13. Analysis of Brittle Crack Propagation in TMCP Steel Rolled at Temperature in Austenite–Ferrite Region

Junichi KATSUTA*, *Member*, Masahiro TOYOSADA**, *Member*, Hiroshi YAJIMA***, *Member*

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Summary

It is well known that the TMCP steel rolled in the temperature of austenite–ferrite region has high brittle crack arrestability (K_{ca}). The cause is generally considered to be related with the generation of separations ahead just in advance the main brittle crack.

However it has been sometimes experienced that there are no observation of appearance of separations on the brittle fracture surfaces for TMCP steel plate with high K_{ca}.

In this paper, the authors carried out not only the double tension tests but also the CTOD tests and the Charpy impact tests with various test directions by using two TMCP steel plates, which are produced from same slab but are rolled at the different finishing temperature, thus leads to different maximum separation index. By analyzing these test results, it is understood that high K_{ca} value comes from zigzag path of brittle crack which is caused by anisotropy of fracture toughness of steel plates.

1. Introduction

In recent years, TMCP steel plates have increasingly been used for steel structures. The TMCP method comprises AcC (Accerelate Cooling) type and Non–AcC type[1). The Non–AcC type TMCP method is, in general, employed for production of steel plates thinner than approximately 15mm and AcC type TMCP method for steel plates thicker than approximately 15mm. When controlled rolling in austenite–ferrite region (two–phase region) is employed in TMCP method, such steel plates would generate numerous cracks parallel to their rolled surfaces as "Separation" on their brittle fractured surfaces of Charpy test specimen in some temperature range. At present, although it is not clear whether the occurrence of separations actually affects the safety of steel structures or not, employment of controlled rolling in two–phase region (austenite–ferrite region) is generally applied so as to avoid separations in the TMCP method for neither Non–AcC nor AcC type.

* The University of Nagasaki
** The University of Kyushu
*** Mitsubishi Heavy Industries, Ltd.

Meanwhile, there are published reports that steel plates control–rolled in two–phase region are excellent in their brittle crack arrestability[1)] which might due to the occurrence of separations and that its effect can be greater particularly if controlled rolling is made at a lower temperature in the anrecrystallized gammar–phase region[2)]. An effective use of the steel plates with an excellent brittle crack arrestability would greatly contribute to the improvement of steel structure integrity. However causes of the improvement of brittle crack arrestability due to controlled rolling in two–phase region have not yet been clarified because it has some experience that brittle surfaces with high K_{ca} have no separations. Furthermore, although it is known that such brittle crack propagates in a zigzagging behavior, its causes or the relationship to the improvement of brittle crack arrestability have not yet been established.

The authors previously investigated[3),4),5)] that the influences of separation index on tensile strength, fracture toughness and fatigue strength in the rolling or thickness direction of steel plates. Those researches clarified that steel plates control–rolled in two–phase region have various characteristics equivalent to or better than those of conventional process type steel plates without generation of separations, if the maximum separation index is less than about 0.5.

In this paper, the reasons for improvement of brittle crack arrestability are investigated by considering the propagation path of brittle crack in the double tension tests. The test steel plates were control-rolled at different finishing rolling temperatures using slab materials with the same chemical composition. This paper also proposes estimation methods of the generative direction from initial crack and propagation path of brittle crack by taking the in-plane fracture toughness distribution into account.

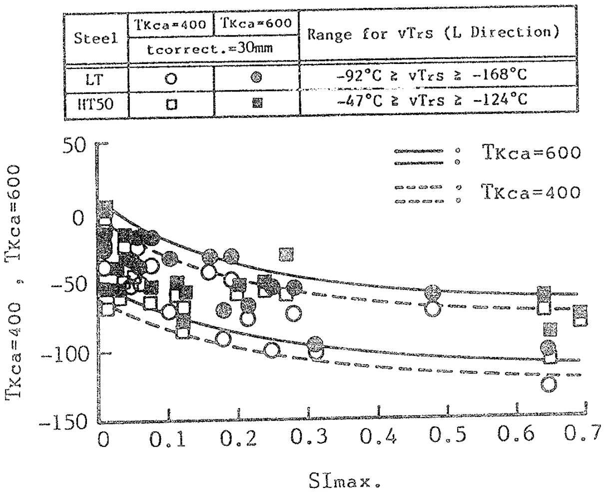

Fig. 1 Relation between critical temperature for brittle crack propagation-arrest [$T_{Kca=400}$, $T_{Kca=600}$ ($t_{correct.}$=30mm)] and maximum separation index

2. Propagation Behavior of Brittle Crack in Two-phase Region Rolled Steel Plate

2.1 Relationship between the maximum separation index and the brittle crack arrestability

To evaluate quantitatively the relative amount of separation in steel plates control-rolled in two-phase region, the separation index (SI) defined as the total of separation lengths divided by the fracture area has been often used. The maximum value of SI with respect to temperature is called the maximum separation index ($SI_{max.}$). Researches have clarified that $SI_{max.}$ becomes larger as the finishing rolling temperature in two-phase region is lower. The $SI_{max.}$ is also considered to be affected greatly not only by the finishing rolling temperature but also by the rolling reduction in two-phase region. Therefore $SI_{max.}$ is considered to represent not only the characteristics of a steel plate but also the condition of control rolling.

As reported in our previous paper[3), it has been clarified that a steel plate of a larger $SI_{max.}$ exhibit a higher brittle crack arrestability (K_{ca}). One example of the improvements is shown in Fig. 1. $T_{Kca=***}$ in the figure is defined as the temperature where K_{ca} indicates *** kgf/mm$^{3/2}$ with the thickness of 30mm in which other thickness data were converted to the thickness of 30mm.

Table 1 shows the chemical composition and mechanical properties of steel plates by Non-AcC type TMCP method used for testing. These steel plates were made by slab materials with the same chemical composition at different finishing rolling temperatures. Steel A is a steel plate with its control rolling terminated at around A_{r3} transformation temperature while

Table 1 Chemical composition and mechanical properties of steels used

Steel		Thick. (mm)	Chemical Composition (%) C	Si	Mn	P	S	Cu	Ni	Cr	Sol. Al	Ceq.**	Mechanical Properties Y.P. (kgf/mm²)	T.S. (kgf/mm²)	El. (%)
LT*	A	25	0.12	0.36	1.44	0.013	0.002	0.01	0.02	0.02	0.076	0.366	38.5	51.1	28
	C												42.5	53.8	25

*:TMCP Type Low Temperature Application Steel (SLA33B Equivalent)

**:Ceq. = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15 for Steel C, two control rollings were carried out in two-phase region. $SI_{max.}$ and temperature ($T_{SImax.}$) to show $SI_{max.}$ of test steels obtained from the rolling directional (L direction) Charpy impact tests are shown in Table 2.

Results of double tension tests in L direction are shown in Fig. 2 for steels A and C respectively. This figure also indicates that steel plate of a larger $SI_{max.}$ has a higher K_{ca}.

Table 2 $SI_{max.}$ and $T_{SImax.}$ of test steels

Steel	SImax.	TSImax.(°C)
A	0.05	-80
C	0.66	-120

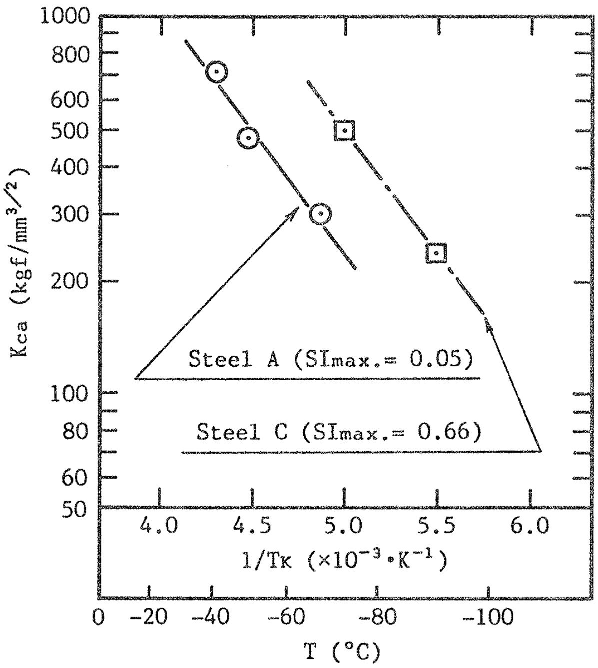

Fig. 2 Standard double tensile test results in L direction of Steel A and C

2.2 Discussion on causes of improved brittle crack arrestability

Previous researches[1),2)] explains that the improvement of K_{ca} in steel plate control-rolled in two-phase region would be caused by refining of ferrite structures and the thickness effect due to multiplate layers of sheets brought about by separations which occur ahead of the main propagating brittle crack.

As a result of the microstructural examination of steels tested, grain size of ferrite structures in Steel C had become somewhat larger than that in Steel A. It was considered to be a cause for the fact that Steel C had not been control-rolled at around A_{r3} transformation temperature, effective to refining ferrite structures. Therefore, it is rather difficult to regard refining of ferrite structures as the major cause of great improvement of K_{ca}.

The published reports have clarified that fracture toughness of multiple-layered plates is excellent in the Deep Notch Test[6)] or the Charpy impact test[7)]. Therefore, the thickness effect due to multiple layers of sheets brought about by occurrence of separations immediately before the main fracture has conventionally been presumed as one of the major causes to improve K_{ca}. However, separations had not occurred in the broken surface of the double tension test specimen for Steel C control-rolled in two-phase region.

According to WES 3003[8)] the thickness effect on K_{ca} for the steel plate thinner than 35mm in given by

$$f(t) = 1 - 0.05(t - 30) \quad (1)$$

where, t : thickness of test steel plate in mm

Here, we assume that the cause of K_{ca} in L direction of Steel C having beyond K_{ca} in L direction of Steel A is attributable only to the thickness effect due to occurrence of separations. According to the test results given in Fig. 2 and equation (1), K_{ca} in L direction of Steel C would become the same K_{ca} in L direction of Steel A as the case where the thickness of Steel A is divided into approximately five sheets. Then, four separations should have appeared on the fracture surface of specimen in L direction of Steel C. But, separations could not observed on the fracture surface of the specimen, and thus, it is unreasonable to presume that the thickness effect due to occurrence of separation would be the major cause of improvement of K_{ca} in L direction of Steel C.

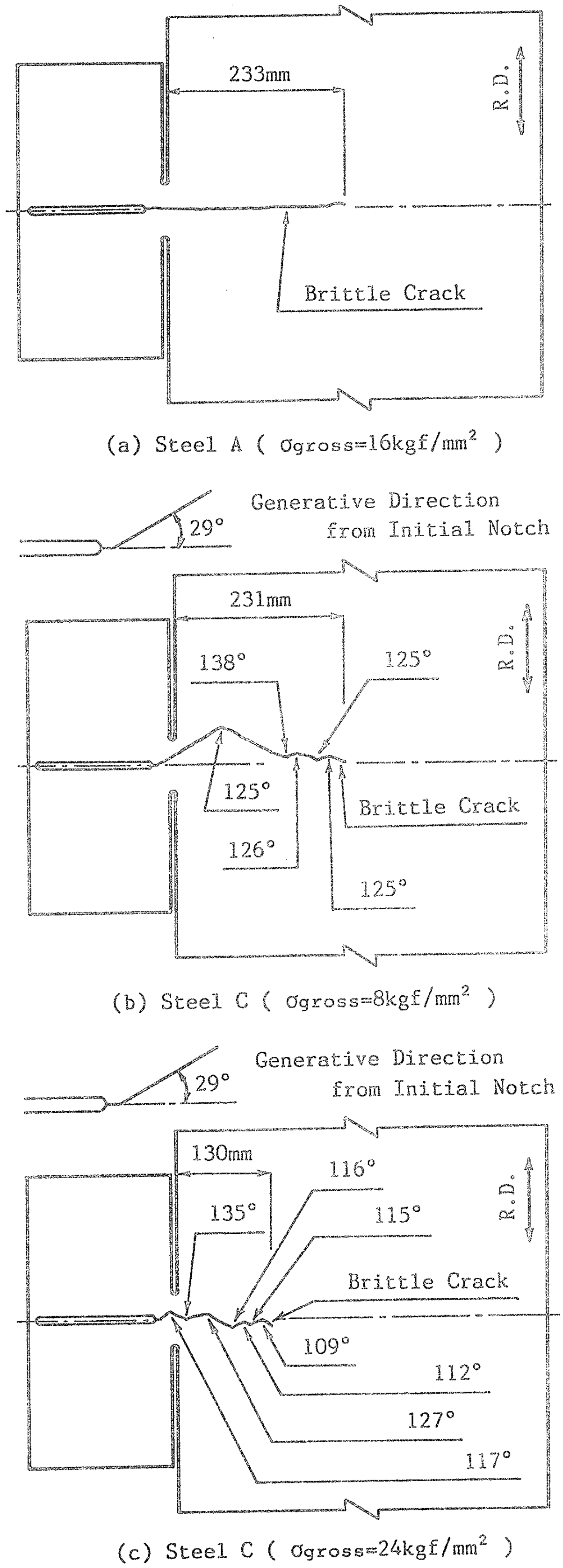

Fig. 3 Propagation path of brittle crack in double tensile test

Examples of propagation path of brittle crack in the double tension test is shown in Fig. 3. From this figure, it is found that the brittle crack propagated straight along the notch line in the specimen in L direction of Steel A, whereas the brittle crack propagated in the direction of approximately 30° to the notch line, and propagated a zigzagging path at angles of 100° to 140° in the specimen in L direction of Steel C. It is also found that in the specimen in L direction of Steel C, the zigzag amplitude became smaller with propagation of the brittle crack and the crack approached the notch line asymptotically. And test results show the tendency that the zigzag amplitude of brittle crack became smaller, as stress applied on the specimen became greater.

Subsequently, results of double tension test using test specimens in the direction at an angle of 45° (R45 direction) to the rolling direction of Steel C are shown in Fig. 4, together with the test results of Fig. 2. From this figure, it can be understood that K_{ca} in R45 direction of Steel C was nearly equal to K_{ca} in L direction of Steel A which showed almost none of separations. However, $SI_{max.}$ in R45 direction of Steel C was

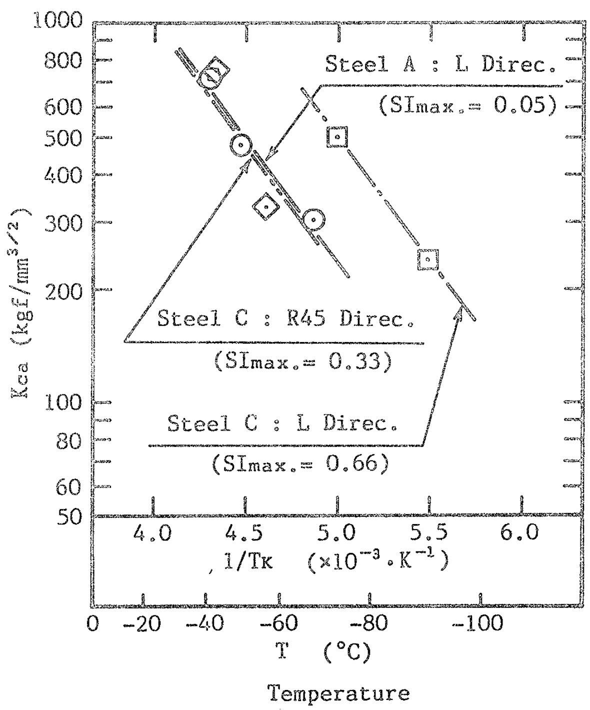

Fig. 4 Standard double tensile test results in R45 direction of Steel C

0.33, which differs greatly from $SI_{max.}$ (0.05) in L direction of Steel A. Again, according to this result, it was considered that the occurrence of separations would not cause the improvement of $K_{ca.}$ Also, the brittle crack in the specimen in R45 direction of Steel C propagated straight along notch line as same as the brittle crack in L direction of Steel A.

From the above results, it is considered that the zigzag propagation of brittle crack may affect a certain improvement of K_{ca}.

In–plane distribution of transition temperature ($_vT_{rs}$) with 50% brittle fracture by Charpy impact tests with the various directions are shown in Fig. 5. As evidenced in this figure, there exists an anisotropy which shows higher toughness in L direction or in the direction at a right angle (T direction) to the rolling direction especially for Steel C. It is inferable that the in–plane toughness anisotropy can affect the zigzagging propagation of brittle crack. And it can be considered that since this anisotropy of in–plane toughness distribution is greatly effected by crystal orientation, as steel plate is control–rolled at lower temperature in two–phase region, anisotropy in the in–plane toughness distribution become large.

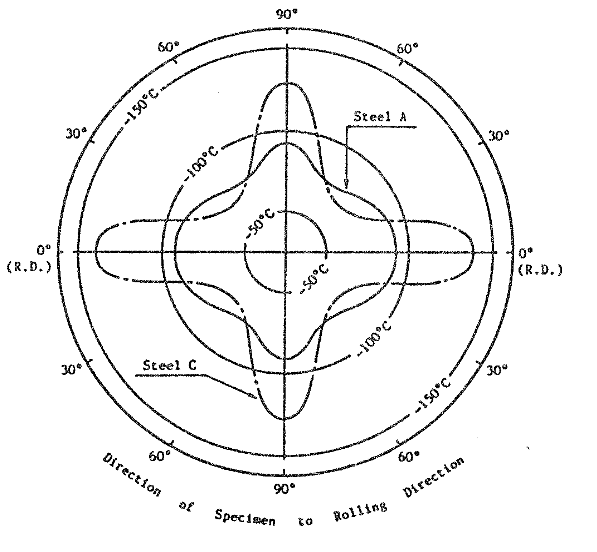

Fig. 5 $_vT_{rs}$ obtained by Charpy impact tests with various directions of test steels

3. In–plane Anisotropy of Fracture Toughness in Steel Plates Rolled in Two–phase Region

3.1 Outline of testing

The CTOD test was carried out in accordance with BS–5762[9] using sub–sized–specimens in the three directions of R0(L), R22 and R45 as shown in Fig. 6 for the purpose of obtaining the in–plane fracture toughness distributions. The zigzagging propagation of brittle crack can occur at temperature higher than −160°C in the double tension test. But in this temperature region, fracture surfaces of specimens of the CTOD test showed ductile with separations, therefore, K_c could not be obtained from results of the CTOD test.

Accordingly, equation (2) proposed by Yajima et al.[10] to estimate values of K_c from $_vT_{rs}$ was used. Although equation (2) can give an estimation of K_c at an arbitrary temperature, only values of K_c at $_vT_{rs}$ were obtained from Fig. 5.

$$K_c = F \cdot 5.60\,\sigma_{yo} \cdot \exp\{k_0(1/_{\sigma=\frac{1}{2}\sigma_{yo}}[T_i]_{a=40} - 1/T_K)\} \tag{2}$$

where, F : Conversion ratio of notch acuity affect on fracture toughness

$$(F = K_{c,\ \mathrm{fatiguue\ cracked\ notch}} / K_{c,\ \mathrm{machined\ notch}} = 0.68)$$

$$k_0 = 5.70\ \{_{\sigma=\frac{1}{2}\sigma_{yo}}[T_i]_{a=40}\} - 170$$

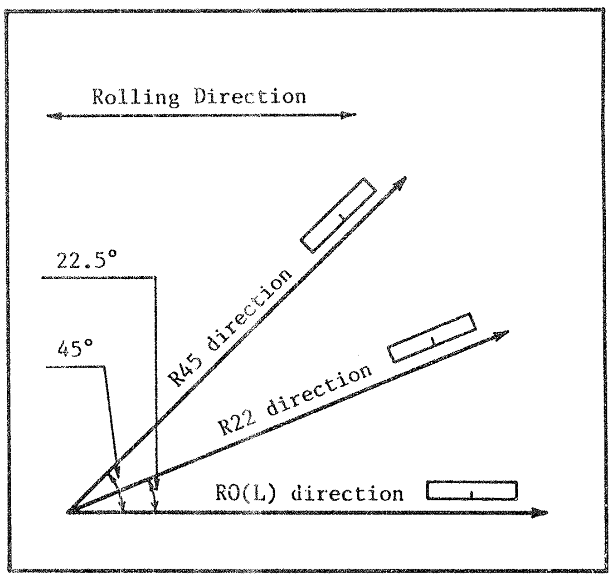

Fig. 6 Cut–out method of specimens

$$\sigma = \tfrac{1}{2}\,\sigma_{y0}\,[T_i]_{a=40} = (0.00321\,\sigma_{y0} + 0.391)\,{}_{v}T_{rs} + 2.74\sqrt{t} + 17.3$$

σ_{y0} : Yield stress at room temperature (kgf/mm^2)

T_K : Tested temperature (K)

3.2 Influences of the finishing rolling temperature on the in–plane fracture toughness distribution

Values of critical crack tip opening displacement (δ_c) obtained from CTOD test results in three directions of Steel A and C was converted to K_c using equation (3)[9]. Values of K_c in each direction are given in Fig. 7 for Steel A and in Fig. 8 for Steel C. These figures also show relations between values of K_c which were estimated from ${}_{v}T_{rs}$ and temperatures.

$$K_c = \sqrt{\{2\sigma_y E\,\delta_c/(1-\nu^2)\}} \qquad (3)$$

where, σ_y : Yield stress at testing temperature of CTOD test (kgf/mm^2)

E : Young's moduls (kgf/mm^2)

ν : Poisson ratio

K_c distribution in the arbitrary diagonal direction to rolling direction for each 20°C interval are shown in Fig. 9 for Steel A and in Fig. 10 for Steel C, from the Fig. 7 and Fig. 8 respectively. Also, K_c values in the directions of 45° to 90° to the rolling direction were obtained from symmetric relations with those in the directions of 0° to 45° because ${}_{v}T_{rs}$ in L and T directions had been almost equal to each other as shown by Fig. 5. Again, these figures also observed that there exists an anisotropy of K_c distribution in Steel C which was control–rolled in two–phase region whereas no large difference is recognizable in K_c distribution of

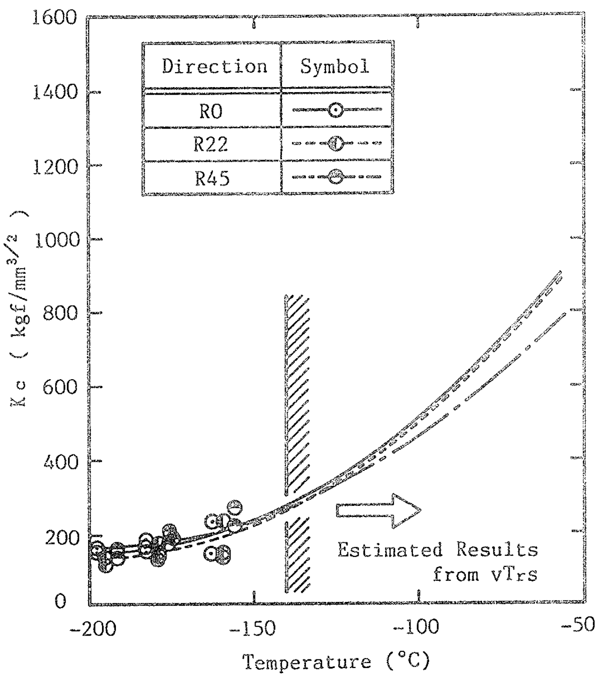

Fig. 7 Relation between K_c and temperature in Steel A

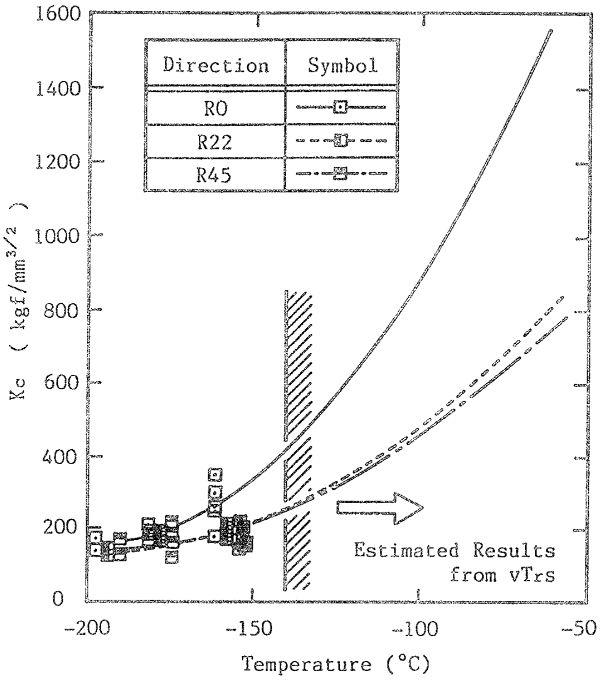

Fig. 8 Relation between K_c and temperature in Steel C

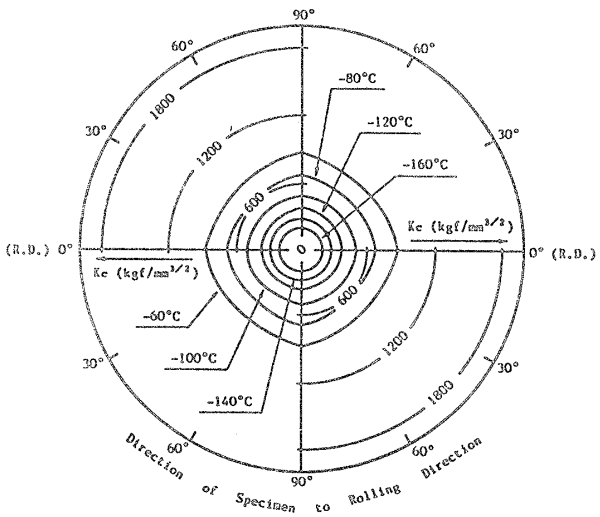

Fig. 9 Distribution of in–plane K_c in Steel A

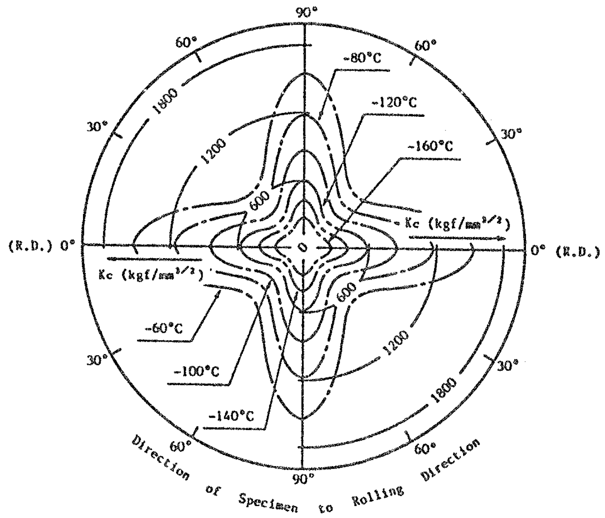

Fig. 10 Distribution of in–plane K_c in Steel C

Steel A which was finally control–rolled at around A_{r3} transformation temperature.

4. Estimation of Generative Direction of Brittle Crack Considering the In–plane Fracture Toughness Distribution

4.1 Consideration of criteria of brittle fracture initiation for a steel plate with in–plane anisotropy of fracture toughness

In CTOD specimens, brittle crack propagated along the crack line from the notch tip even in L directional specimen for Steel C. This may be because the ligament is small and then the degree of normal stress distribution along the crack line becomes dominant due to be back surface effect compared with that to diagonal directions. Then the fracture toughness for each direction can be obtained by using ordinary stress intensity factor.

On the other hand, in case of the specimen with large ligament such as a double tension specimen, the degree of normal distribution along the crack line ($\theta=0°$) does not become dominant, and then the crack may have a tendency to generate to the most deteriorated direction if the steel plate has large anisotropy of fracture toughness.

The degree of normal stress distribution to radial directions from a crack–tip ($K_k(\theta)$) can be expressed as

$$K_k(\theta)=k_{\sigma_\theta}(\theta)\cdot K \quad (4)$$

where, K : Stress intensity factor

$k_{\sigma_\theta}(\theta)$: Correction factor for radical direction (θ)

For a steel plate with anisotropy of fracture toughness, brittle fracture may be postulated to first approximation to initiate when $K_k(\theta)$ first become equal to and excess $K_c(\theta)$ and propagate to the direction of θ, where $K_c(\theta)$ is a fracture toughness for a direction of θ.

Normal stress around the crack tip was calculated by the FEM using constant strain triangular elements. The analysis model was a half of width of finite strip with a center crack loaded uniform tensile stress. Also, length of the initial crack ($2a_o$) was at 10% of the finite strip width ($2W$).

4.2 Estimation of generative direction of brittle crack

Based on an above assumption, brittle crack initiates in the direction where the value of $K_k(\theta)$ first reaches the value of $K_c(\theta)$. Here, the $K_c(\theta)$ for analysis was used at the temperature of $-160°C$ nearly equal to the temperature in the vicinity of the initial notch tip of specimen for the double tension test.

Generative direction of brittle crack in L direction of Steel A with almost isotropy in $K_c(\theta)$ is shown in Fig. 11. This figure shows that the $K_k(\theta)$ first reaches the $K_c(\theta)$ in the direction of $\theta=0°$. Thus, the brittle crack of Steel A (L direction) may be estimated to

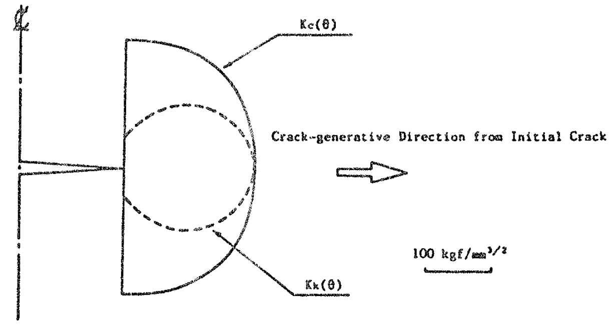

Fig. 11 Crack–generative direction from initial notch in L direction of Steel A

initiate in the initial crack direction.

Generative direction of brittle crack in L direction of Steel C with anisotropy in $K_c(\theta)$ is shown in Fig. 12. From this figure, it is found that the $K_k(\theta)$ first becomes equal to and excess the $K_c(\theta)$ in the direction of $\theta=27°$ or $-27°$. Thus, it may be estimated that the brittle crack of Steel C (L direction) will initiate to a direction of 27° or −27° to the initial crack direction. Here, it is probability that crack initiates in either positive or negative direction.

Result of Steel C in R45 direction is shown in Fig. 13. In this case where the $K_k(\theta)$ first reaches the $K_c(\theta)$ in the direction of $\theta=0°$, this crack may be estimated to initiate in the initial crack direction.

Generative direction of estimated results are compared with those double tension test results in Table 3. This table verifies that the test results are nearly in a good agreement with estimated results and thus, it is apparent that

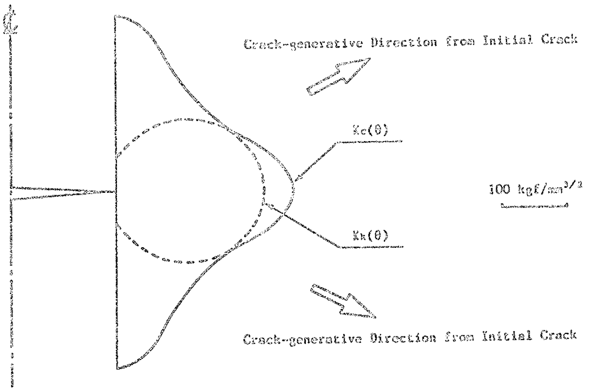

Fig. 12 Crack-generative direction from initial notch in L direction of Steel C

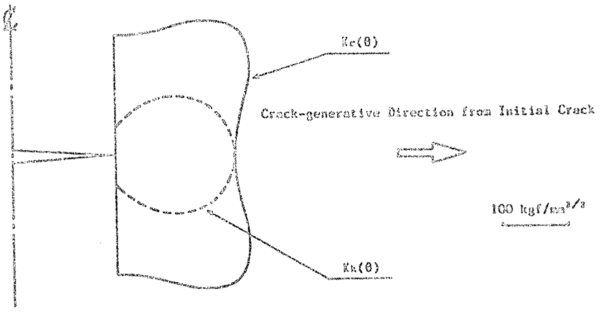

Fig. 13 Crack-generative direction from initial notch in R45 direction of Steel C

Table 3 Estimated results of crack-generative direction

Steel	Direction of Specimen	Crack-generative Angles of Test Results	Crack-generative Angles of Estimated Results
A	L	0° 0° 0°	0°
C	L	29° 29°	27°
	R45	0° 0°	0°

in the steel plates with anisotropy in $K_c(\theta)$, the generative direction can be estimated on the basis of this method.

5. Estimation of the Brittle Crack Zigzag Propagation Path Taking into Account the In-plane Fracture Toughness Distribution

5.1 Model for the estimation of brittle crack propagation path

When double tension test was carried out for the steel plate (Steel C) with an anisotropy of $K_c(\theta)$, the brittle crack of specimen in L direction propagated a zigzagging path while the brittle crack of specimen in R45 direction propagated straight along the notch line.

Then, we investigated an estimation method of propagation path of a brittle crack in L direction of Steel C. Here, the $K_c(\theta)$ of Steel C at the temperature of −160°C was used for analysis.

Stage I of analysis expresses the case which the crack is propagating straight in the direction of $\theta=27°$ to initial crack direction. In Stage I of analysis, the position and angle which the propagating crack first turns after its initiate in the direction of $\theta=27°$ are obtained. Then, the case to obtain the second turning point while the crack is propagating in the second direction obtained in Stage I is defined as Stage II of analysis. Analysis was carried out till Stage IV by repeating the same procedure as described above.

Because propagation of brittle cracks is a dynamic phenomenon, it should be considered that dynamic effects on the propagation path of brittle crack could be large. However, the propagation path was estimated on the basis of a statics in consideration of the stress distribution around the crack tip was obtained by statical analysis and $K_c(\theta)$ was static fracture toughness.

5.2 Estimation of the zigzagging propagation path of brittle crack

Length of cracks and trans–directional angles in each stage of analysis for the crack propagation path were estimated by finding propagated directions which the $K_k(\theta)$ reaches first the $K_c(\theta)$ under the propagating crack length for 10% of a_0. However, when the crack turned in the first calculation, the turning direction was calculated again using a shorter length.

An example of estimated propagation path which analyzed till Stage Ⅳ is shown in Fig. 14. This figure indicates the respective trans–directional angles and the ratios of propagated crack lengths (a_i) in each stage to a_0. From this figure, it is observed that the trans–directional angles in the respective stages nearly agree with the results of double tension test. However, estimated crack length a_i in each stage propagated extremely shortly as compared with a_0, which varies greatly from the double tension test results. This cause may be considered as follows: In the Stage Ⅰ of Static analysis, the difference between σ_θ in the direction of turning for Stage Ⅱ and σ_θ in the direction of propagation in the Stage I was only 1%. But in the Stage Ⅰ of double tension tests, the brittle crack propagated straight in the direction of $\theta = 29°$ to initial notch direction by dynamic effect until a significant difference of σ_θ in the propagating and turning directions.

It is also inferred that once the brittle crack under propagation at a steady–state speed (normally, about 500m/s) turns, speed of propagation slows down considerably as compared with speed of propagation before its turn. It has been verified[11] that in the case of branch–off of the brittle crack, a shear lip appears at that point and propagation speed slows down momentarily, and that the branched brittle crack takes a time of propagation 1.5 to 2.0 times as great as the straight propagated brittle crack. Accordingly, considering that dynamic effects in Stage I are far larger than dynamic effects in subsequent stages, one assumes here that a_1 in Stage Ⅰ propagates $2a_0$ although somewhat uncertain. In Stage Ⅱ and subsequently, length of cracks and trans–directional angles were estimated by finding propagated directions which the $K_k(\theta)$ reaches the $K_c(\theta)$ under propagating crack for each 10% of a_0.

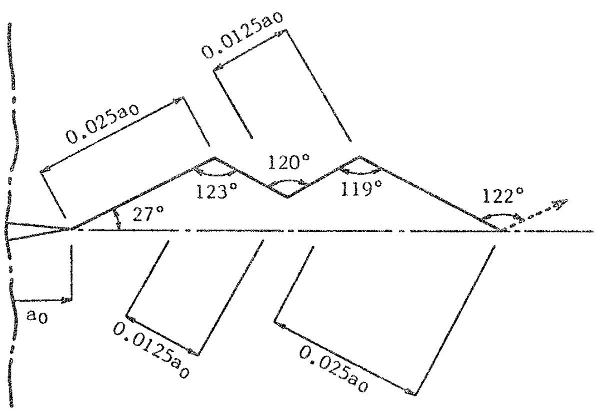

Fig. 14 Estimated path of crack propagation in L direction of Steel C

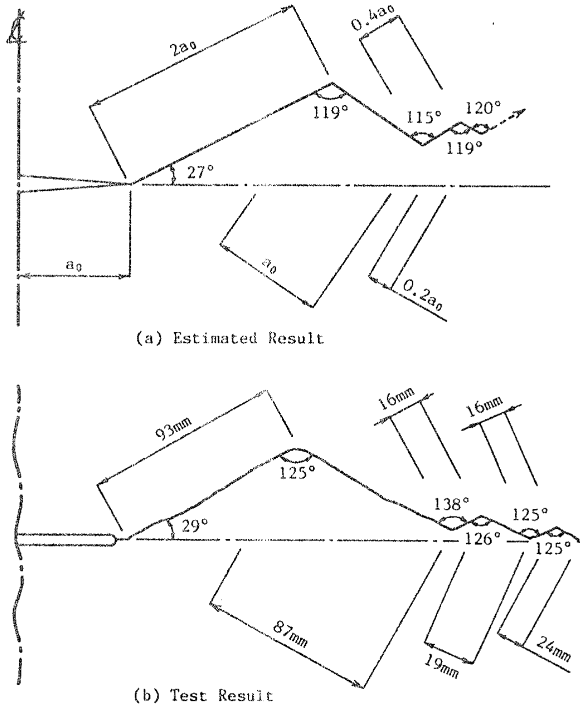

Fig. 15 Comparison between estimated path and experimental one for double tension test specimen of Steel C
($\sigma_{gross}=8kgf/mm^2$, L direction)

The analyzed results of propagation path are given in Fig. 15. In this case, the difference between σ_θ in the propagating direction of Stage I and σ_θ in turning direction was at 14%. This figure indicates trans-directional angles and ratios of a_i to a_0 estimated in the respective stages of analysis and also, the propagation path in the double tension test in L direction of Steel C, loaded with 8.0kgf/mm^2. From this figure, it is found that the trans-directional angles in each of estimated stages nearly agree with the test results. Although direct comparison between estimated length of propagation path and experimental one in each stage may be unavailable, it is known that propagation path of the brittle crack in the estimated and test results are very similar to each other in that propagation path was not symmetric in the initial notch direction or in that both propagation paths became shorter for each stage.

In the estimation of the generative direction of brittle crack, the generative direction of the crack was greatly affected by $K_c(\theta)$. On the other hand, in the estimation of zigzag propagation path of the brittle crack, because the energy release rate in the post-turn direction became 17% greater than that in the direction of $\theta=0°$ in the first turning point in Stage I, zigzag propagation path was affected by the σ_θ distribution coupled with another influence of the $K_c(\theta)$. Using the above estimation method, it has almost been clarified that the cause of zigzagging propagation of brittle crack and the propagation path of the brittle crack in steel plate with anisotropy of in-plane fracture toughness distribution.

One can not assume that the this estimation method is sufficient for the quantitative evalution of excellent values of K_{ca} in TMCP steel, which has an anisotropy in the in-plane fracture toughness distribution due to control-rolling in two-phase region. However, in analysis results shown in Fig. 15, the energy release rate in the post-turn direction in Stage I became about 10% smaller than that of a straight crack which was projected zigzagging crack along the initial crack direction. In Stage II of analysis, the energy release rate in the post-turn direction was about 15% smaller than that of a straight crack. Also, considering that K_c in L direction of Steel C is much greater than K_c in L direction of Steel A and that the zigzagging brittle crack gradually converges toward the direction of a greater value of K_c, it is obviously considered that the brittle crack arrestability of steel plate control-rolled in two-phase region is improved.

6. Conclusions

This paper discussed causes of the improvement of the brittle crack arrestability by investigating the propagation path of brittle crack in double tension test using two kinds of steel plates having different values of $SI_{max.}$, which were control-rolled in two-phase region. Also, generative direction and propagation path of brittle crack were estimated, taking into account in-plane fracture toughness distributions of test steels.

As a result, the following were clarified.

1) The major cause of the improved brittle crack arestability is not attributable to the thickness effect due to occurrence of separation in fracture surface.
2) An anisotropy of in-plane fracture toughness which exhibits excellent fracture toughness in the rolling direction and in perpendicular direction to the rolling direction exists in steel plates control-rolled in two-phase region.
3) The major cause of initiation of the brittle crack at a certain angle to the initial notch direction in the double tension test using a specimen of L direction of test steel plate control-rolled in two-phase region is due to an anisotropy in in-plane fracture toughness distribution.
4) The brittle crack in the double tension test using a specimen of L direction of test steel plate control-rolled in two-phase region propagate zigzag principally because of the normal stresses to radial directions from crack tip further affected by anisotropy of in-plane fracture toughness distribution.

5) It is considered that the improvement of brittle crack arrestability in the L direction of test steel plate control–rolled in two–phase region is caused by the zigzagging propagation crack which has a smaller energy release rate than that in straight propagation crack. However, it should be added that the sufficient quantitative evaluation was difficult only on the basis of the estimation method presented in this paper.

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