Materials Physics and Mechanics 42 (2019) 522-527 Received: October 6, 2018

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 $\dot{\varepsilon}_{smooth} = u/tl$. For notched specimens, however, the strain rate at the notch root $\dot{\varepsilon}_{notch}$ should be analyzed accurately. In this study, therefore, the strain rate concentration factor defined as $K_{t\dot{\varepsilon}} = \dot{\varepsilon}_{notch}/\dot{\varepsilon}_{smooth}$ 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.

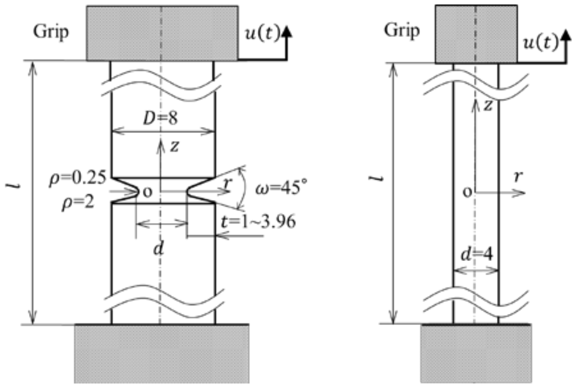
Previously the authors have proposed that the stress concentration factor formulas useful for arbitrary notch dimensions in notched specimens [17-23]. Regarding the strain rate concentration factor, however, the notch shape effects have not been clarified yet. In this paper, therefore, the strain rate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

http://dx.doi.org/10.18720/MPM.4252019_5

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. Definittion of the strain rate concentration factor

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



(a) Notched specimen (b) Smooth specimen

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 $K_{t\dot{\varepsilon}}$ (see Equation (2)). Here, $u(t)$ is the displacement applied to the specimen end, which is assumed to be proportional to the time *t*.

$$\dot{\varepsilon}_{smooth} = \frac{u(t)/l}{t}. \quad (1)$$

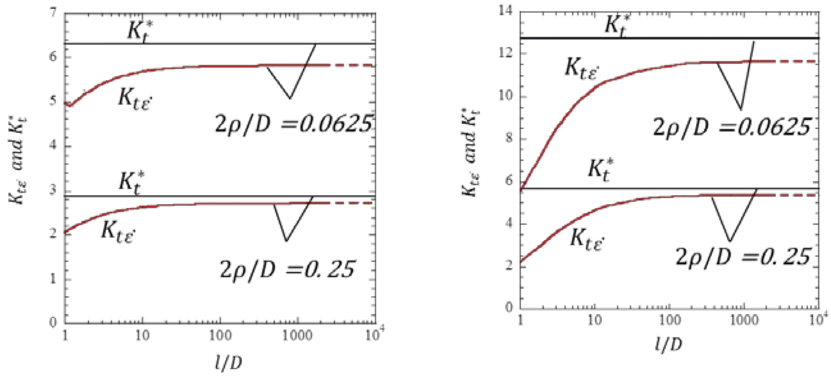
$$K_{t\dot{\varepsilon}} = \frac{\dot{\varepsilon}_{notch}}{\dot{\varepsilon}_{smooth}},$$

$$\dot{\varepsilon}_{notch} = K_{t\dot{\varepsilon}} \cdot \dot{\varepsilon}_{smooth} = K_{t\dot{\varepsilon}} \cdot \frac{u(t)/l}{t}. \quad (2)$$

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 $u(t)/t \leq 5000$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 $u(t)/t$=20mm/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 $l/D \geqq 1$ in Fig.1 (a). However, different from the net stress concentration factor K_t, the strain rate concentration factor $K_{t\dot{\varepsilon}}$ is depending on the specimen length l/D.



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

Fig. 2. Strain rate concentration factor $K_{t\dot\varepsilon}$ 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*=8mm in Fig.1(a))

l/D	*l*(mm)	*t*=0.0625mm (2*t/D*=0.015625)		*t*=0.25mm (2*t/D*=0.0625)		*t*=1mm (2*t/D*=0.25)		*t*=2mm (2*t/D*=0.5)	
		$\rho=$ 0.25mm (2*ρ/D*= 0.0625)	$\rho=$ 2mm (2*ρ/D*= 0.25)	$\rho=$ 0.25mm (2*ρ/D*= 0.0625)	$\rho=$ 2mm (2*ρ/D*= 0.25)	$\rho=$ 0.25mm (2*ρ/D*= 0.0625)	$\rho=$2mm (2*ρ/D*= 0.25)	$\rho=$ 0.25mm (2*ρ/D*= 0.0625)	$\rho=$ 2mm (2*ρ/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
$K_{t\dot\varepsilon}/K_t$									
5	40	0.992	1.012	1.105	1.092	1.569	1.581	2.992	2.921
$K_{t\dot\varepsilon}/K_t^*$									
5	40	0.962	0.980	0.971	0.960	0.883	0.889	0.748	0.730

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

Figure 2 compares the strain rate concentration factor $K_{t\dot\varepsilon}$ 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 $\sigma_{gross} = 4P/\pi D^2$.

$$K_t = \frac{\sigma_{max}}{\sigma_{net}}. \tag{3}$$

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

In Figure 2, it is seen the results for *2ρ/D* = 0.0625 is always larger than the results for *2ρ/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 $K_{t\dot{\varepsilon}}$ increases with the increasing specimen length *l*, and becomes constant.

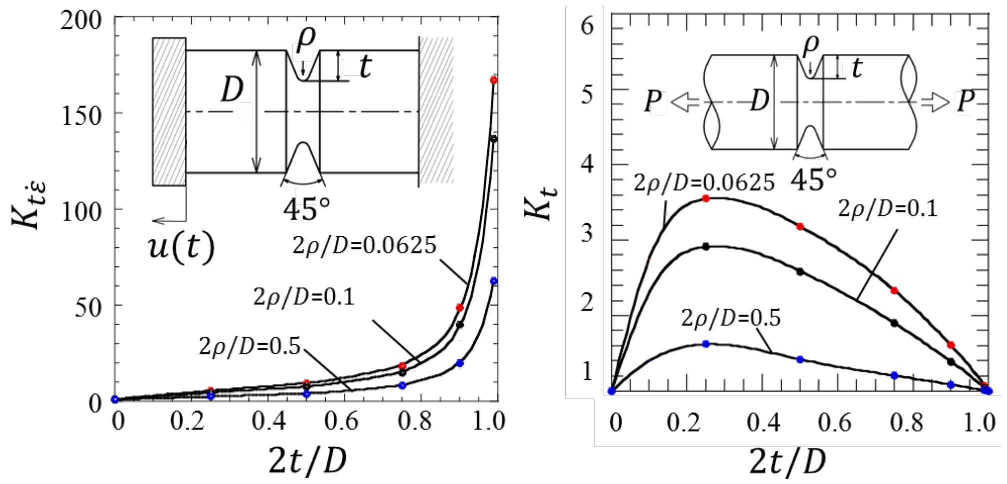
4. Relationship between the strain rate concentration factor and the stress concentration factor

The specimen length *l*=40mm and the diameter *D*=8mm are assumed in this chapter. The results of the strain rate concentration factor $K_{t\dot{\varepsilon}}$ are shown in Fig. 3 by varying the relative notch depth $2t/D$ for fixed relative notch radius 2*ρ*/*D* = 0.0625 and 2*ρ*/*D* = 0.5. Here, 2*ρ*/*D* = 0.0625 corresponds to the notch radius *ρ*=0.25mm of the specimen used in the Charpy impact test. Also, *ρ*=2mm with *D*=8mm 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 $\sigma_{net} \to \infty$ as $2t/D \to 1$, $K_t \to 1$ as $2t/D \to 1$. 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 $K_{t\dot{\varepsilon}}/K_t$ vs. the relative notch depth $2t/D$. When the relative notch depth $2t/D$ →1, the ratio $K_{t\dot{\varepsilon}}/K_t \to \infty$. 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 $2t/D$ →1, the strain rate concentration factor $K_{t\dot{\varepsilon}} \to \infty$ but the net stress concentration factor K_t →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 $2t/D \to 1$, the strain rate concentration factor $K_t^* \to \infty$.

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



(a) Relationship between $K_{t\dot{\varepsilon}}$ and .2*t*/*D* when *l*/*D*=5 (*l*=40mm, *D*=8mm)

(b) Relationship between K_t and .2*t*/*D* when *l*/*D*=5 (*l*=40mm, *D*=8mm)

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

Figure 5 shows the relationship between the ratio $K_{t\dot{\varepsilon}}/K_t^*$ and the relative notch depth $2t/D$. It is found that the value of $K_{t\dot{\varepsilon}}/K_t^*$ is almost the same for $2\rho/D$ = 0.0625 and $2\rho/D$ = 0.5 when the relative notch depth $2t/D$ ≤0.5. From Fig. 5, it is found that the value of $K_{t\dot{\varepsilon}}/K_t^*$ is insensitive to the notch root radius in the range of $2t/D$ ≤0.5. By using this fact, the strain rate concentration factor $K_{t\dot{\varepsilon}}$ can be estimated from the gross stress concentration factor K_t^*.

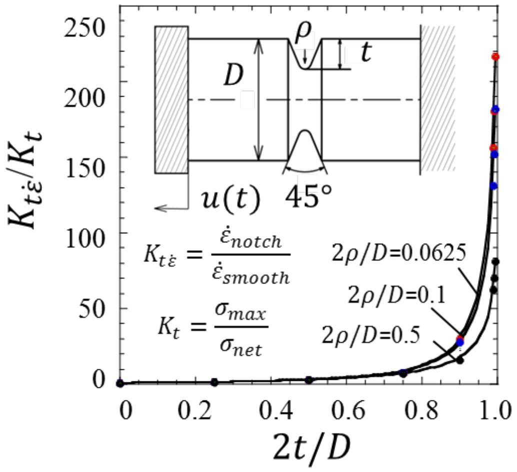


Fig.4. Relationship between $K_{t\dot{\varepsilon}}/K_t$ and $2t/D$ when *l*/*D*=5 (*l*=40mm, *D*=8mm)

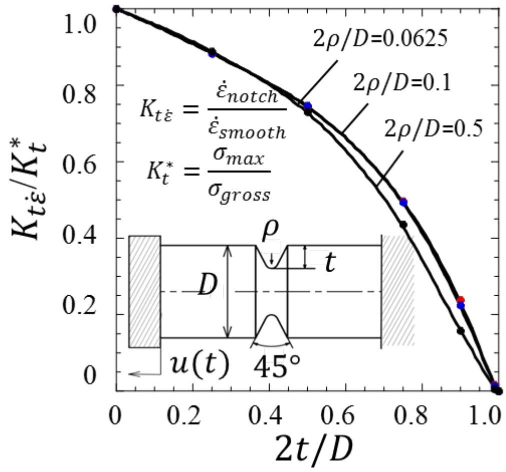


Fig.5. Relationship between $K_{t\dot{\varepsilon}}/K_t^*$ and $2t/D$ when *l*/*D*=5 (*l*=40mm, *D*=8mm)

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 $K_{t\dot{\varepsilon}}$ was defined as the ratio of the strain rate in notched specimen to the strain rate in smooth specimen. Then, the maximum strain rate $\dot{\varepsilon}$ 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 $K_{t\dot{\varepsilon}}$ increases with increasing the specimen length and then become constant as shown in Fig. 2.

(3) It is found that the value of $K_{t\dot{\varepsilon}}/K_t^*$ is almost the same independent of the notch root radius when the relative notch depth $2t/D$≦0.5. By using this relationship, the strain rate concentration factor $K_{t\dot{\varepsilon}}$ can be determined from the stress concentration factor K_t.

Acknowledgements. *No external funding was received for this study.*

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