Test Method for Plane Stress Fracture Toughness of Thin Sheet Metal

Wen Zheng, Kai-Ye Xiao, Hai Xu, and Zhi-Wei Guo

***Abstract*—In this paper, the plane stress fracture toughness (KC) of sheet metal similar to 60Si2Mn with a thickness of about 0.9mm is measured through the central crack tensile specimen (MT specimen) and the compact tensile specimen (CT specimen). The compliance calibration curve and KR curve are obtained on the basis of the reasonably designed fixture and anti-buckling device. Then the KC values are calculated by CT specimens. This paper also discussed the minimum plate width when MT specimens satisfied the requirements for validity judgement.**

***Index Terms*—Plane stress fracture toughness, MT specimen, CT specimen, compliance calibration curve, K_R curve.**

I. Introduction

Modern engineering failure problems are often related to some thin-wall metal parts bearing greater working stress, such as thin-wall parts used in pressure vessels or high-speed rotating parts, which are the key structural or functional parts in the whole system. The failure conditions of these thin-wall parts are various, but the process of the cracks extending to unstable fracture is the most difficult to detect and extremely damaging. Therefore, accurate measurement of the plane stress fracture toughness KC of materials under the working thickness is the primary requirement of the design of thin-wall parts.

Data shows that few tests of the plane stress fracture toughness are conducted on thin plates with a thickness of less than 1 mm. On one hand, structures cannot reach such a small thickness under high stress; on the other hand, the extreme thickness will cause serious buckling of the specimen, so that it is difficult to satisfy the ideal test conditions. Therefore, it is particularly important to design properly the fixture and anti-buckling device. In this paper, 60Si2Mn-like rolled steel sheet with about 0.9mm thickness is selected for KR curve test of central crack tensile (MT) and compact tensile (CT) specimens to obtain the KC values of the material [1].

II. Design of the Specimens and Fixtures

The key lies in the design of thickness B and width W of plane stress fracture toughness specimens. In this paper, the thickness B of two specimens is close to 0.9mm under actual working condition, and W is different. To ensure that the test will not be affected by anisotropy, the length of the specimen is uniformly in the rolling direction (i.e. L-T direction), and the other mechanical parameters related to K_R calculation are measured by the same specimen preparation method.

A. MT Specimens

Theoretically, the greater width of MT specimen is beneficial to the test, but practically the width is often limited by material specifications and the stroke of test machine. In this paper, the width of MT specimen W is 100mm and the length of loaded surface is greater than 3W. As shown in Fig. 1, multi-pin clamp is used to ensure uniform load distribution. The L segment is a prefabricated crack by wire cutting (wire diameter is about 0.12mm). The length is different, depending on the test requirements. Fig. 2 represents the fixture [2].

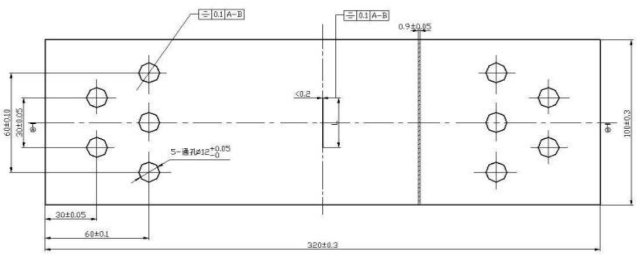

Fig. 1. MT specimens.

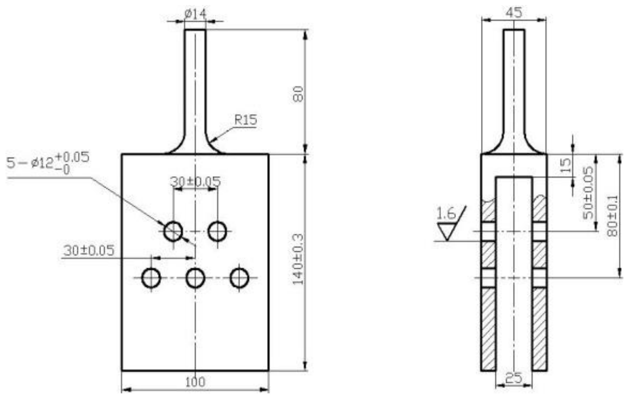

Fig. 2. Fixture of MT specimens.

For a cracked plate under unidirectional tension, the crack face bears compressive stress of the same magnitude as the longitudinal tensile stress. If the thickness of the plate is small, the compressive stress is likely to buckle the section of the plate adjacent to the crack, especially in anisotropic materials, the crack itself is easy to bend in the grain orientation with a weak resistance to crack propagation, and the buckling of the specimen will aggravate the occurrence of this situation, so it is necessary to give sufficient

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constraint to the specimen in the buckling direction. As shown in Fig. 3, the specimen is clamped with two anti-buckling plates and locked with bolts around, leaving a window large enough in the plate to deform the extensometer and observe the crack growth [3]. In practice, solid lubricant should be applied between anti-buckling plate and specimens to reduce friction, and lubricant should be prevented from entering the crack tip.

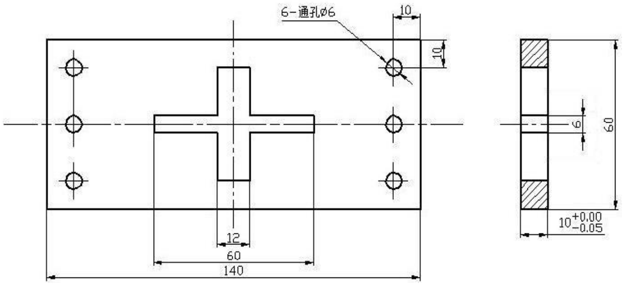

Fig. 3. Anti-buckling plate of MT specimens.

B. CT Specimens

The width W of the CT specimen is the horizontal distance from the loading line to the edge of the crack tip of the specimen. In this paper, *W*=80mm. As shown in Fig. 4, the dovetail groove on the right side of the specimen is designed to fit the COD extensometer. Fig. 5 represents the fixture [4].

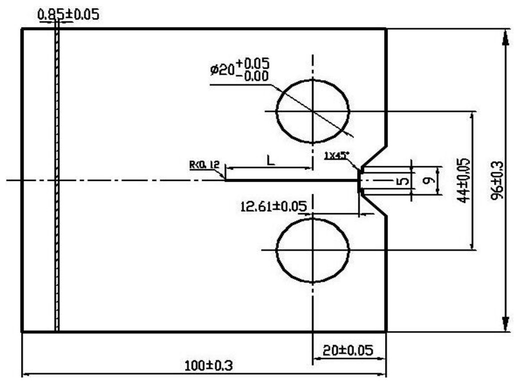

Fig. 4. CT specimen.

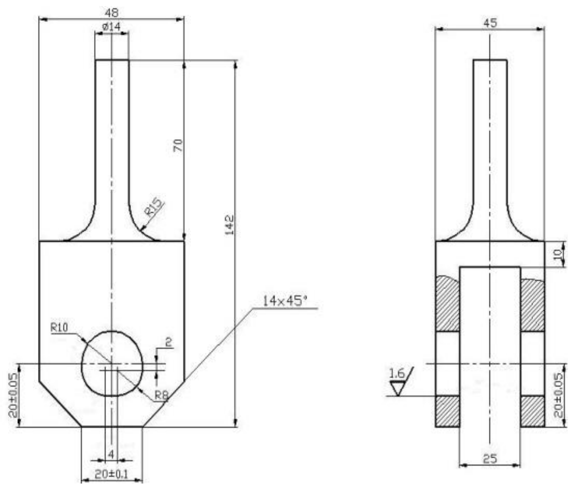

Fig. 5. Fixture of CT specimen.

The deformation of CT specimens during the loading process is different from that of MT specimens, for that the single dowel is adopted. It is difficult to maintain the tensile force in a plane because of the gap between the dowel hole and the dowel shaft, and the specimen is easy to be warped. At the same time, the tensile deformation of the specimens is large, and it is necessary to maintain good anti-buckling ability and observation effect in a long distance. Therefore, the lower dowel is made to maintain free stroke in the stretching direction, as shown in Fig. 6.

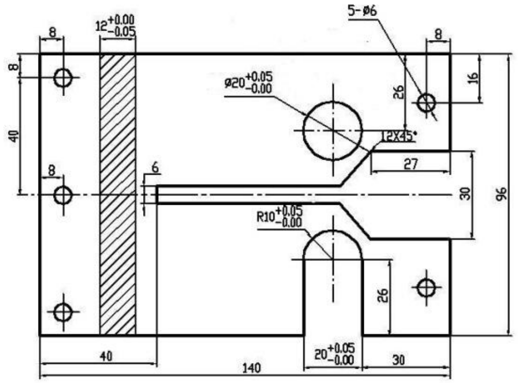

Fig. 6. Anti-buckling plate of CT specimens.

C. Verification of anti-Buckling Effect

Refer to the relevant regulations of ASTM E561 [1], a periodic partial unload of the specimen is performed by reversing the deformation direction to detect whether buckling or friction are affecting, as shown in Fig. 7. If the slopes differ by more than 2%, or if one or both have no linear range, or if the unload-reload trace forms a loop, then buckling or friction may be affecting the test results sufficiently. It is necessary to adjust the tightness of the anti-buckling plates, or add more lubricant.

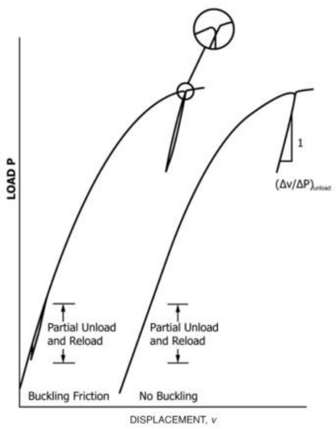

Fig. 7. Detection of bucking from compliance test records.

III. Experiment

A. Compliance Calibration Curve

As the effective crack length must be corrected by compliance calibration curve, and there is an error between the result calculated by the empirical formula and the measured result, this paper presents a compliance calibration curve obtained by experiment. Specimens were prepared at the values of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 and 0.7 for $2a_0$/W (i.e. L/W of MT specimen) and a_0/W (i.e. L/W of CT specimen), then the tensile tests at single direction were carried out at the rates of 0.5 kN/s and 0.03 kN/s respectively, and the P-2V curves were recorded, as shown in Fig. 8 and Fig. 9

[5], [6].

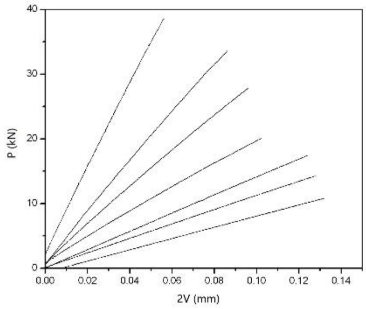

Fig. 8. P-2V curves of MT specimens.

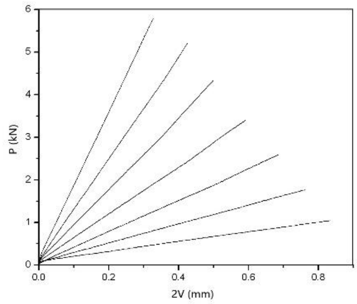

Fig. 9. P-2V curves of CT specimens.

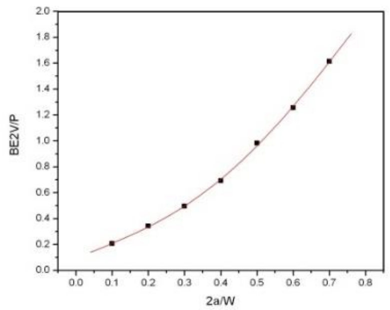

Fig. 10. Compliance calibration curve of MT specimens.

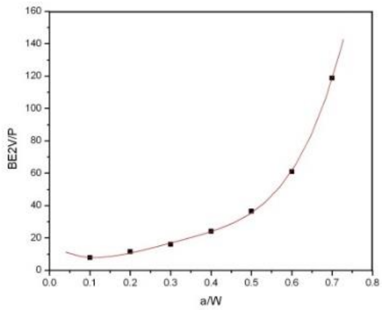

Fig. 11. Compliance calibration curve of CT specimens.

Based on the slope of P-2V curve, BE2V/P-2a/W and BE2V/P-a/W curves were made, as shown in Fig.10 and 11, then the formula of compliance calibration curve can be fitted:

For the MT specimen, if the value of 2a/W belongs to (0.1, 0.7),

For the CT specimen, if the value of a/W belongs to (0.1, 0.7),

If there is no condition to test the compliance calibration curve, the empirical formula in ASTM E561 can be used [1]. In this paper, the effective crack length calculated by empirical formula may be relatively smaller, so it is still necessary to measure the compliance calibration curve.

B. Test of Formal Specimens

Formal specimens need prefabricated cracks through fatigue. Two specimens with L=30mm are taken, and the length of the crack in MT specimen is 35mm, which was fatigued with F_{max}=22kN, F_{min}=2.2kN, f=10Hz; the length of the crack in CT specimen is 33mm with F_{max}=1.5kN, F_{min}=0.15kN, f=10Hz, and then P-2V curves are tested. As shown in Fig.12 and 13, the fatigue crack grows steadily, and the tensile fracture presents 45 degree angle, which proves that the anti-buckling device is effective [7], [8].


Fig. 12. Fracture of MT specimen.


Fig. 13. Fracture of CT specimen.

As shown in Fig. 14 and Fig. 15, the P-2V curves of MT formal specimens show some difference in maximum loads by contrast with CT test. It is caused by the systematic error of the MT test or the insufficient width of MT specimens, which still needs more tests to verify.

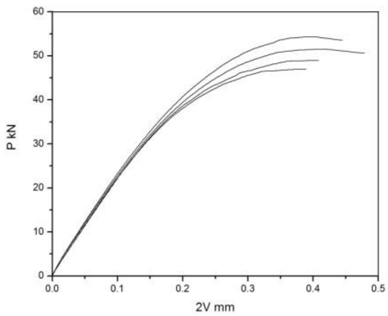

Fig. 14. P-2V curves of MT formal specimens.

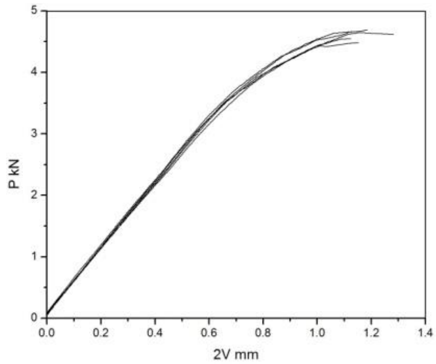

Fig. 15. P-2V curves of CT formal specimens.

IV. Data Processing and Discussion of Findings

A. Plot of the K_R Curve

Starting from the end point A of the elastic section of P-2V curve as the starting point, as shown in Fig. 16, draw at least five secant lines uniformly in the non-proportional part of the curve, and calculate the compliance value BE2V/P of each intersection point. The effective crack length corresponding to each intersection point is calculated from the compliance calibration curve. The crack length corresponding to point A is the initial crack length a_0. If the error between the value and measured a_0 exceeds 0.003W, it should be corrected. Taking the compliance value of point A and the measured a_0 of point A as a point, move the compliance calibration curve vertically to pass through this point, and then check the effective crack length a of other points can be found on the curve after moved.

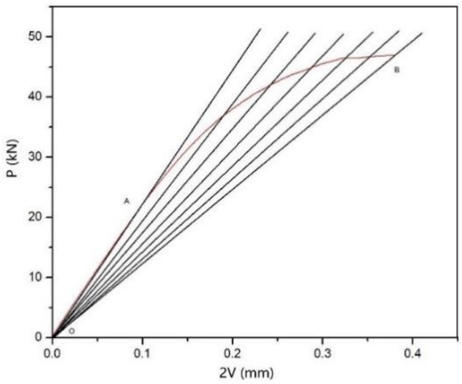

Fig. 16. Analysis of P-2V curve.

Based on the load and effective crack length of each point, the corresponding K_R value can be calculated. The calculation results are shown in Table I and Table II.

For MT specimens, use the following calculation formula [1]:

For CT specimens, use the following calculation formula:

And

(effective range a/W>0.35)

B. Validity Judgement

The validity of K_R values should be judged. For MT specimens, the net section stress σ_N is required to be less than the yield strength σ_Y (The σ_Y of 60Si2Mn-like material has been measured as 1109MPa), and for CT specimens, the length of the unbroken ligament is required to be more than eight times the length of the plastic zone, as shown by the following expressions:
for MT specimens,

for CT specimens,

As shown in Table I and Table II, the measured K_R values of MT specimens cannot satisfy the validity criterion, so the data points are invalid, which may be caused by the insufficient width of the plate, but all data points of CT specimens are valid.

TABLE I: Calculation Results of MT Specimens

	W (mm)	B (mm)	P (kN)	$2a$ (mm)	K_R (MPa·m$^{1/2}$)	σ_N (MPa)	Criterion σ_N<1109
1	100	0.86	22.46	34.70	65.99	400	valid
2	100	0.86	27.95	35.65	83.61	505	valid
3	100	0.86	32.96	36.98	101.10	608	valid
4	100	0.86	36.98	38.66	117.00	701	valid
5	100	0.86	41.08	41.31	136.42	814	valid
6	100	0.86	43.09	43.07	147.69	880	valid
7	100	0.86	45.07	45.66	161.80	964	valid
8	100	0.86	45.69	46.64	166.88	996	valid
9	100	0.86	46.21	47.62	171.75	1026	valid
10	100	0.86	46.52	48.54	175.78	1051	valid
11	100	0.86	46.75	50.98	184.48	1109	invalid
12	100	0.86	46.94	54.42	197.15	1198	invalid

TABLE II: Calculation Results of CT Specimens

	W(mm)	B(mm)	P(kN)	a(mm)	$\triangle a$(mm)	K_R(MPa·m$^{1/2}$)	$8r_y$(mm)	Criterion W-a>$8r_y$
1	80	0.87	3.02	33.16	0	92.77	8.9	valid
2	80	0.87	3.48	33.65	0.49	108.99	12.3	valid
3	80	0.87	3.68	33.97	0.81	116.50	14.1	valid
4	80	0.87	3.85	34.29	1.13	123.03	15.7	valid
5	80	0.87	4.06	34.95	1.79	132.75	18.2	valid
6	80	0.87	4.25	35.64	2.48	142.39	21.0	valid
7	80	0.87	4.33	36.01	2.85	146.92	22.3	valid
8	80	0.87	4.43	36.51	3.35	152.85	24.2	valid
9	80	0.87	4.53	37.03	3.87	159.35	26.3	valid
10	80	0.87	4.65	38.03	4.87	169.51	29.7	valid
11	80	0.87	4.62	39.79	6.63	179.95	33.5	valid

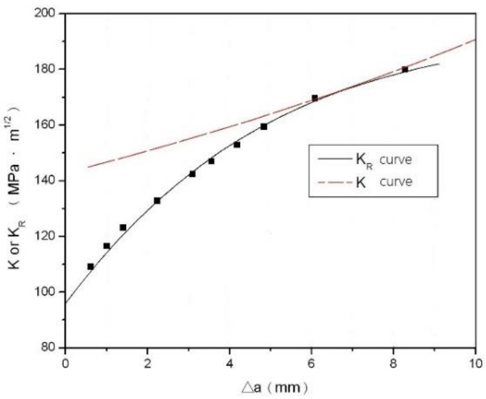

Fig. 17. K_R curve of CT specimens.

Based on Table II, the K_R curve of the CT specimen is made (Fig. 17). And the formula is fitted:

$$K_R = e^{4.582} \times (\Delta a + 0.8421)^{0.2789}$$

C. Determination of K_C Value

The K curve is drawn on the K_R curve. K is the stress intensity factor, which changes with load and crack length. By adjusting the P value constantly, the K curve will be tangent to the K_R curve. The K_R value corresponding to the tangent point is the K_C value of the material. The calculated result is $K_C \approx 170 \pm 4 \text{MPa} \cdot \text{m}^{1/2}$.

D. Discussion of Width

Based on $Kc \approx 170 \pm 4 \text{MPa} \cdot \text{m}^{1/2}$, the plastic zone size r_y is calculated to be 3.74mm. For MT specimens, the width of 100 mm used in this paper is approximate to $27r_y$ [1], which does not meet the test requirements. If the width W is further increased to be $W > 35r_y$ [2], [9], W_{min} should be at least 131 mm.

The width of CT specimen is 80 mm, which is greater than $16r_y = 59.2$mm, and there is some margin. The specimens of this specification can be used in a small range of K_C values. Data show that the test results of the two types of specimen are consistent [10], and CT specimen has lower requirement for plate width, so it is easier to get effective results for this material.

V. Conclusion

Based on the K_R curve method, MT and CT test schemes are designed for 60Si2Mn-like rolled steel sheet with thickness of about 0.9mm. The reasonable design of anti-buckling device can make the test more accurate. For this paper, effective results can be measured more easily by CT test scheme.

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