A statistical study on fracture toughness data of Japanese RPVS

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ABSTRACT:
In a cooperative study for investigating fracture toughness on pressure vessel steels produced in Japan, a number of heats of ASTM A533B cl.1 and A508 cl.3 steels have been studied. As a result of this study, approximately 3000 fracture toughness data and 8000 mechanical properties data were obtained and filed in a computer data bank. In this study, statistical characterization of toughness data in the transition region has been carried out using the computer data bank. Curve fitting technique for toughness data has been examined. Approach using the tanh function to model the transition behaviours of each toughness has been applied. The aims of fitting curve technique were as follows;(1) Summarization of an enormous toughness data base to permit comparison heats, materials and testing methods;(2) Investigating the relationships among static, dynamic and arrest toughness;(3) Examining the ASME K_{IR} curve statistically. The methodology used in this study for analyzing a large quantity of fracture toughness data was found to be useful for formulating a statistically based K_{IR} curve.

1 INTRODUCTION

There is a trend for the requirements for the reliability of nuclear power plants and for structural integrity of their components to become more stringent. In this respect it is necessary to have overall and detailed informations about the properties of materials used in current heavy-walled nuclear reactors to ensure the reliable fabrication of nuclear pressure vessels. The subcommittee of the Japan Welding Engineering Society set up a program for measuring the fracture toughness of nuclear pressure vessel steels (ASTM A533B cl.1 and A508 cl.3) under the direction of the Japan Atomic Energy Institute [1,2 and 3]. As a result of the study, approximately 3000 fracture toughness data were obtained. A common concern in toughness testing is to make clear the relationship between toughness and temperature , and to compare the results with the ASME K_{IR} curve. However, it was noted from the study that it was rather difficult to define a temperature-toughness relationships exactly since the fracture toughness data usually varies widely at transition region. Moreover, in general, the lower boundary of toughness data will be lowered as increasing the number of toughness data, which may cause such a possibility that one or two data among a numerous data base fall below the ASME K_{IR} curve though overall toughness of the material is sufficiently high. Consequently,

Table 1 Heats Code and Products Dimensions

Steel	*Heat code*	*Dimensions (mm)*		
		t	*W*	*L*
A533B cl. 1	1A	250	4 400	5 700
	2A	250	4 000	7 050
	3A	250	3 500	4 400
	4A	250	4 400	7 050
	5A	250	4 000	8 000
	6A	250	4 000	5 000
A508 cl. 3	1B	(5 562)[a]	(4 962)	(3 119)
	2B	(2 620)	(2 200)	(1 250)
	3B	300	1 450	2 150
	4B	(2 800)	(2 200)	(1 600)
	5B	250	1 860	6 000
	6B	300	2 200	3 700

[a] Parentheses indicate forged ring (OD, ID, H respectively).

Table 2 Chemical Composition of Each Heat (1/4*t*, Bottom) (wt.%)

Steel	*Heat code*	*C*	*Si*	*Mn*	*P*	*S*	*Ni*	*Cr*	*Cu*	*Mo*	*T.Al*
A533B cl. 1	Mean	0·18	0·26	1·43	0·006	0·004	0·66	0·15	0·02	0·55	0·022
A508 cl. 3	Mean	0·20	0·26	1·38	0·004	0·005	0·72	0·11	0·03	0·49	0·021

Table 3 Results of Tensile,Charpy V-notch and Drop Weight Tests

Steel	Heat Code	Y.S. (MPa)	T.S. (MPa)	vEshelf (J)	T_{NDT} (°C)	RT_{NDT} (°C)
A533B cl.1	mean	486	623	225	30	30
A508 cl.3	mean	458	604	201	30	30

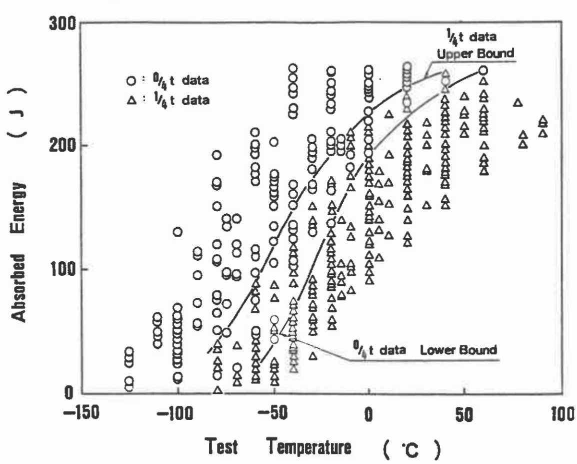

Fig.1 Temperature dependence of Charpy absorbed energy

an adequate statistical approach is available to provide a rational basis for establishing a statistically significant lower bound curve. For this reason, it is advantageous to apply a staistically defined transition curve to the data. Several approaches were tried to describe the relationship between toughness and temperature, and an approach using tanh function was selected as a most promising regression analysis method. Tanh model can be fitted to the test data by suitable computational procedures and give a well-defined relationship, which make it ease to realize the statistical meanings of the toughness data and the relationships among the toughness data from various test methods.

2 DATA BASE

In the present study,toughness data from six heats of ASTM A533 Grade B class 1 steel and 6 heats of ASTM A508 class 3 steel were used. The code names and products dimensions of each heat are described in Table 1. The mean values of chemical compositions for each steel at quarter thickness location are listed in Table 2. All of these compositions for present materials were fully acceptable to the ASTM specification requirements. The results of tensile,drop weight and Charpy V-notch properties are given in Table 3.The details of these fundamental properties were reported in else-where [1].

2.1 Charpy absorbed energy data

Charpy V-notch impact test were carried out in accordance with ASTM standard A370. Fig.1 depicts the temperature dependence of absorbed energy at 0/4t(surface of the plate) and 1/4t(quarter thickness location) with the orientation of the T-direction for test materials. Apparently,absorbed energy shows dependences on the thickness location and temperature.

2.2 Static fracture toughness data

Static fracture toughness tests were conducted on compact tension and three point bend specimens according to ASTM Method E399.Fig.2 illustrates the temperature dependence of static fracture toughness K_{IC} and K_Q values at quarter thickness location for both steels. The valid K_{IC} values were obtained at -25°C using 10TCT specimens, however, above this temperature, valid K_{IC} values could not be obtained though full thickness specimens were used.

2.3 Dynamic fracture toughness data

Instrumented precracked Charpy impact tests (PCI) were performed under the test velocity 1-5 m/s in pendulum impact test machines with DYNATUP (model 500) instrumentations. Fig.3 depicts the temperature dependence of dynamic fracture toughness K_{PCI} at quarter thickness location for both steels. In the figure, K_{PCI} increases abruptly at transition region as increasing temperature and there is almost no difference between the toughness of the two steels.

2.4 Crack arrest toughness data

Crack arrest toughness tests were performed using the weld embrittled crack arrest test specimens in accordance with ASTM proposed crack arrest toughness test method. Fig.4 depicts well the temperature dependence of crack arrest toughness values. Valid K_{Ia} values were obtained at room temperature using large specimens and form the lower bound at the temperature region from -75°C to room temperature.

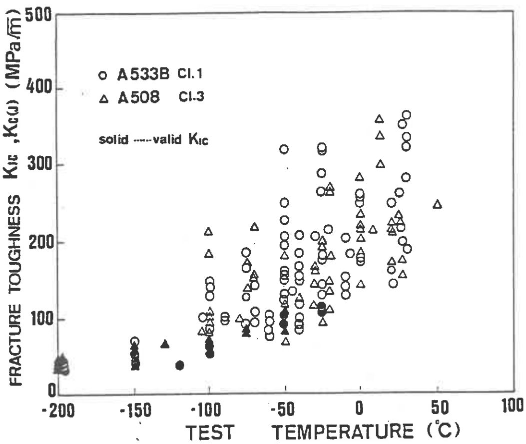

Fig.2 Temperature dependence of static fracture toughness (1/4t)

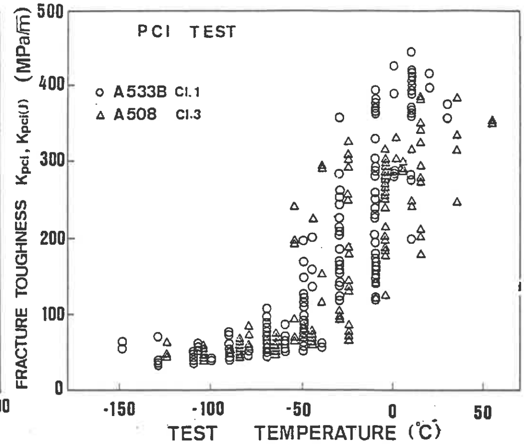

Fig.3 Temperature dependence of dynamic fracture toughness (1/4t)

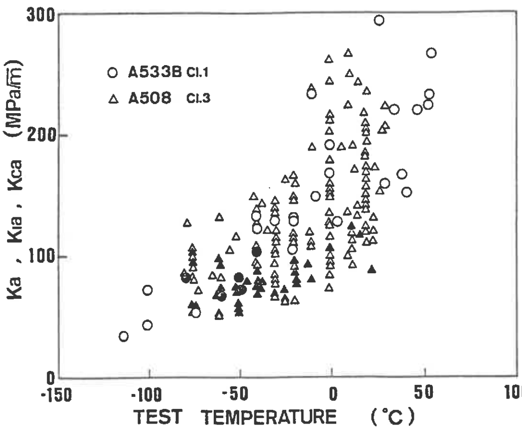

Fig.4 Temperature dependence of crack arrest toughness (1/4t)

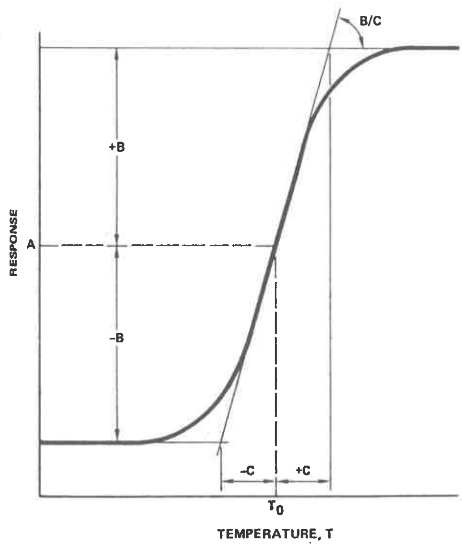

Fig.5 Schematic illustration of Tanh curve

Heat	Statistical Factors , C_v					
	A	B	C	To	s	vEshelf (A+B)
A533B-1	118	105	40.4	-12.2	13.9	221
-2	98	103	58.7	-10.1	13.8	201
-3	134	100	30.8	-3.0	14.6	234
-4	129	104	39.0	-22.0	19.7	233
-5	132	100	29.5	-25.0	18.1	232
-6	127	105	40.1	-12.2	14.2	232
Average	123	103	39.8	-14.1	15.8	226
A508 -1	83	117	57.1	-15.1	14.8	200
-2	112	88	43.0	-1.4	14.7	200
-3	118	99	36.2	-10.2	15.5	217
-4	122	99	31.5	-11.3	17.6	221
-5	113	98	43.3	-3.2	22.0	211
-6	116	89	28.5	-11.3	14.5	205
Average	111	98	39.9	-8.7	16.4	208
Average (A533B+A508)	117	100	39.9	-11.7	16.1	217

Table 4 Summary of analese for Charpy absorbed energy

3 Tanh curve fitting

As a useful curve-fitting procedure for the toughness data, the following tanh curve was proposed and have been described in detail by Oldfield [4];

$$Y = A + B \ Tanh(\frac{T - To}{C}) \qquad (1)$$

The coefficients in the regression - A, B, To and C - have physical significance as follows;

Lower shelf = A - B
Upper shelf = A + B
Transition temperature = To
Slope at To = B/C

These features are also summarized in Fig.5. Statistical analyses were performed using Tanh regression program on the toughness data bank.

4 ANALYSIS

4.1 Charpy absorbed energy data

Fig.6 shows an example of tanh curve fit for the Charpy V-notch data. In the figure, tanh regression coefficients (A,B,C,To,s) calculated in the computer program were also written , and the curve fit plotts indicate the 2s limits as dotted lines and 3s limits as dashed lines, where "s" denotes standard deviation of the data. As shown in the figure,tanh curve fit method was succesfully applicable to Charpy absorbed energy data. Tabel 4 shows the results of the statistical analyses for Charpy absorbed energy data at quarter thickness location. The upper shelf energy varied from 200 to 234 J and transition temperature varied from -1.4 to -25°C. It is apparent that the toughness of heat A533B-5 was the highest and A508-2 was the lowest. However, there is not so large difference of toughness among test materials.

Fig.7 shows the transition curves defined by statistical analyses for A533B steel. The transition curves for each thickness location were drawn using the mean values of statistical factors for the steel. For an example, the transition curve for 1/4t data was defined using the upper shelf energy (A+B) of 217 J, transition temperature (To) of -12°C, slope at To(B/C) of 2.51 and standard deviation of 16.1 J in Table 4.
It was noted from Fig.7 that toughness at 0/4t was superior to those at 1/4t and 2/4t locations, and that the toughness at 1/4t was slightly higher than at 2/4t though the upper shelf energies for both locations were almost equal.

4.2 Static fracture toughness data

An example of the tanh curve fit for static fracture toughness data (heat A508-1) at 1/4t is shown in Fig.8. For fracture toughness data, there are several difficuities to apply tanh curve fit analysis; first, as shown in Fig.8, the expense of testing larger test specimens (two to ten inches thickness) limited the fracture toughness data to two or three points per heat. This limited number of samples was barely adequate to define the lower and transition region, and second, at upper shelf region fracture toughness is usually defined by the elasto-plastic analysis (J-evaluation), on the contrary, LEFM (K-evaluation) is applied to lower and transition regions. However, the use of the tanh statisti-

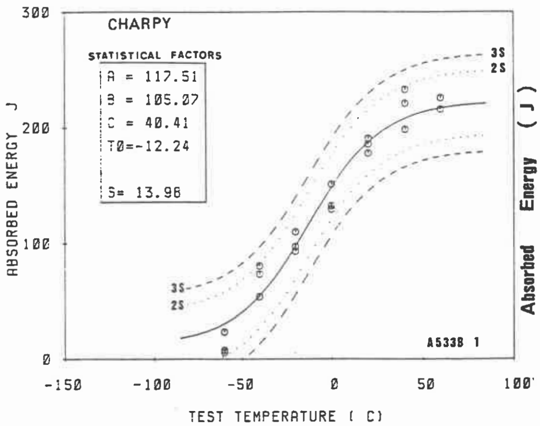

Fig.6 An example of tanh curve fit for Charpy absorbed energy

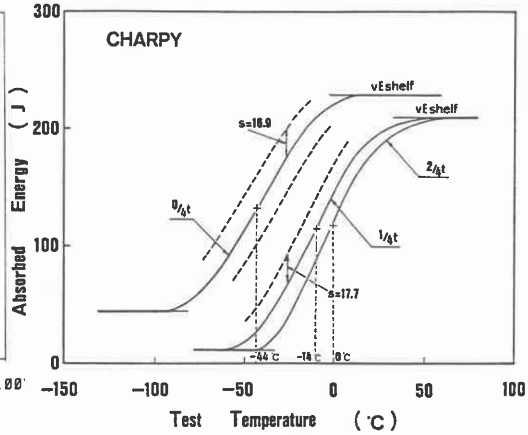

Fig.7 Transition curves of Charpy absorbed energy

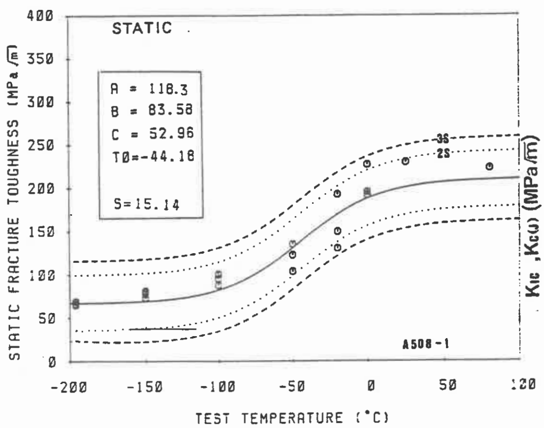

Fig.8 An example of tanh curve fit for static fracture toughness

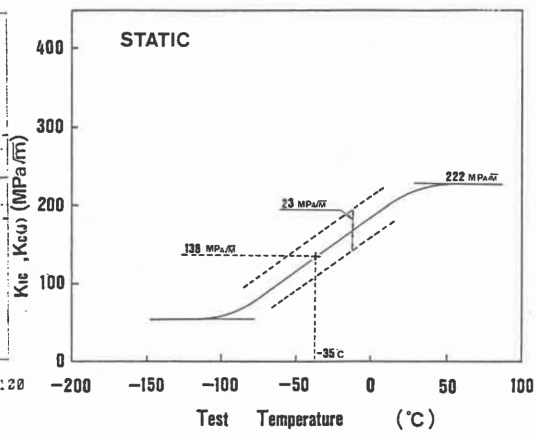

Fig.9 Transition curve of static fracture toughness

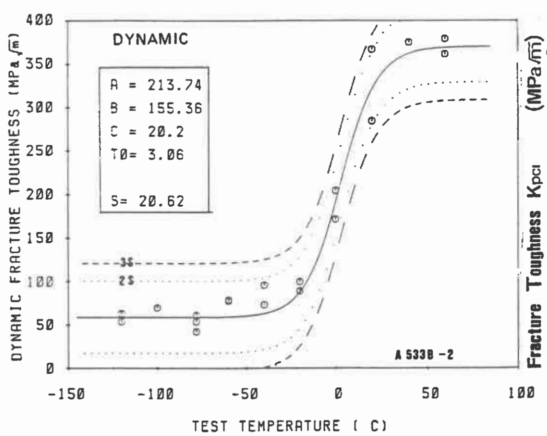

Fig.10 An example of tanh curve fit for dynamic fracture toughness

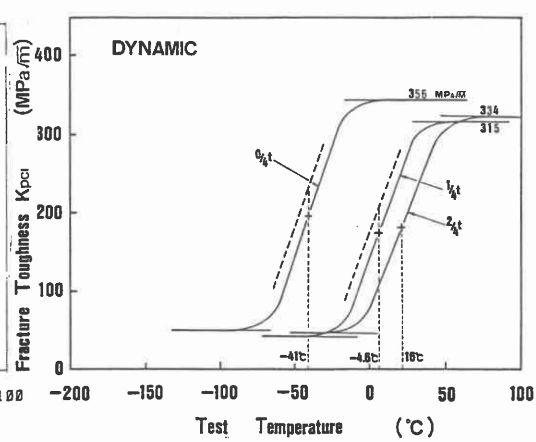

Fig.11 Transition curves of dynamic fracture toughness

cal curve fit analysis requires a full transition curve including the upper shelf. In our preliminary study, we assumed that the data from small specimens could also dictate the transition behavior of a material though they were not exactly satisfied with the size requirements of ASTM Method E399. At upper shelf reion, the stress intensity factor K values were converted from J-values using the following relation ;

$$K = \left(\frac{E\,J}{1 - \nu^2} \right)^{1/2} \qquad (2)$$

where E is Young's modulous and ν is poisson's ratio. As shown in Fig.8, tanh curve fit could also be applied with the aid of two values from J-evaluation at 20°C and 80°C. The transition curve shown in Fig.9 was defined using the mean values of statistical factors for various heats. The lower and upper shelf values were 54 and 222 Ma$\sqrt{m}$, respectively, and the temperature (To) was -35°C. The transition region ranged from -100°C to room temperature and the slope of transition curve was rather moderate in comparison with Charpy absorbed energy data.

4.3 Dynamic fracture toughness

An example of the tanh curve fit for instrumented precracked Charpy impact test data (heat A533B-2) at quarter thickness location is shown in Fig.10. The transition behavior of the property with temperature was generally same as Charpy absorbed energy data (Fig.6). The lower and upper shelves were well defined and the variation of the data was comparatively small. Fig.11 depicts the transition curves for instrumented precracked Charpy impact test data at each thickness location using mean values of statistical factors for every heats of A533B steel. As shown in this fugure, the toughness at the surface of the plate was the highest and at the center of the plate was the lowest. The transition temperatures at each location were almost equal to those of Charpy absorbed energy data.

4.4 Crack arrest toughness

An example of the tanh curve fit for crack arrest toughness data (heat A508-2) at quarter thickness location is shown in Fig.12. As a whole, tanh curve fit could express the transition behavior of the toughness data. Fig.13 depicts the transition curve for crack arrest toughness data at quarter thickness location using mean values of statistical factors for A533B steel. The transition temperature To(mean) was -15°C with the toughness level of 160MPa$\sqrt{m}$ and the difference between upper and lower shelves was relatively small.

5 RELATIONSHIPS AMONG EACH TOUGHNESS

From the results described in the previous section, the statistical features of each fracture toughness had been clarified. Fig.14 shows the fracture toughness mean curves obtained in the previous analyses. It is apparent that the dynamic fracture toughness values were the lowest and formed the lower bound function. In addition, the transition temperature shift from static fracture toughness to arrest toughness is about 25°C and the shift from arrest toughness to dynamic fracture toughness is about 20°C at transition region. The transition curve of dynamic fracture toughness shows a steep slope at transition region, whereas static fracture toughness changed gradually from a lower shelf to a upper shelf. In this figure, the statistically defined transition temperature curves for each toughness make clear the fact that the static fracture toughness is generally highest and that the dynamic fracture toughness is the most critical property for assessing the integrity of structural steels.

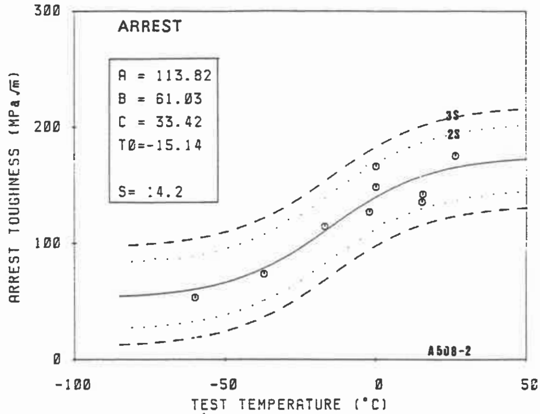

Fig.12 An example of tanh curve fit for arrest toughness

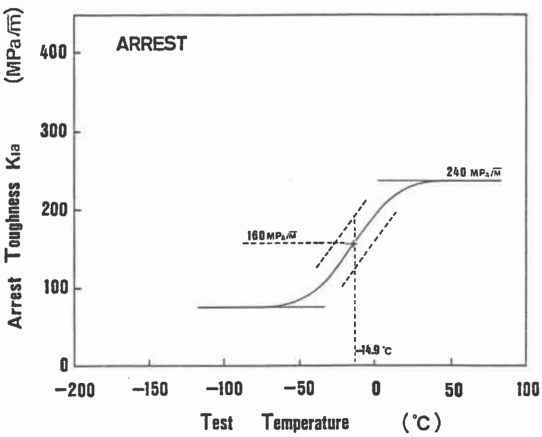

Fig.13 Transition curve of crack arrest toughness

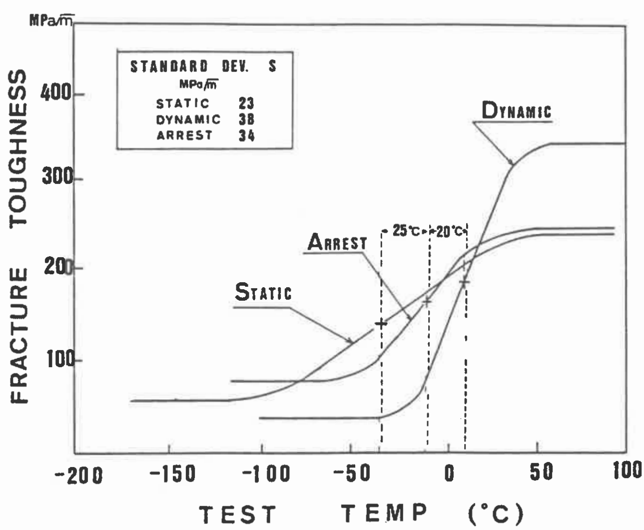

Fig.14 Relations among each transition curve

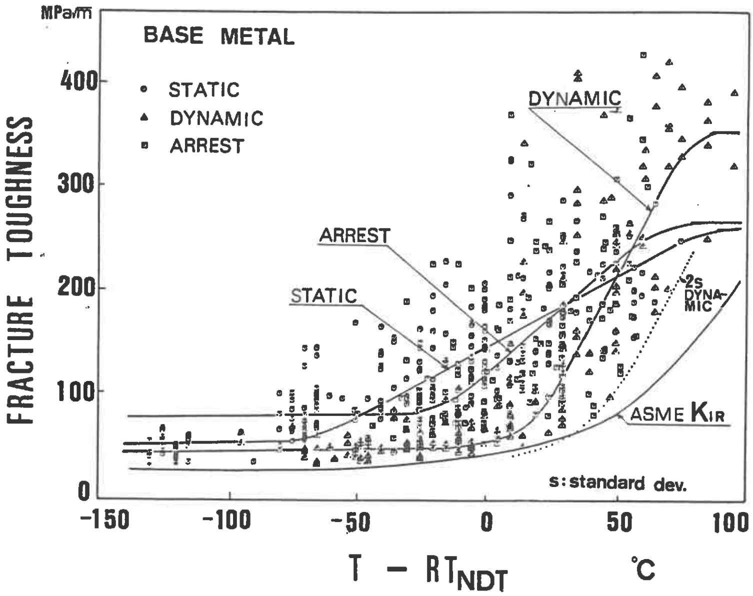

Fig.15 Comparison of the toughness data and ASME K_{IR} curve

The ASME K_{IR} curve was put forward the lowest boundary of fracture toughness(static, dynamic and crack arrest toughness) data. Fig.15 shows the fracture toughness plotted against $T - RT_{NDT}$. It is clear from the figure that all of the data obtained by static, dynamic and crack arrest toughness tests were above the K_{IR} curve, and the lower boundary of the data shows a good agreement with the K_{IR} curve below $T - RT_{NDT} = 50°C$. The ASME K_{IR} curve was found to be the valid reference curve which could be applied to all heats examined in this study. The K_{IR} curve meets well with the lower 2s limits of dynamic fracture toughness below $T - RT_{NDT} = 30°C$ and static fracture toughness below $T - RT_{NDT} = -60°C$. As a result,the K_{IR} curve was a envelope of lower 2s limits of each toughness data.

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