fig 5.b indicates that crack expansion ends off in martensite phase zone. The structure translates to tempered sorbite which consists of ferrite and carbide dispersion[11] distributed after tempering treatment at high temperature(620°C). Energy of crack expansion is absorbed by the tempered sorbite which is a beneficial organization for cracking.

The cross section fracture surface (Fig 5.a.) after tensile test visualised at lower magnification indicates lots of secondary crack existed. Fig 5.b represents the fracture surface after tensile test at higher magnification. The fracture surface exhibits mostly ductile dimples resulting from the coalescence of microvoids but also a certain amount of brittleness zone. Based on the above analysis, the area of the dimple is actually a martensite region.

3.6.2. Fracture characteristics after impact testing

Overall view on the fracture surface of as-received 1Cr17Ni1 steel after impact testing at room temperature is documented in Fig 7., The fracture mode is mostly characterised by river regime which is brittleness zone from cleavage fracture. The termination of the river regime expansion is a small amount ductile dimples (Fig 7.b). Fig 7.d. represents more ductility zones consisting of the ductile dimples in contrast to Fig 7.c. It indicates that the toughness of 1Cr17Ni1 steel after solution treatment at high temperature is more splendid than the toughness at low temperature. Martensite content of Fig 7.d is also higher than Fig 7.a, Fig 7.b, Fig 7.c. By comparing Fig 7. and Fig 3., direct correlation between the content of the martensite and the ductility zone is obviously.
As fracture characteristics of dynamic mechanics Fig 7.a represents more brittleness than Fig 6.a which indicates fracture characteristics of quasistatic mechanics after identical treatment. The more apparent difference exists at Fig 5.b and Fig 4.b. The proportion of the brittleness zone and the ductility zone of each view is reverse. It results from the different mechanics mechanics and structure which is consistent with the data at table.1. The mechanical property of the dynamic state is more lower than the quasistatic state.

![Fracture surface of as-received 1Cr17Ni1 steel after impact testing](image)

Fig 7. Fracture surface of as-received 1Cr17Ni1 steel after impact testing  
a,b,c : solution temperature : 1000°C; d: solution temperature : 1100°C

3.7 Calculation method and calculation model

In the granular structure, martensite island is dispersed in the ferrite matrix. The typical granular structure is shown in Fig 3. The black part is a small island and the white part is a ferrite matrix. It is reasonable to simplify the martensite islands into ellipsoids or spheres. In the calculation, it is assumed that the martensite islands are randomly distributed in ferrite, and the shape of martensite islands is approximated by ellipsoids. The length-to-short axis ratio of the ellipsoids reflects the different shapes of martensite islands. Influence of mechanical properties.

By extending Ehselby's equivalent inclusion model and according to Mori's mean field theory[^12^], the calculation model is established. Under the action of external force \( \overline{\varepsilon}^A \) lance, the strained \( \overline{\varepsilon}^F \) of ferrite in granular tissue and the strained \( \overline{\varepsilon}^M \) corpse of martensite in granular tissue are expressed as follows, respectively.

\[
\overline{\varepsilon}^F = \overline{\varepsilon}^A + \overline{\varepsilon}^b \tag{1}
\]

\[
\overline{\varepsilon}^M = \overline{\varepsilon}^A + \overline{\varepsilon}^b + \overline{\varepsilon}^c \tag{2}
\]

In formula (2), \( \overline{\varepsilon}^A \) denotes the strain of pure ferrite matrix under the action of external force spear
\( \sigma \) without martensite; \( \sigma' \) indicates the additional strain due to the presence of martensite in ferrite matrix. \( \varepsilon^c \) denotes the perturbed strain of martensite relative to ferrite. In elastoplastic state, the stress-strain relationship between ferrite and martensite is respectively.

According to the research in literature [6] Liu, the deformation behavior of the material in the dual-phase steel composed of martensite and ferrite can be divided into three stages: (1) ferrite and martensite are in the elastic deformation stage; (2) ferrite yield and martensite are still in the elastic stage; (3) ferrite and martensite are in the plastic deformation state.

The work hardening behavior of the matrix can be expressed as

\[
\sigma_F = 1200(0.046 + \varepsilon_F^{0.55})
\]

(3)

According to formula (3), we can assume that the martensite island is spherical. Granular group can be obtained.

Martensite is in elastic deformation stage with different martensite content. The effect of martensite content on the strength of granular microstructure steel is mainly through two aspects [10]: (1). Microscopically the existence of martensite islands impedes the movement of dislocations in ferrite, which is mainly in ferrite matrix. A three direction stress state is generated in the body, resulting in ferrite strengthening. (2) Direct. participation in deformation. It can be seen that the strength of granular microstructure steel increases with the increase of martensite volume fraction when the shape of martensite islands is the same and elastic deformation occurs.

![Fig 8. Yield strength of granular structure steel varying with the martensite volume fraction](image)

Fig 8. Yield strength of granular structure steel varying with the martensite volume fraction

The lower the volume fraction of martensite is, the lower the critical martensite strength that martensite does not deform when it reaches the failure stress is. That is to say, the lower the volume fraction of martensite is, the more difficult the martensite to deform when the strength of martensite is the same. The lower the amount of martensite is, the higher the carbon content of martensite is, the higher the strength of martensite is. Therefore, when the content of martensite is small, the plastic deformation of martensite does not occur in the uniaxial tensile process of granular microstructure steel, and the strength of martensite island has no effect on the strength of granular microstructure steel; when the content of martensite is large, the plastic strain passes through ferrite with the increase of macro-strain. The interface of martensite island is transferred to ferrite Island, and martensite gradually has plastic deformation [13-15].

3.8 Effect of martensite island shape on mechanical properties of granular steel

The shape of martensite islands has little effect on the stress-strain relations of granular microstructure steel; the strength of granular microstructure steel increases slightly with the increase of the ratio of
long to short axis of martensite islands; some studies have shown that \cite{16-22}, in short fiber reinforced composites, the strength of granular microstructure steel increases slightly with the increase of the ratio of long to short axis of martensite islands. According to Fig 5a and b, although the martensite islands are aligned along the direction of external force, martensite islands has great influence on the stress-strain curves of ferrite-martensite dual-phase steels when the ferrite islands are aligned directionally. However, in granular microstructure steels, the shape of martensite islands has little effect on the random distribution of martensite islands on the ferrite matrix, so the martensite islands can be approximated to spherical.

Nakagawa and Thomas \cite{23} reported that martensite particles tend to possess the same crystallographic orientation as that of ferrite maintaining the continuity of slip planes and directions across the ferrite–martensite interfaces in microstructures consisting of predominantly lamellar/acicular arrangements of ferrite and martensite as that found in specimens containing a maximum of $\sim 60\%$ martensite in the present investigation. In such cases, the interfaces are believed to be coherent and maintain a low angle matching with low interfacial energy. Besides, the deformation of such ferrite–martensite phase aggregates is believed to occur more homogeneously due to effective load transfer between ferrite and martensite for having very fine distribution of elongated phase constituents \cite{24}. The low interfacial energy, continuity of slip planes and direction, and homogeneous deformation of the phase aggregate, all together, make the formation of interfacial voids difficult, resulting in higher uniform strain in lamellar ferrite–martensite phase aggregates containing a maximum of $\sim 60\%$ martensite.

3.9. The analysis of correlation about quasistatic and dynamic fracture mechanics.

From above observation and initiative analysis the difference of the mechanical property of the dynamic state and the quasistatic state is obvious, the factors are as below.

The structure of the 1Cr17Ni1 steel consists of the lath martensite and ferrite.

Crack source comes into being due to the stress concentration at the boundary between the martensite and ferrite \cite{2}. Based on the above results, crack expansion occurs mainly between ferrite and martensite.

The sample of tensile test is loaded by one-way stress. On the condition of quasistatic tensile test the stress concentration relaxes because the orientation of the crystalline grain is adjustment at the time of rotary movement. It results that crack expansion develops slowly. Otherwise secondly crack can increase the toughness \cite{8}. Lots of cracks edd off in martensite phase zone because mostly energy is absorbed by the lath martensite.

However, during the procedure of dynamic impact test the sample is loaded by the three-dimensional stress and tensile stress at the U-shaped notch. It results that the brittleness of the material increase and then the toughness is lower. In addition, compared with the tensile test, the strain rate of dynamic impact test is $6\sim 7\;\text{orders of magnitude higher}$ \{impact testing (dynamic state): $10^2\sim 104\;\text{s}^{-1}$; tensile test (quasistatic state): $10^5\sim 10^2\;\text{s}^{-1}$\}. The brittleness of the material increases by effect of the strain ratio \cite{21}. Otherwise like tensile test mostly energy is absorbed by the lath martensite. So if the content of martensite is more, the toughness is better. In this essay the author increases the content of austenite by increasing the solution temperature. Then the content of martensite increases and the content of ferrite is suppressed. Therefore impact toughness increases with the solution temperature increasing. The synthesis mechanical property of the dynamic state and the quasistatic state is excellent when the temperature of solution is $1100^\circ\text{C}$.
4. Conclusions
In this study the room temperature fracture behaviour of the 1Cr17Ni1 steel is investigated. The obtained results are summarised in the following conclusions:

(1) The microstructure of 1Cr17Ni1 typically consists of the tempered martensite and δ-ferrite structure. The content of the martensite increases with the temperature of solution treatment raising but the content of the ferrite reversing. The yield stress (Rp0.2), ultimate tensile strength (Rm), Rockwell hardness (HRB), and impact ductility are increase with the content of martensite raising yet reduction in area (Z), total elongation (A), electrical resistivity, and magnetic permeability is negligible. The mechanical property of the dynamic state is more lower than he quasistatic state at the solution temperature of lower 1100 ℃.

(2) The calculated results based on the Ehselby equivalent inclusion model are in good agreement with the experimental results, which shows that the Eshelby model is effective in analyzing the effect of microstructure of granular structure on the macro-mechanical properties. The yield strength and the work hardening rate of martensite in elastic stage of granular microstructure steel increase with the increase of martensite volume fraction, and show some nonlinearity.

(3) Due to the random distribution of martensite islands in granular microstructure steels, the shape of martensite islands has little effect on the stress-strain curves of granular microstructure steels during uniform deformation, so the martensite islands can be approximately spherical. The strength of martensite island has no effect on the yield strength of granular microstructure steel; the critical engineering stress of martensite plastic deformation increases with the increase of martensite strength; the lower the volume fraction of martensite is, the more difficult the martensite plastic deformation is.

(4) The fracture surfaces after tensile testing are characterised by mostly ductile dimple mode with a bit of brittle river regime cleavage mode. Crack expansion proceeds along the boundaries between the martensite and ferrite in which stress concentration occur by the extrusion pressure of phase transition and ends off in martensite phase zone.

(5) The fracture surfaces after impact testing of the samples are characterised almost exclusively by brittle river regime cleavage mode and a bit of ductile dimple mode. The impact toughness after solution treatment at high temperature is more splendid than the toughness at low temperature.

(6) The sample of tensile test is loaded by one-way stress yet during the procedure of dynamic impact test three-dimensional stress and tensile stress at the U-shaped notch. The strain ratio is the mainly factor, higher strain ratio, lower mechanical property. Moreover, The synthesis mechanical property of the dynamic state and the quasistatic state is more excellent with the content of martensite raising, the best heat treatment is solution at 1100 ℃ for 1h and tempered at 620 ℃ for 2h.

References
[1] Y. Q. Liu, J. H. Liu, (1989) The micromechanism of the ferrite morphology on the mechanical properties of dualphase structure Journal of xi’an JiaoTong University, 23(6): 1-10.
[2] Akhtar S. Khan*, (1999) Riqiang Liang, Behaviors of three BCC metal over a widerange of strain rates and temperatures: experiments and modeling, International Journal of Plasticity, 15: 1089–1109.
[3] H. Zhang, B. Long, Y. (2008) Dai. Metallography studies and hardness measurements on ferritic/martensitic steels irradiated in STIP. Journal of Nuclear Materials, 377: 122–131.
[4] Seong-Gu Hong, Soon-Bok Lee, (2004) The tensile and low-cycle fatigue behavior of cold worked 316L stainless steel: influence of dynamic strain aging, International Journal of Fatigue, 26: 899–910.
[5] R. Chaouadi, J.L. Puzzolante (2008) Loading rate effect on ductile crack resistance of steels using
precracked Charpy specimens, International Journal of Pressure Vessels and Piping, 85:752–761.

[6] Y.Q. Liu, J.H. Liu. (1984) Influence of martensite volume fraction on the mechanical behavior of the dual phase structure and its micromechanism. (1984) Journal of Xi’an JiaoTong University, 18(3):105-114.

[7] Shen X P, Lei T Q. (1984) Acta Metall Sin., 20: A271

[8] Tomota Y, Kuroki K, Mori T, Tamura I. (1976) Mater Sci Eng., 24: 85

[9] Uthaisansuk V, Prahl U, Bleck W. (2008) Comput Mater Sci., 43: 27

[10] Xia Y M, Zhou Y x, Yang B C. (1997) Mater Sci Technol., 5(1): 60

[11] Jiang Z H, Guan Z L, Lian J S. (1993) J Mater Sci., 28: 1814

[12] Mori T, Tanaka K. Acta Metall., 1973; 21: 571

[13] Hiiper T, Endo S, Ishikawu N, Osawa K. (1999) ISIJ Int., 39; 288

[14] Davies R G. (1978) Metall Trans., 9A: 451

[15] Goel N C, Tseng D, Tangri K. (1984) Scr Metall., 18: 873

[16] Araki K, Takada Y, Nakaoka K. (1977) Trans Iron Steel Inst Jpn., 17: 710

[17] Al Abbasi F M, Nemse J A. Int J Mech Sci., 45: 1449

[18] Prahl U, Papaefthymiou S, Uthaisansuk V, Bleck W, Sietsma J, Zwaag S V D. (2007) Comput Mater Sci., 39: 17

[19] Tszeng T C. (1994) J Comp Mater, 28: 800

[20] Jongmin Shim, Dirk Mohr. (2009) Using split Hopkinson pressure bars to perform large strain compression tests on polyurea at low, intermediate and high strain rates, International Journal of Impact Engineering, 36(9):1116-1127.

[21] P.C. Chakraborti, M.K. Mitra. (2007) Microstructure and tensile properties of high strength duplex ferrite-martensite (DFM) steels, Materials Science and Engineering A, 466:123–133.

[22] Juraj Blach, Ladislav Falat. (2008) Fracture characteristics of thermally exposed 9Cr–1Mo steel after tensile and impact testing at room temperature, Engineering Failure Analysis, 09(003):1-7.

[23] A.H. Nakagawa, G. Thomas, (1985) Metall. Trans. A 16: 831.

[24] G.E. Dieter, (1988) Mechanical Metallurgy, 224.