# QUANTITATIVE STUDY ON DUCTILE-BRITTLE TRANSITION TEMPERATURE OF FERRITIC STAINLESS STEEL Cr24A12Si

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## ABSTRACT

Based on the theories proposed priviously, we've been studied the effects of grain size, stress concentration factor, loading rate and embrittlement on ductile-brittle transition temperature of ferritic stailess steel Cr24Al2Si experimently. After investigating the quantitative relations of these factors with transition temperature respectively and taking account of the interactions between them, we've got a comprehensive and quantitative formula. The results of 29 sets of specimens calculated by the formula conform to those from tests-quite well. In experiments transition temperatures are found by curvilinear regression, and the posibility and error of transition temperature calculation with minimum test points are also discussed.

## KEYWORDS

Ductile-brittle transition, transition temperature, fracture mechanisms, grain size influence, stress concentration influence, loading rate influence, embrittlement influence.

## INTRODUCTION

Many steels and alloys, such as low carbon steels, low alloy steels and titanium alloys, have a ductile to brittle transition with descent of temperature. Studies on the transition and the effects of various factors have always been paid great attention (Tetelman and McEvily, 1967; Knott, 1966, Cottrell, 1958; Barson and Rolfe, 1970). Some correlations between the transition temperature and these factors have been proposed, but most of the work are qualitative. The quantitative relation between them ramain to be lack of knowledge.

Based on the theories proposed previously, this paper devotes to the combined effect of factors, including grain size, stress concentration factor, loading rate and embrittlement, on ductile-brittle transition temperature experimently and try to draw out a quantitative formula.

## EXPERIMENTS AND CALCULATIONS

The studied alloy is ferritic stailess steel Cr24Al2Si(Cr,23.5%;Al,1.6%;Si,1.0%;C,0.17%;Fe,bal.). Rolled plate of 16mm in thickness were machined to tensile specimens of 5*40mm,U-type notch impact specimens of 10*10*50mm and torsion specimens of 8*60mm. All the specimens,in five degrees of grain size, three tyres of embrittlement, different notch shapes and at three loading rates, were tested in the temperature range from 78K(-195°C) to 907K(634°C). The variation of temperature was ±2K for the temperature above zero and ±1K for those bellow zero.

Ductile-brittle transition temperature curves for the reduction of area and the impact energy of all the sets of specimens were tried to fit several functions by least square method. Following function was found to be fitted in all the curves best:

$$T = T_c - \frac{1}{b} Ln( Y_{max}/Y - 1) \qquad (1)$$

Where Y - the test value; T - test temperature; $T_c$ - the transition temperature; $Y_{max}$ - the upper shelf value of the curve; and b - a constant related to temperature range of transition. Results showd, the correlation coefficients of regression for two third of these curves were higher than 0.98, the lowest was not less than 0.93. It indicated that eq.(1) characterize the ductile-brittle transition quite well, so the transition temperature calculated by eq.(1) are accurate and reliable.

According to eq.(1), we were ableto get transition temperatures by minimum amount of specimens. When the value of b is known, only one test point on the curve Y = f(T) is enough for getting transition temperature. If b is unknown, it should be found by two test points(their temperature inteval should not less than 30K), first:

$$b = Ln \left(\frac{Y_1' - Y_1'Y_2'}{Y_2' - Y_1'Y_2'}\right)/(T_2 - T_1) \qquad (2)$$

$$Y_1' = Y_1/Y_{max}; \quad Y_2' = Y_2/Y_{max}$$

Where $T_1$ and $T_2$ are test temperatures; $Y_1$ and $Y_2$ -- the test values at $T_1$ and $T_2$, respectively. Then we can get transition temperatures easily.Calculations for nearly two hundred pairs of test points showd that the values of b and transition temperatures by two test points had relatively large errors.Taking three test points within temperature range of transition and finding the average value of b as $b_{aver}$ first, then take the average value of three transition temperature from b as $T_c$. We found that all the absolute errors of $T_c$ with those from test curves by 8-10 test points are less than 5K, 70% of them are less than 2K. Obviously, the accuracy is good enough to application, meanwhile it can cut down number of specimens and tests.

## EFFECTS OF FACTORS ON TRANSITION TEMPERATURE

Heating the specimens to various temperatures from 800°C to 1300°C and holding for 20 min, the measured average diameters of grain size are 0.0395 - 0.346mm. Transition temperature for all the sets in different grain size are taken linear regress to grain size $d^{\frac{1}{2}}$. The results are as following(Fig. 1):

a. in torsion:

$$T_c = 384.14 - 60.70d^{\frac{1}{2}} \qquad corr = 0.9934 \qquad (3)$$

b. in tension:

$$T_c = 475.03 - 50\ 30d^{\frac{1}{2}} \qquad corr = 0.9971 \qquad (4)$$

c. in notch impact:

$$T_c = 568.84 - 41.95d^{\frac{1}{2}} \qquad corr = 0.9830 \qquad (5)$$

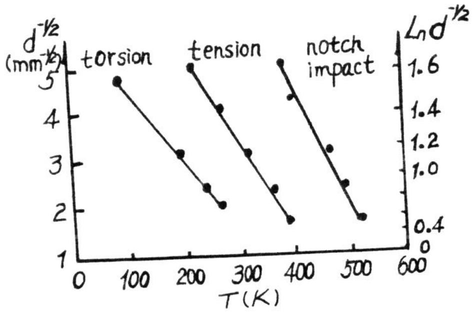

Fig. 1. Transition temperature vs. grain size in different tests.

The results are in good agreement with the relation of grain size and transition temperature by Petch(1959). Comparison of the values of the slopes in different tests shows that they vary with the variation of stress concentration factor in different tests, the larger the stress triaxility, the smaller the value of the slope. This is conform to the theory by Cottrell (1959) that when the stress triaxility is large (e.g. normal stress component is large), pick-up of less dislocations at barrier is enough for forming a microcrack and making it propagating in brittle way. This would reduce the effect of grain size on forming microcracks and so on transition temperature.

Six sets of specimens with different notch shapeswere tested in tension and in slow three-point bending. According to the theory by Neuber(1958), notch shapes and their coefficients of stress concentration are showing in Table 1. Under these two conditions there are the relationship of stress concentration factor and transition temperature:

a. $$T_c = 442.98 - 432.37\frac{1}{\alpha} \qquad corr = 0.9896 \qquad (6)$$

b. $$T_c = 617.03 - 455.75\frac{1}{\alpha} \qquad corr = 0.99997 \qquad (7)$$

According to the thermal activation theory, there is a Arrhenius relation between strain rate and the test temperature(Wilsnow and Platt,1965). We also found that the relation of loading rate $\varepsilon'$ with transition temperature for studied alloy in the range from 0.1mm/sec to 5420mm/sec both in tension and in notch impact conform to the Arrhenius relation:

$$Ln\varepsilon' = A - B\frac{1}{T_c} \quad or \quad \frac{1}{T_c} = A - \frac{1}{B}Ln\varepsilon' \qquad (8)$$

a. in tension:

$$\frac{1000}{T_c} = 4.553 - 0.049Ln\varepsilon' \quad corr = 0.9863 \qquad (9)$$

TABLE 1 Notch Shapes and Their Coefficients of Stress Concentration

| | $\omega$ (°) | $\rho$(mm) | t/d | K | $\frac{\sigma_{max}}{\tau_{max}} = \alpha$ | $\frac{1}{\alpha}$ |
|---|---|---|---|---|---|---|
| notch tention | 0 | $\infty$ | 0 | 1 | 2 | 0.5 |
| | 122 | 0.56 | 0.20 | 1.245 | 2.490 | 0.4016 |
| | 40 | 0.225 | 0.244 | 1.584 | 3.167 | 0. 3157 |
| three point bending | 0 | 1 | 0.2 | 2.408 | 4.816 | 0.2076 |
| | 0 | 0.8 | 0.5 | 3.319 | 6.637 | 0.1507 |
| | 0 | fatigue crack | 0.5 | 4.265 | 8.530 | 0.1172 |

$\omega$ - angle between notch slopes; $\rho$ - curvature radiu; t - depth of notch; d - thickness of specimen.

b. in notch impact:

$$\frac{1000}{T_c} = 2.753 - 0.0178 \mathrm{Ln}\varepsilon' \qquad \text{corr} = 0.9846 \qquad (10)$$

Where $\varepsilon'$ - the loading rate. We think the difference of the values of the two slopes is related to the effect of other factors.

There are two types of embrittlement in studied alloy by heat treatment: 475°C and $\sigma$ phase embrittlement (Nichid and co-workers, 1980). After being keeped 150h at 520°C and 500h at 760°C respectively, specimens were significantly embrittled with much higher yield strength, very small reduction of area and much lower impact energy. We take the upper shelf value of the transition curve of the impact energy to repress the degree of embrittlement. So we take the ratio of the upper shelf values between the unbrittled and embrittled specimens as coefficient of embrittlement:

$$\beta = (a_{k\ max})_{unbrittled} / (a_{k\ max})_{embrittled} \qquad (11)$$

Where $a_{k\ max}$ - the value of the upper shelf in transition curve of impact energy.

First we found the value of $\beta$ and the transition temperature at the same grain size for the change of grain size resulted from keeping the specimens at high temperature may effect the value of $a_{k\ max}$, then we got:

$$T^*_c = 293.02 + 105.75\beta \qquad \text{corr} = 0.9978 \qquad (12)$$

Where $T^*_c$ - the modified transition temperature. The test data we've got in tension with same heat treatment were also taken linear regression to the same value of $\beta$, we have:

$$T^*_c = 136.65 + 107.3\beta \qquad \text{corr} = 0.9837 \qquad (13)$$

It is obviously that the value of the slopes in eq.(12) and (13) are nearly the same, although the conditions of the two tests are great different.

## COMBINED EFFECT OF MULTIPLE FACTORS ON TRANSITION TEMPERATURE

It is necessary to take account the interactions of the individual factors.

As stated above, the effect of grain size on transition temperature are influenced by stress triaxility. The values of the slopes in different tests and their stress concentration factors are listed in Table 2.

TABLE 2 The Values of the Slopes in Eq.(3),(4),(5) and their Stress Concentration Factors.

| $\frac{1}{\alpha}$ | 0.8 | 0.5 | 0.2076 |
|---|---|---|---|
| S | 60.70 | 50.30 | 41.95 |

Where S - the value of the slope in eq.(3),(4),(5). From Table 2 we have:

$$S = 35.06 + 31.66\frac{1}{\alpha} \qquad \text{corr} = 0.9985 \qquad (14)$$

We also found that the variationa of transition temperature with stress concentration factor were nearly the same as loading rate changed from 5420mm/sec to 0.1mm/sec. So we think that the change of loading rate have no great influence on the stress concentration factor-transition temperature relation.

The Arrhenius relation between strain rate and temperature were deduced on the basis of the mechanism in which strain rate alone controlls the process. So we can cinsider the other factors first and then the loading rate alone. From the eq.(8), as $\mathrm{Ln}\varepsilon' = 0$, we have:

$$A = \frac{1}{T_{c\ \mathrm{Ln}\varepsilon'=0}} = \frac{1}{T'_c}$$

$$\text{so} \qquad T_c = \frac{1}{\frac{1}{T'_c} - B\ \mathrm{Ln}\varepsilon'} \qquad (15)$$

Then the relation of loading rate and transition temperature may have the form as:

$$T_c = \frac{1}{\frac{1}{T'_c} - B\ \mathrm{Ln}\varepsilon'} = \frac{T'_c}{1 - B'\ \mathrm{Ln}\varepsilon'} \qquad (16)$$

Where B' - a coefficient related to $T'_c$.

The effect of embrittlement is little influenced by other factors as shown above.

After considering the interactions of the factors and modifying some coefficients according to the test data, we've got following comprehensive and quantitative formula for calculating transition temperature of the studied alloy:

$$T'_c = 528 - (35+32\frac{1}{\alpha})d^{\frac{1}{2}} - 320\frac{1}{\alpha} + 112\beta$$

$$T_c = \frac{T'_c}{1 - \frac{2}{T'_c}\mathrm{Ln}\varepsilon'} \qquad (17)$$

The $T_c$ calculated by taking test data of 29 sets into eg.(17) conform to the $T_c$ from tests quite well. There only two sets whose absolute errors of calculated $T_c$ with those from tests are larger than 20K, amounting to 6.9%; but 21 sets whose absolute errors are within 10K, amounting to 73%.

## CONCLUSION

The results of studied alloy tested in different conditions and test modes shows that the effects of grain size, stress concentration factor, loading rate and embrittlement on trasition temperature of this alloy conform to the theories proposed previously quite well. We have got a quantitative formula describing the combined effect of these factors after getting the quantitative relations of these factors on transition temperature respectively and considering the interactions between them. The results of 29 sets of specimens calculated by this formula prove to be in good agreement with those from tests. We think the work is meanful for understanding the extents and forms of the effects of these factors and many others, such as yield strength, specimen size, composition of alloys, complex stress etc., on transition temperature and the interactions between them.

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