14. New Impact Test and Arrestability of High–toughness 9% Ni Steel

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Summary

Recent steel manufacturing produces 9% Ni steels with high toughness through minimizing impurities in steel and improving heat treatment. These 9% Ni steels show ductile fracture and absorbed energy more than 20 kgf·m in V–Charpy impact test at −196°C, which indicates V–Charpy impact test to be insufficient for the material selection. It is difficult to know the arrestability of these 9% Ni steels through the "surface–notched double tension test" using liquid nitrogen (−196°C) as refrigerant, though the method has been developed to get the arrestability for high–toughness materials.

In this paper the crack arrestability of 9% Ni steels which were varied in toughness was examined by means of surface–notched double tension tests and Charpy impact tests of two specimen types. The former were conducted to check Kca values and the latter were conducted at temperatures ranging −100～−269°C in order to clarify the effect of specimen notch shape on the ductile/brittle transition phenomenon of the high–toughness 9% Ni steels and crack initiation/propagation energy. The following conclusions are obtained.

(1) "Three surface slitted Charpy impact test" is available for the material selection of high–toughness 9% Ni steels because their transition temperature shifts 45～84°C higher than that of V–notched one.

(2) The crack arrestability of 9% Ni steels can be estimated based on the transition temperature and the propergation energy of three surface slitted Charpy impact test.

1. Introduction

The low temperature toughness of 9% Ni steels has recently been improved through the advance of steel–making processes such as reduction of steel impurity and improved heat treatment. For such high–toughness 9% Ni steels, it becomes difficult to know their fracture toughness against the brittle crack initiation and propagation arrest by using the common refrigerant, liquid nitrogen (−196°C). It also becomes difficult to evaluate arrestability by the surface–notched double tension test[1) 2)] (hereinafter referred to as SDT test) which has been developed as the method of crack arrest test for high–toughness materials.

On the other hand, the standard V–notched Charpy impact test under the temperature of liquid nitrogen, which is generally conducted as an industrial toughness evaluation method for 9% Ni steels, is considered insufficient for the material selection, since the absorbed energy in this test exceeds 20 kgf·m in many cases and the fracture mode seldom contains brittle fracture.

This paper describes that crack arrestability can be evaluated from the results of "three surface slitted Charpy impact test", which has been newly developed by using 9% Ni steels varied in toughness deliberately. Three surface slitted Charpy impact test has proved effective as an industrial toughness evaluation test method for recent high–toughness 9% Ni steels.

2. 9% Ni steels Used for Tests

Table 1 shows the mechanical properties of 9% Ni steels used for tests. Their toughness

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Table 1 Mechanical properties of 9% Ni steels used

Steel Code	Thick. (mm)	Mechanical Properties: Tensile Test (at R.T.) 0.2%P.S. (kgf/mm²)	T.S. (kgf/mm²)	El. (%)	V Charpy Impact Test (at −196°C) vE (kgf·m)	Crystallinity (%)
A	32	69	72	28	7.0	75
B	25	71	76	28	19.9	20
C	30	65	74	32	22.3	0
D	32	69	72	30	24.8	0
E	30.5	66	73	24	26.0	0

levels were varied by changing heat treatments and chemical compositions, and their thicknesses were in the range of 25mm to 32mm.

Steel A was produced as a low-toughness steel by adding impurities, P and S, deliberately and Steel B was also produced as a relatively low-toughness steel by adding P. Steels C, D and E were pure 9% Ni steels with an extremely low amount of P and S.

3. Evaluation of Arrestability of 9% Ni steels by SDT Test

Fig. 1 shows the dimensions of SDT test specimen[2]. In the SDT tests of 9% Ni steels the surface-notched part (crack initiating part) of the specimen was cooled down to −196°C by liquid nitrogen and the temperature was kept constant while testing, the crack propagation line being also cooled in the condition of either constant or gradual temperature.

Fig. 2 shows the SDT test results of five kinds of 9% Ni steel plates. The brittle crack arrest toughness Kca is calculated by Equation (1).

$$K_{ca}=F_p\cdot\sigma\sqrt{\pi a}\cdot\sqrt{(2W/\pi a)\cdot\tan(\pi a/2W)}\quad (kgf/mm^{3/2}) \qquad (1)$$

where F_P: correction factor taking account of load reduction due to crack propagation[2)]

σ: applied stress (kgf/mm²)

W: width of crack propagation zone (mm)

a: length of arrested crack [effective length of crack in case of a test specimen having W of 1000 mm ($a_{eff.}=0.1a+190$)][2)3)] (mm)

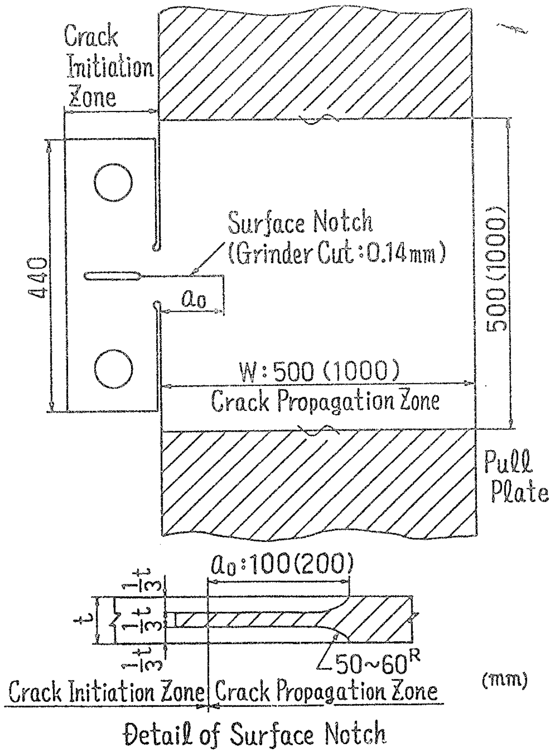


Fig. 1 Shape of surface-notched double tension test specimen

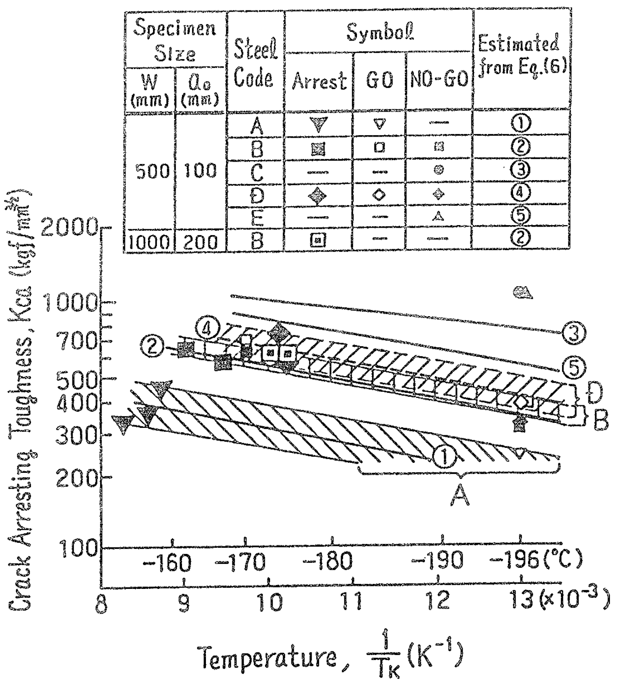


Fig. 2 Relation between Kca value and temperature (comparison between experimental and estimated value)

For Steels A and B which showed brittle fracture in their standard V-notched Charpy impact tests at −196°C (see Table 1), SDT test was effective in evaluating their arrestability. On the other hand for Steels C, D and E which showed no brittle fracture and exhibited good toughness in the V-Charpy test at −196°C their arrestability shows different properties. The arrestability of Steel D was evaluated to be similar to that of Steel B. The arrestability of Steels C and E was difficult to evaluate quantitatively even by SDT test at −196°C.

For 9% Ni steels, the V-Charpy impact test at −196°C is conducted as the common material receiving test specified by JIS. As shown in Table 1 and Fig. 2, V-Charpy impact test at −196°C can evaluate a low-toughness steel like Steel A, however, it is insufficient to judge arrestability of a steel with higher toughness than that of Steel B.

4. Low Temperature Impact Characteristics of High-toughness 9% Ni Steels

4.1 Shape Effect of Test Specimen on Ductile/Brittle Transition Phenomenon

A newly developed three surface slitted Charpy impact test was conducted to know the ductile/brittle transition phenomenon of 9% Ni steels at low temperature. Fig. 3 shows the test specimen dimensions compared with those of V-Charpy impact test. This specimen has three slits, one of which is 0.14mm in width, replacing 2mm deep V-notch and the other two are 0.14 mm wide in each side. To examine the effect of specimen shape on the fracture mode, the depth of side slits were varied from 0 to 2.5mm. Consequently as 2S(2) type test specimen whose side slits were 2mm in depth was proved to be most effective to know the ductile/brittle transition phenomenon, it was selected for this experiment.

2S(2) type three surface slitted Charpy impact tests and V-notched Charpy impact tests (2V) were conducted under the low temperature in the range of −100°C to −269°C. Table 2 and Fig. 4 show the test results and the examples of transition curves. vE and sE show the absorbed energy by 2V and 2S(2)

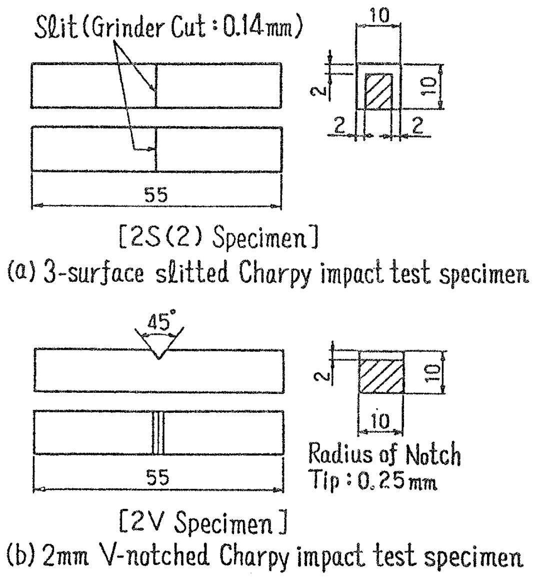


Fig. 3 Shape of Charpy impact test specimens

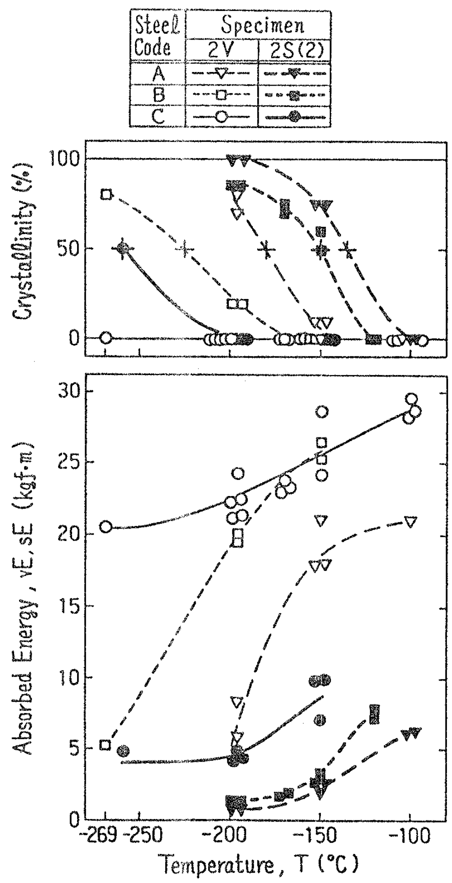


Fig. 4 Comparison of transition curves between 3-surfaces slitted and V-notched Charpy impact tests

Table 2 Results of Charpy impact test

Steel Code	Thick. (mm)	Absorbed Energy at −196°C (kgf·m)		Transition Temperature (°C)		
		vE [2V]	sE [2S(2)]	vTrs [2V]	sTrs [2S(2)]	ΔTrs (1)
A	32	7.0	0.7	−180	−135	45
B	25	19.9	1.2	−225	−150	75
C	30	22.3	4.4	—	−259	—
D	32	24.8	1.8	−269	−185	84
E	30.5	26.0	3.3	—	−196	—

(1) ΔTrs = sTrs − vTrs

impact tests respectively. These impact tests at the temperature of liquid helium were conducted insulating with foam polystyrene sheets after the preliminary cooling by liquid nitrogen. The temperature were detected by the thermo—couple of gold/iron—chromel. It was confirmed that the foam insulating sheet had little effect on the absorbed energy.

In 2V impact tests at the temperature of liquid nitrogen (−196°C), ductile/brittle transition was observed only on Steel A which showed brittle fracture of more than 50%. Steels B and D showed the transition at the extremely low temperature such as liquid helium. Steels C and E showed no transition even at the liquid helium temperature.

On the other hand in 2S(2) impact tests the transition phenomena were observed on all the four kinds of steel plates except Steel C above the liquid nitrogen temperature, and as for Steel C the same was observed when the temperature went down to that of liquid helium.

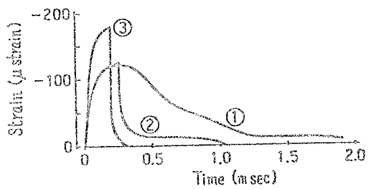
It is clarified from the tests that due to the notch acuity and side slits restraint, the transition temperature sTrs obtained by 2S(2) impact tests is 45–84°C higher than vTrs by 2V impact tests. The absorbed energy at −196°C (sE_{-196}) of 2S(2) impact tests coincides with the grade of arrestability in SDT test and its sTrs is available within the temperature up to −196°C because of its shift to the higher temperature range. Consequently the three surface slitted Charpy impact tests is effective as an industrial toughness evaluation method for high—toughness 9% Ni steels.

4.2 Phenomenon of Fracture in Extremely Low Temperature Charpy Impact Test

The transient strain of impact hammer was measured in the former impact tests. Fig. 5 shows the hammer strain transient curves. Hammer strain rises immediately after the hammering on the specimen. In both 2S(2) and 2V impact tests the strain reaches its maximum value and then gradually decreases when ductile fracture occurs. On the other hand if brittle fracture is included, the strain rapidly falls in the midst of its rise.

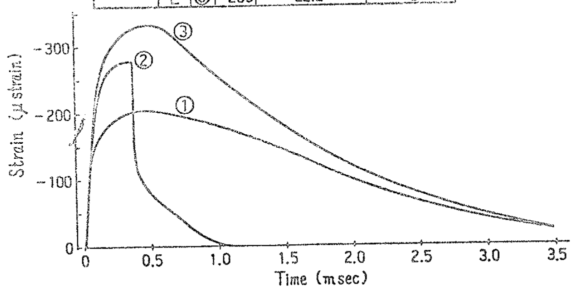
The maximum hammer strain at the liquid helium temperature (−269°C) was 40–60% greater than the strain at the higher temperature. This phenomenon is considered to be caused by the enhancement of strength of 9% Ni steel under extremely low temperature. Therefore the absorbed energy of Steels C and

Specimen	Steel Code	No.	Temp. (°C)	Absorbed Energy sE (kgf·m)	Crystallinity (%)
2S(2)	E	①	−150	7.4	0
		②	−196	3.2	55
		③	−269	3.8	80



(a) 3-surfaces slitted Charpy impact test

Specimen	Steel Code	No.	Temp. (°C)	Absorbed Energy vE (kgf·m)	Crystallinity (%)
2V	D	①	−196	22.6	0
		②	−269	8.5	50
	E	③	−269	22.2	0



(b) 2mm V-notched Charpy impact test

Fig. 5 Hammer strain—time curves in Charpy impact test result

E at the liquid helium temperature had almost the same value as the one obtained under ductile fracture at liquid nitrogen temperature, though brittle fracture was included 50% or even more. In the case of ordinary ferritic and martensitic steels, the transition temperature of fracture appearance almost coincides with that of energy transition because transition occurs in the temperature region without notable enhancement of strength. Such transition phenomenon that does not entail a fall in energy can be said to be the characteristics of high–toughness materials like 9% Ni steels. However, it is thought that in this temperature zone this transition phenomenon is also influenced by complicated phenomena such as temperature rise due to plastic deformation and transformation of residual austenite to strain induced martensite[4)–6)].

Fig. 6 shows the fractography by scanning electron microscope of 2S(2) and 2V impact specimens conducted in the liquid helium temperature test of Steel E. The 2V specimen shows dimple pattern all over characterizing ductile fracture. On the other hand 2S(2) specimen shows about 80% of brittle fracture. Microscopically the fracture surface is composed of quasi–cleavage facets which characterize brittle fracture and fine dimples which connect these facets. Such fine dimples in brittle fracture prove the existence of stable residual austenite phase derived from ununiformed distribution of nickel[7)], making 9% Ni steel superior in low temperature toughness.

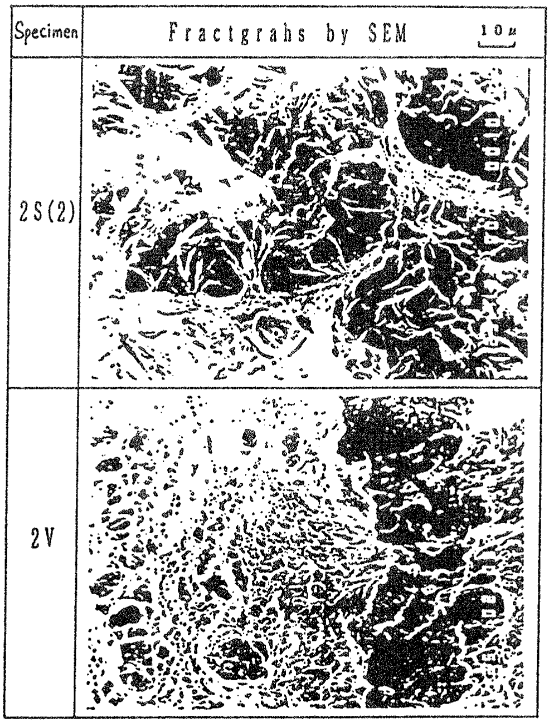


Fig. 6 Fractographs of 3–surface slitted and V–notched Charpy impact test specimens (Steel E at –269°C)

5. Proposal of Expedient Evaluation Method of Arrestability for High–toughness 9% Ni Steels

5.1 Estimation of Arrestability by Transition Temperature of Three Surface Slitted Charpy Impact Test

For high–toughness 9% Ni steels the ductile/brittle transition phenomenon, which seldom occurs in the usual 2V impact test, occurs by the application of 2S(2) impact test. The relation between fracture transition temperature (sTrs) and brittle crack arrestability was examined on the 2S(2) impact test results.

Fig. 7 shows the relation among sTrs, $T_{Kca=400}$ and $T_{Kca=600}$ of steels A, B and D. $T_{Kca=400}$ and $T_{Kca=600}$ are the temperatures at which the Kca value converted to the ability for 30mm thick plate is equal to 400 and 600 $kgf/mm^{3/2}$ respectively. Equations (2), (3) and (4) are used in the conversion of Kca values. Kca value for any plate thickness (t mm) is expressed as Equation (2).

$$Kca(t) = Ko \exp(-ko/T_K) \ (kgf/mm^{3/2}) \quad (2)$$

where Ko and ko : material constants
T_K : temperature (K)

Kca (t=30mm) value at the temperature T_K can be expressed by Equations (3) and (4).

$$Kca(t=30mm) = \{Ko/f(t)\} \exp(-ko/T_K) \ (kgf/mm^{3/2}) \quad (3)$$

where f(t) : coefficient of thickness effect[8)]

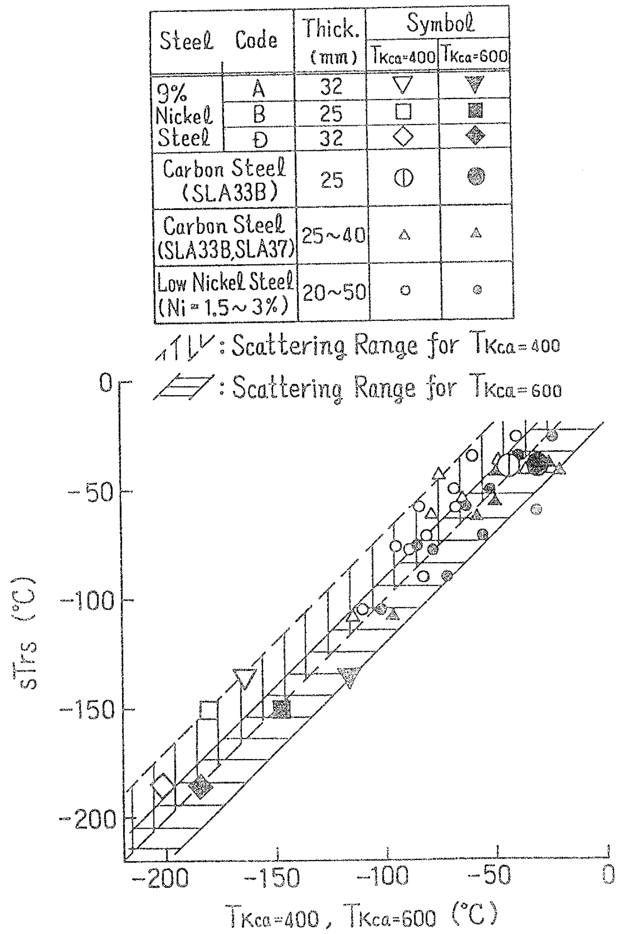


Fig. 7 Relation between sTrs and critical temperature for crack arrest [$T_{Kca=400}$, $T_{Kca=600}$ (t=30mm)]

$$f(t)=\begin{cases}1-0.05(t-30) & : t\leqq 35\text{mm}\\(54/65)-(3t/1300) & : 35\text{mm}<t\leqq 100\text{mm}\end{cases} \qquad (4)$$

The results of the same analysis of carbon steels and low-nickel steels for low temperature service is also shown in Fig. 7.

It is obvious that good relationship exists between arrestability and the transition temperature sTrs obtained by three surface slitted Charpy impact tests. Therefore Equation (5) can be proposed as an arrestability estimation method for high-toughness 9% Ni steels by means of sTrs.

$$\begin{aligned}T_{Kca(t=30)=400}&=({}_sT_{rs}-12)\pm 14 \quad (^\circ C)\\T_{Kca(t=30)=600}&=({}_sT_{rs}-\ 7)\pm 14 \quad (^\circ C)\end{aligned} \qquad (5)$$

5.2 Estimation of Arrestability from Absorbed Energy

Hammering strain transient curves in Charpy impact tests differ greatly in the fracture mode as to whether brittle fracture is included or not. In both cases fracture takes place through the process of notch bottom deformation, crack initiation and propagation. The first phase of crack initiation and stable crack development accompanied by increasing fracture resistance can be called as "initiation stage" and the second phase of crack unstabilization as "propagation stage" where material can no more resist crack propagation and fracture resistance decreases[9) 10)]. The transient hammer strain features due to the fracture mode difference were clearly observed in the propagation stage. Fracture resistance decreases gradually in ductile fracture and rapidly in brittle fracture.

The arrestability of high-touhness 9% Ni steels was analyzed in view of the absorbed energy in the propagation stage which clearly showed the transition phenomenon. Fig. 8 shows the relation between the absorbed energy and the integrated area of hammer strain-time curves obtained in the Charpy

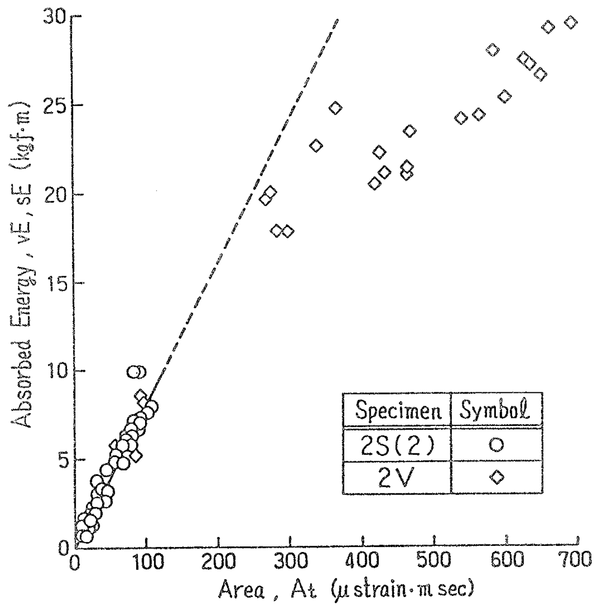


Fig. 8 Relation between absorbed energy and integrated area of hammer strain-time curve in Charpy impact test result

impact tests. They are proportional to each other when the absorbed energy is relatively small. When the absorbed energy is 10 kgf·m using the impact testing machine of 30 kgf·m in capacity, the hammer speed is estimated to be reduced to about 82% of the initial speed after the breaking of specimen. Since the absorbed energy was less than 10 kgf·m in the case of 2S (2) impact tests, crack initiation/propagation energy can be estimated within the error of about 10% from the integrated area of hammer stain–time curves. Accordingly the integrated area of strain is said to be almost proportional

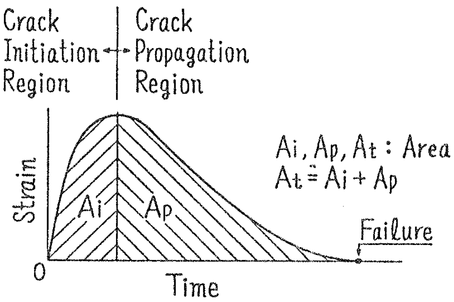


Fig. 9 Schematic diagram of hammer strain transient

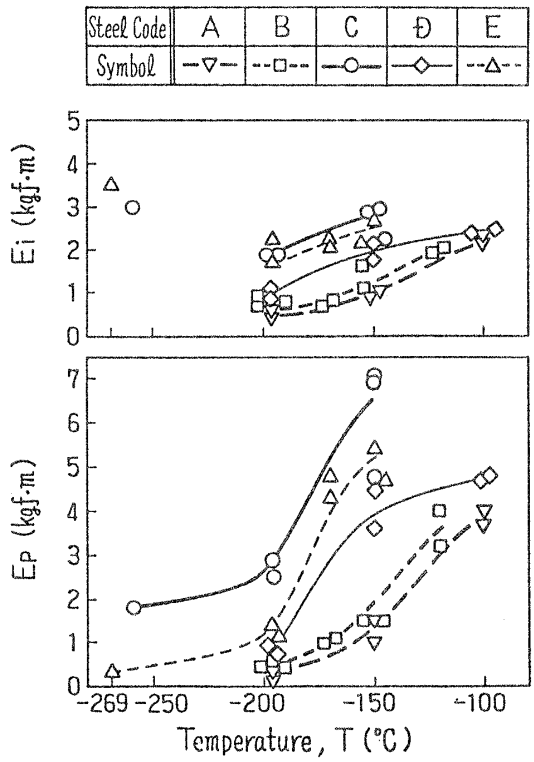


Fig. 10 Energy transition curves of crack initiation propagation in 3–surface slitted Charpy impact test result

to the work done in the process of specimen breaking and eventually proportional to the absorbed energy. Applying this relation, the absorbed energy were separated into the crack initiation energy (Ei) and the propagation energy (Ep) in accordance with the area ratio shown in Fig. 9. Fig. 10 shows the Ei/Ep transition curves of five kinds of 9% Ni steel. Ep shows the transition more clearly compared with Ei. Under extremely low temperature of liquid helium, Ei increases remarkably, differentiating it from the usual transition phenomena, which is thought to be due to the strength enhancement in this temperature range.

Fig. 11 shows the relation between the crack propagation energy Ep and Kca values for Steels A, B, and D as well as the result of carbon steel for low temperature service (JIS SLA33B). Kca values here were converted for 30mm thick plate by using Equations (3) and (4). Equation (6) clearly shows the existence of the relation between Ep and the converted Kca for three kinds of 9% Ni steel with different toughness levels.

$$Kca\,(t=30\text{mm}) = 450\,E_P^{0.5}\,(\text{kgf/mm}^{3/2}) \quad (6)$$

where E_P : crack propagation energy (kgf·m)

The arrestability of 9% Ni steel, that is Kca value, can be estimated by Equation (6). The relation between the temperature and Kca values estimated from Ep was compared with that obtained by SDT tests in Fig. 2. Both

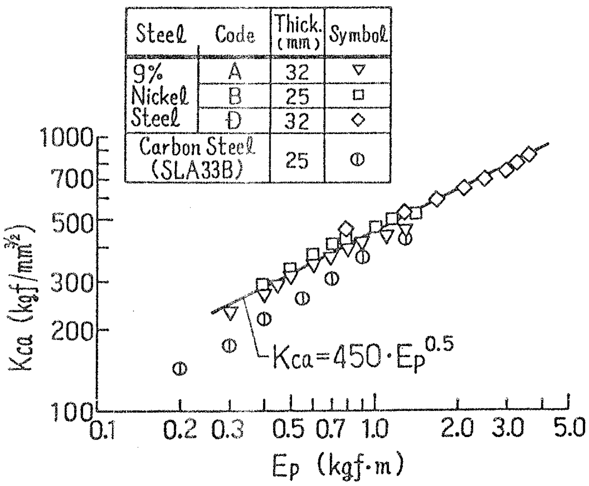


Fig. 11 Relation between Kca and Ep

coincide well for Steels A, B and D.

6. Conclusion

Three surface slitted Charpy impact tests are proposed in order to know the arrestability of high–toughness 9% Ni steel. Various estimation methods were considered based on the results of three surface slitted Charpy impact tests, using 9% Ni steels whose toughness levels were deliberately varied.

(1) Toughness evaluation for the recently developed 9% Ni steels based on the standard V–notched Charpy impact test is insufficient and the application of three surface slitted Charpy impact test is effective.

(2) Though the surface–notched double tension test (SDT) is effective to obtain the arrestability of usual high–toughness materials, it is still difficult for recent high–toughness 9% Ni steels to identify Kca values at the liquid nitrogen temperature.

(3) Equations (5) and (6) are proposed as formulae to estimate crack arrestability of high–toughness 9% Ni steels based on the result of the three surface slitted Charpy impact test.

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