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THE STRAIN RATE CONCENTRATION FACTOR FOR ROUND AND FLAT TEST SPECIMENS

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Abstract. In this study, the strain rate concentration is considered for high speed tensile test, which is now being recognized as a standard testing method. To evaluate the impact strength of engineering materials, Izod and Charpy tests are unsuitable since they cannot control the impact speeds and therefore the testing results do not coincide with the real failure of real products. For smooth specimens, the strain rate can be determined from the tensile speed u/t and specimen length l as $\dot{\epsilon}_{smooth} = u/tl$. For notched specimens, however, the strain rate at the notch root $\dot{\epsilon}_{notch}$ should be analyzed accurately. In this study, therefore, the strain rate concentration factor defined as $K_{t\dot{\epsilon}} = \dot{\epsilon}_{notch}/\dot{\epsilon}_{smooth}$ is studied with varying the notch geometry and specimen length for round and flat test specimens. In particular, the relationship between the strain rate concentration factor and the stress concentration factor is investigated by varying the notch geometry and specimen length.

Keywords: notch fracture, high speed tensile test, strain rate concentration factor, stress concentration factor

1. Introduction

Charpy and Izod tests are widely used to investigate the impact property of structural materials [1-4]. The strength of engineering materials varies depending on the temperature and impact speed, especially known as the brittle–ductile transition behavior. Charpy impact test provides the absorbed energy under different temperature; however, the results are not closely related to the tensile properties such as tensile strength, yield strength and fatigue strength used in machine design. Moreover, Charpy impact speed does not correspond to the real failure of the real products. By considering those disadvantages, the high-speed tensile test is now being recognized as the standard impact strength test. Several researchers were focusing on high speed deformation [5-8]. In our previous studies, the tensile strength can be discussed through notched flat and round bar specimens under different tensile speed and temperature [9,10].

Previous studies suggested that the strain rate at the notch root may control the brittle–ductile transition behavior [11-16]. In the high speed tensile testing, it is therefore necessary to know the strain rate at the notch root accurately. Since it is almost impossible to measure the strain rate at the notch root experimentally, the strain rate concentration factor should be investigated analytically.

Previously the authors have proposed that the stress concentration factor formulas useful for arbitrary notch dimensions in notched specimens [17-23]. Regarding the strain rate concentration factor, however, the notch shape effects have not been clarified yet. In this paper, therefore, the strain rate concentration factor will be studied by varying the notch

geometry. Then, the effects of notch root radius and notch depth on the strain rate concentration factor will be discussed. Finally, the relationship between the strain rate concentration factors and the previously studied stress concentration factors [17-23] will be clarified to evaluate the impact strength of engineering materials conveniently.

2. Definition of the strain rate concentration factor

The strain rates in notched and smooth specimen (Fig. 1 (a),(b)) $\dot{\epsilon}_{notch}, \dot{\epsilon}_{smooth}$ increase with increasing the tensile speed. However, the ratio $K_{t\dot{\epsilon}} = \dot{\epsilon}_{notch} / \dot{\epsilon}_{smooth}$ is always constant independent of the tensile speed.

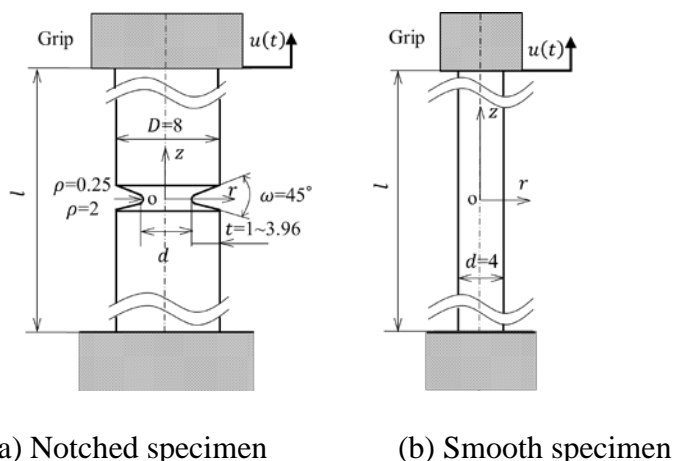


Fig. 1. Geometry of specimens (Dimensions: mm)

Since the strain rate in smooth specimen is expressed in equation (1), the strain rate at the notch root can be obtained from the tensile speed $u(t)/t$ and the strain rate concentration factor $K_{t\dot{\epsilon}}$ (see Equation (2)). Here, $u(t)$ is the displacement applied to the specimen end, which is assumed to be proportional to the time t .

$$\dot{\epsilon}_{smooth} = \frac{u(t)/l}{t} \tag{1}$$

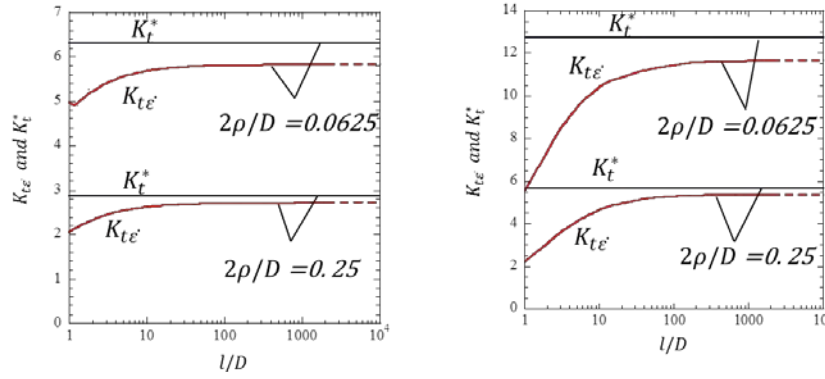
$$K_{t\dot{\epsilon}} = \frac{\dot{\epsilon}_{notch}}{\dot{\epsilon}_{smooth}}$$

$$\dot{\epsilon}_{notch} = K_{t\dot{\epsilon}} \cdot \dot{\epsilon}_{smooth} = K_{t\dot{\epsilon}} \cdot \frac{u(t)/l}{t} \tag{2}$$

In our recent study, the validity of elastic strain rate concentration was confirmed by using the elastic-plastic analysis for polymeric materials [23]. In our previous study [10], the relationship between the tensile speed and the strain rate was also considered. Then, it was found that the strain rate is proportional to the tensile speed when $u(t)/t \leq 5000\text{mm/s}$. This is related to the fact that stress wave propagation speed is equal to the sonic wave propagation speed [10]. The present results may be useful for this range where linear relationship is confirmed. In this study, since the strain rate is considered at the $u(t)/t=20\text{mm/s}$ much smaller than the sonic speed in metals [24], the wave propagation effect can be neglected.

3. Effect of specimen length on the strain rate concentration factor

It is known that the net stress concentration factor K_t is independent of the specimen length l if $l/D \geq 1$ in Fig.1 (a). However, different from the net stress concentration factor K_t , the strain rate concentration factor $K_{t\dot{\epsilon}}$ is depending on the specimen length l/D .



(a) $K_{t\dot{\epsilon}}$ and K_t^* for specimen which $t=1$ (b) $K_{t\dot{\epsilon}}$ and K_t^* for specimen which $t=2$

Fig. 2. Strain rate concentration factor $K_{t\dot{\epsilon}}$ and gross stress concentration factor K_t^* ($K_t^* = K_t \cdot (D/d)^2$) under different length in Fig. 1(a)

Table 1. Stress concentration factor under different length ($D=8\text{mm}$ in Fig.1(a))

l/D	$l(\text{mm})$	$t=0.0625\text{mm}$ ($2t/D=0.015625$)		$t=0.25\text{mm}$ ($2t/D=0.0625$)		$t=1\text{mm}$ ($2t/D=0.25$)		$t=2\text{mm}$ ($2t/D=0.5$)	
		$\rho = 0.25\text{mm}$ ($2\rho/D=0.0625$)	$\rho = 2\text{mm}$ ($2\rho/D=0.25$)	$\rho = 0.25\text{mm}$ ($2\rho/D=0.0625$)	$\rho = 2\text{mm}$ ($2\rho/D=0.25$)	$\rho = 0.25\text{mm}$ ($2\rho/D=0.0625$)	$\rho = 2\text{mm}$ ($2\rho/D=0.25$)	$\rho = 0.25\text{mm}$ ($2\rho/D=0.0625$)	$\rho = 2\text{mm}$ ($2\rho/D=0.25$)
K_t									
all		1.944	1.295	2.697	1.518	3.553	1.615	3.185	1.420
$K_t^* = K_t \cdot (D/d)^2$									
all		2.006	1.336	3.069	1.727	6.316	2.871	12.740	5.680
$K_{t\dot{\epsilon}}/K_t$									
5	40	0.992	1.012	1.105	1.092	1.569	1.581	2.992	2.921
$K_{t\dot{\epsilon}}/K_t^*$									
5	40	0.962	0.980	0.971	0.960	0.883	0.889	0.748	0.730

Under fixed maximum specimen diameter $D=8\text{mm}$, the strain rate concentration factor $K_{t\dot{\epsilon}}$ is calculated by varying the specimen length l . Figure 2 shows the results for the relative notch radius $2\rho/D = 0.0625$, $2\rho/D = 0.5$ and the relative notch depth $2t/D = 0.25$, $2t/D = 0.5$ by varying the relative specimen length $l/D = 1 \sim 2560$.

Figure 2 compares the strain rate concentration factor $K_{t\dot{\epsilon}}$ and the gross stress concentration factor K_t^* by varying the relative specimen length l/D . Table 1 shows the net stress concentration factor K_t and the gross stress concentration factor $K_t^* = K_t \cdot (D/d)^2$ under different specimen length. The net stress concentration factor K_t is usually defined as $K_t = \sigma_{max}/\sigma_{net}$ as shown in equation (3) based on the net nominal stress $\sigma_{net} = 4P/\pi d^2$. The gross stress concentration factor K_t^* is defined as shown in equation (4) based on the gross tensile stress $\sigma_{gross} = 4P/\pi D^2$.

$$K_t = \frac{\sigma_{max}}{\sigma_{net}} \quad (3)$$

$$K_t^* = \frac{\sigma_{max}}{\sigma_{gross}} = K_t \cdot \left(\frac{D}{d}\right)^2, \quad \sigma_{gross} = \sigma_{net} \cdot \left(\frac{d}{D}\right)^2 \quad (4)$$

In Figure 2, it is seen the results for $2\rho/D = 0.0625$ is always larger than the results for $2\rho/D = 0.5$ and varies depending on $2t/D$ similar to the gross stress concentration factor K_t^* . Although the gross stress concentration factor K_t^* is constant independent of the specimen

length, the strain rate concentration factor $K_{t\dot{\epsilon}}$ increases with the increasing specimen length l , and becomes constant.

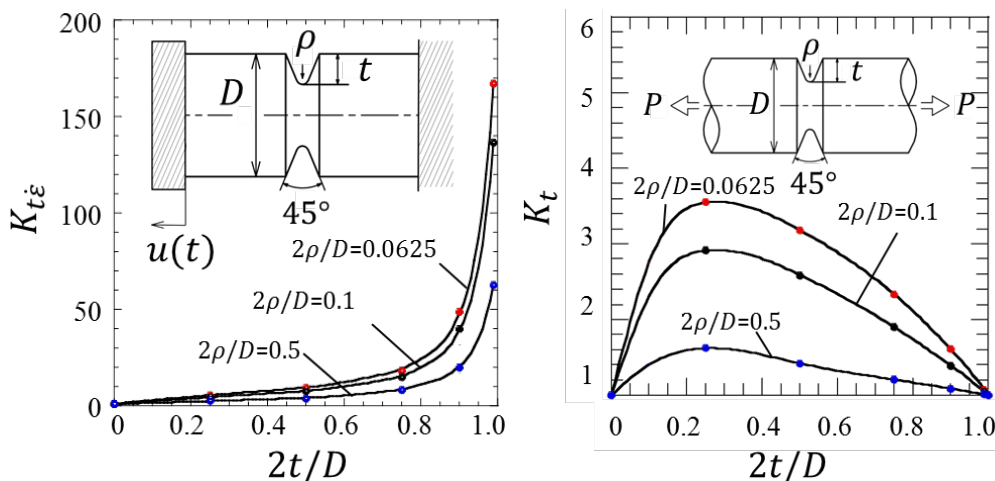
4. Relationship between the strain rate concentration factor and the stress concentration factor

The specimen length $l=40\text{mm}$ and the diameter $D=8\text{mm}$ are assumed in this chapter. The results of the strain rate concentration factor $K_{t\dot{\epsilon}}$ are shown in Fig. 3 by varying the relative notch depth $2t/D$ for fixed relative notch radius $2\rho/D = 0.0625$ and $2\rho/D = 0.5$. Here, $2\rho/D = 0.0625$ corresponds to the notch radius $\rho=0.25\text{mm}$ of the specimen used in the Charpy impact test. Also, $\rho=2\text{mm}$ with $D=8\text{mm}$ corresponds to the sharpest case of the notch root radius when high Si ductile cast iron is used as structural components [9]. As shown in Fig. 3(a), the strain rate concentration factor increases with increasing the relative notch depth. The same results are also indicated in Fig. 3(b).

The net stress concentration factor K_t is usually defined as $K_t = \sigma_{max}/\sigma_{net}$ based on the net nominal stress $\sigma_{net} = 4P/\pi d^2$. Since $\sigma_{net} \rightarrow \infty$ as $2t/D \rightarrow 1$, $K_t \rightarrow 1$ as $2t/D \rightarrow 1$. Under a fixed value of $2\rho/D$, the results of $2t/D=0$ correspond to the smooth specimen without notch.

Figure 4 shows the ratio $K_{t\dot{\epsilon}}/K_t$ vs. the relative notch depth $2t/D$. When the relative notch depth $2t/D \rightarrow 1$, the ratio $K_{t\dot{\epsilon}}/K_t \rightarrow \infty$. Here, the net stress concentration factor K_t is defined as equation (3) from the maximum stress σ_{max} and the net nominal stress σ_{net} at the minimum cross section. When the relative notch depth $2t/D \rightarrow 1$, the strain rate concentration factor $K_{t\dot{\epsilon}} \rightarrow \infty$ but the net stress concentration factor $K_t \rightarrow 1$. Therefore, the gross stress concentration factor K_t^* is defined as equation (4) from the maximum stress σ_{max} and the gross tensile stress σ_{gross} . When the relative notch depth $2t/D \rightarrow 1$, the strain rate concentration factor $K_t^* \rightarrow \infty$.

Then, the relationship between the strain rate concentration factor $K_{t\dot{\epsilon}}$ and the gross stress concentration factor K_t^* investigated.



(a) Relationship between $K_{t\dot{\epsilon}}$ and $2t/D$ when $l/D=5$ ($l=40\text{mm}$, $D=8\text{mm}$) (b) Relationship between K_t and $2t/D$ when $l/D=5$ ($l=40\text{mm}$, $D=8\text{mm}$)

Fig. 3. $K_{t\dot{\epsilon}}$ vs. $2t/D$ and K_t vs. $2t/D$ when $l/D=5$ ($l=40\text{mm}$, $D=8\text{mm}$)

Figure 5 shows the relationship between the ratio $K_{t\dot{\epsilon}}/K_t^*$ and the relative notch depth $2t/D$. It is found that the value of $K_{t\dot{\epsilon}}/K_t^*$ is almost the same for $2\rho/D = 0.0625$ and $2\rho/D = 0.5$ when the relative notch depth $2t/D \leq 0.5$. From Fig. 5, it is found that the value of $K_{t\dot{\epsilon}}/K_t^*$ is insensitive to the notch root radius in the range of $2t/D \leq 0.5$. By using this fact,

the strain rate concentration factor $K_{t\dot{\epsilon}}$ can be estimated from the gross stress concentration factor K_t^* .

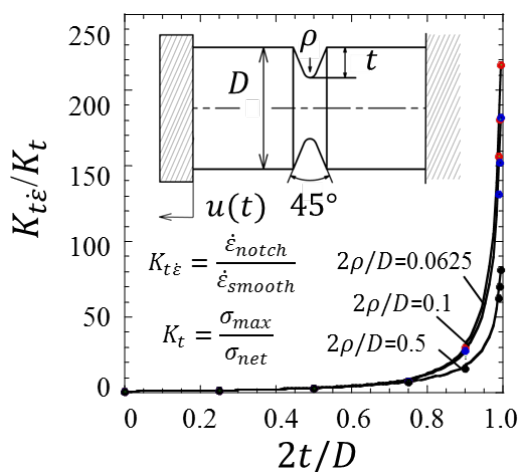


Fig.4. Relationship between $K_{t\dot{\epsilon}}/K_t$ and $2t/D$ when $l/D=5$ ($l=40\text{mm}$, $D=8\text{mm}$)

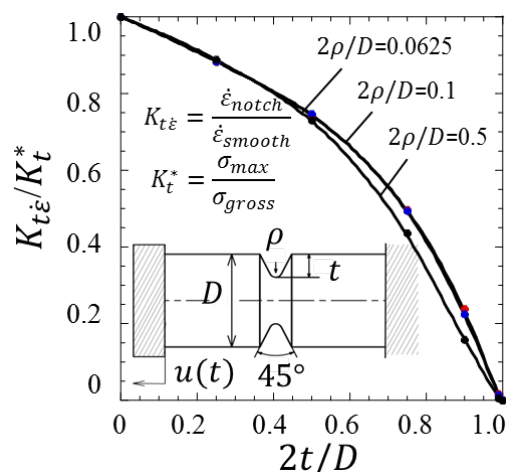


Fig.5. Relationship between $K_{t\dot{\epsilon}}/K_t^*$ and $2t/D$ when $l/D=5$ ($l=40\text{mm}$, $D=8\text{mm}$)

5. Conclusions

In this paper, the strain rate concentration at the notch root is considered in the high speed tensile test which is now replacing Charpy impact test. In particular, the relationship between the strain rate concentration factor and the stress concentration factor was investigated by varying the notch geometry and specimen length. After summarizing the results in Tables and Figures, the following conclusions were obtained.

- (1) The strain rate concentration factor $K_{t\dot{\epsilon}}$ was defined as the ratio of the strain rate in notched specimen to the strain rate in smooth specimen. Then, the maximum strain rate $\dot{\epsilon}$ at the notch root can be obtained easily from the strain rate concentration factor.
- (2) Different from the stress concentration factor K_t independent of the specimen length, the strain rate concentration factor $K_{t\dot{\epsilon}}$ increases with increasing the specimen length and then become constant as shown in Fig. 2.
- (3) It is found that the value of $K_{t\dot{\epsilon}}/K_t^*$ is almost the same independent of the notch root radius when the relative notch depth $2t/D \leq 0.5$. By using this relationship, the strain rate concentration factor $K_{t\dot{\epsilon}}$ can be determined from the stress concentration factor K_t .

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References

- [1] Roebben G, Lamberty A, Pauwels J. Certification of Charpy V-notch reference test pieces at IRMM. *Impact Mach. Proced. Specimens*. 2006;1476: 40-48.
- [2] Seo K, Masaki J. Physical interpretation for the upper shelf energy of weld zone in charpy impact test. *Trans. Japan Weld. Soc.* 1982;51(3): 291-297. (In Japanese)
- [3] Tanguy B, Besson J, Piques R, Pineau A. Ductile to brittle transition of an A508 steel characterized by Charpy impact test: Part II: modeling of the Charpy transition curve. *Eng. Fract. Mech.* 2005;72(5): 413-434.
- [4] Wang CM, Splett JD. Uncertainty in reference values for the Charpy v-notch verification program. *J. Test. Eval.* 2005;34(3): 1-4.
- [5] Bragov A, Konstantinov A, Kruszka L, Lomunov A, Filippov A. Dynamic properties of stainless steel under direct tension loading using a simple. *EPJ Web of Conferences*. 2018;183: 02035.

- [6] Petrov YV, Bragov AM, Kazarinov NA, Evstifeev AD. Experimental and numerical analysis of the high-speed deformation and erosion damage of the titanium alloy VT-6. *Physics of the Solid States*. 2017;59(1): 93-97.
- [7] Bragov AM, Donstatinov AY, Kruszka L, Lomunov AK. Behavior of stainless steel at high strain rates and elevated temperatures. Experiment and mathematical modelling. *Materials Physics and Mechanics*. 2018;40(2): 133-145.
- [8] Magazinov SG, Krivosheev SI, Adamyan YE, Alekseev DI, Titkov VV, Chernenkaya LV. Adaptation of the magnetic pulse method for conductive materials testing. *Materials Physics and Mechanics*. 2018;40(1): 117-123.
- [9] Ando M, Noda NA, Kuroshima Y, Ishikawa Y, Takeda H. Impact properties of polydimethylsiloxane copolymerized polycarbonate and application of the time-temperature superposition principle. *Trans. Japan Soc. Mech. Eng.* 2014;80(814): SMM0310. (In Japanese)
- [10] Noda NA, Ohtsuka H, Zheng H, Sano Y, Ando M, Shinozaki T, Guan W. Strain rate concentration and dynamic stress concentration for double-edge-notched specimens subjected to high-speed tensile loads. *Fatigue Fract. Eng. Mater. Struct.* 2015;38(1): 125-138.
- [11] Bennett PE, Sinclair GM. Parameter representation of low-temperature yield behavior of body-centered cubic transition metals. *J. Basic Eng.* 1966;88(2): 518-524.
- [12] Fujii M, Ohkuma E, Kawaguchi I, Tsukamoto Y. Effects of temperature and strain rate on dynamic fracture toughness of steel. *J. Soc. Nav. Archit. Japan*. 1985;1985(158): 619-629. (In Japanese)
- [13] Ikeda T, Umetani T, Kai N, Ogi K, Noda NA, Sano Y. Influence of silicon content, strain rate and temperature on toughness and strength of solid solution strengthened ferritic ductile cast iron. *Mater. Trans.* 2016;57(12): 2132-2138. (In Japanese)
- [14] Minami N, Hashida F, Toyoda T, Morikawa M, Ohmura J, Arimochi T, Konda K. Dynamic fracture toughness evaluation of structural steels based on the local approach. *J. Soc. Nav. Archit. Japan*. 1998;1998(184): 453-464. (In Japanese)
- [15] Yamamoto H, Kobayashi H, Fujita T. Strain rate dependency of ductile-brittle transition behavior in ductile cast iron. *J. Japan Foundry Eng. Soc.* 2000;72(2): 107-112. (In Japanese)
- [16] Yamamoto H, Kobayashi H, Fujita T. Strain rate-temperature dependency of impact tensile properties and ductile fracture behavior in ductile cast iron. *Tetsu-to-Hagane*. 1999;85(10): 765-770. (In Japanese)
- [17] Noda NA, Takase Y. *Fatigue Notch Strength Useful for Machine Design*. Nikkan Kogyo Shimbun Ltd.; 2010. (In Japanese)
- [18] Noda NA, Takase Y. Stress concentration factor formulas useful for all notch shapes in a flat test specimen under tension and bending. *J. Test. Eval.* 2002;30(5): 369-381.
- [19] Noda NA, Takase Y. Generalized stress intensity factors of V-shaped notch in a round bar under torsion, tension, and bending. *Eng. Fract. Mech.* 2003;70(11): 1447-1466.
- [20] Nishitani H, Noda NA. Stress concentration of a cylindrical bar with a V-shaped circumferential groove under torsion, tension or bending. *Eng. Fract. Mech.* 1984;20(5-6): 743-766.
- [21] Noda NA, Takase Y. Stress concentration formula useful for all notch shape in a round bar (comparison between torsion, tension and bending). *Int. J. Fatigue*. 2006;28(2): 151-163.
- [22] Noda NA, Takase Y, Monda K. Stress concentration factors for shoulder fillets in round and flat bars under various loads. *Int. J. Fatigue*. 1997;19(1): 75-84.
- [23] Noda NA, Takaki R, Shen Y, Inoue A, Sano Y, Akagi D, Takase Y, Galvez P. Strain rate concentration factor for flat notched specimen to predict impact strength for polymeric materials. *Mech. Mater.* 2019;131: 141-157.
- [24] *National Astronomical Observatory of Japan. Chronological scientific Tables*. Maruzen Publishing; 2019. (In Japanese)