Influence of Free Surface Roughening on Ductile Fracture Behavior Under Uni-axial Tensile State for Metal Foils

Tsuyoshi Furushima[1*], Hitomi Tsunezaki[1], Ken-ichi Manabe[1], Ming Yang[2], Sergei Alexandrov[3]

[1] Department of Mechanical Engineering, Tokyo Metropolitan University, 1-1 Minami-osawa, Hachioji, Tokyo 192-0397, Japan
[2] Institute for Problems in Mechanics, Russian Academy of Sciences, 101-1 Prospect Vernadskogo, 119526 Moscow, Russia
* Corresponding author: furushima-tsuyoshi@tmu.ac.jp

Abstract The metal foils indicate low level fracture strain compared with metal sheet. In this study, the free surface roughening is focused on to clarify the mechanism of ductile fracture for metal foils, since the ratio of surface roughness to thickness becomes larger compared with metal sheets. Materials used are pure copper and pure titanium foils and sheets with thickness of 0.05, 0.1, 0.3 and 0.5mm respectively. Free surface roughening and ductile fracture behavior are measured and observed under uni-axial tensile state. As a result, the surface roughening to thickness of metal foils with thickness of 0.05 and 0.1mm was larger than that of metal sheets with thickness of 0.3 and 0.5mm. To investigate the fracture behavior of metal foils, the fracture surface is observed by scanning electron microscope. For pure copper foils with thickness of 0.05 and 0.1mm, dimple pattern cannot be observed, while some dimples for metal sheets such as pure copper and pure titanium sheets with thickness of 0.3, 0.5mm and pure titanium foils with 0.05 and 0.1mm can be observed. As a result, the fracture type of metal foils divides broadly into two categories: existence dimple type for pure titanium and non-existence dimple for pure copper on fracture surface. In addition, the magnitude relation between the increase in ratio of surface roughness to thickness and strain hardening exponent *n* value would affect fracture strain level and existence or non-existence of dimple pattern on fracture surface.

Keywords Metal foil, Free surface roughening, Ductile fracture, Thickness

1. Introduction

Recently, micro metal forming process using metal foils is one of the promising approaches to fabricate micro stamping products such as micro shim, micro gasket, ultra thin valve for micro pump and parts for electric and medical devices. However, it is well known that the micro metal forming for metal foil with ultra thin thickness has problems on size effect. For example of the size effect, Fu reported that fracture strain decreases with decreasing thickness of specimen in uni-axial tensile test [1]. Thus, the metal foils in micro scale indicate different fracture behavior from metal sheet in macro scale. To clarify the fracture mechanism and to predict forming limit of metal foils are absolutely imperative for further development of micro metal forming.

In our previous report, we focused on free surface roughening phenomenon as one of factors related to fracture mechanism of metal foils. It is well known that surface roughness on free surface with non-contact tool situation increases with plastic deformation during metal forming process. An inhomogeneous model has been suggested for prediction of free surface roughening [2, 3]. Our experimental works reported that the ratio of surface roughness to thickness of copper foils with ultra thin thickness becomes large compared with that of conventional sheets [4]. Thus, the free surface roughening of copper foils may affect not only local problem such as accuracy of products and frictional condition but also global deformation behavior such as necking behavior which is onset of fracture. Furthermore, we reported that the forming limit of copper foils in stretching forming cannot be predicted by conventional ductile fracture criterion [5]. Moreover, unlike general metal sheets, dimple pattern on fracture surface cannot be observed of the copper foil. However, the previous reports dealt with limited materials such as copper alloy. The discussion about fracture mechanism of metal foils was not insufficient.

In this study, we investigated the ductile fracture behavior and free surface roughening for not only pure copper foils but also various metal foils such as pure titanium foils. Influence of free surface roughening on ductile fracture behavior under uni-axial tensile state for metal foils was discussed experimentally.

2. Materials and experiment

Pure copper C1020-O and pure titanium TR270C-O foils and sheets with thickness t_0 of 0.05, 0.1, 0.3 and 0.5mm were used. The tensile test specimens were cut along the 0° to the rolling direction. In uni-axial tensile test, gage length was 10mm. A commercial tensile test machine was used for the tensile tests. Since a contact extensometer cannot be pasted for the metal foil, elongation was measured optically by using a video type non-contact extensometer. Tensile tests were conducted at room temperature and a strain rate of 1.6×10^{-3} /s. To get repeatability of experimental result, tensile tests were performed 3 times. After tensile test, fracture surface was observed by scanning electron microscope (SEM). To investigate effect of free surface roughening on ductile fracture behavior, the surface roughness was measured by confocal laser microscope. Until material fractures, surface roughness is measured at same area in five stages.

3. Results and discussion

3.1. Effect of thickness on fracture strain and free surface roughening behavior

Fig. 1 shows the effect of thickness on fracture strain obtained from uni-axial tensile test. Fracture strain decreases with decreasing thickness for all materials used as is the case in previous report [1]. In particular, the fracture strain of pure copper and pure titanium dramatically decrease from thickness of 0.3mm to 0.1mm. Thus, it is found that the thickness strongly affects fracture strain.

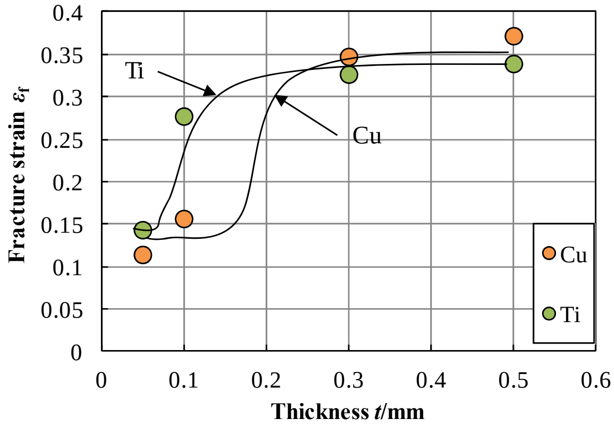
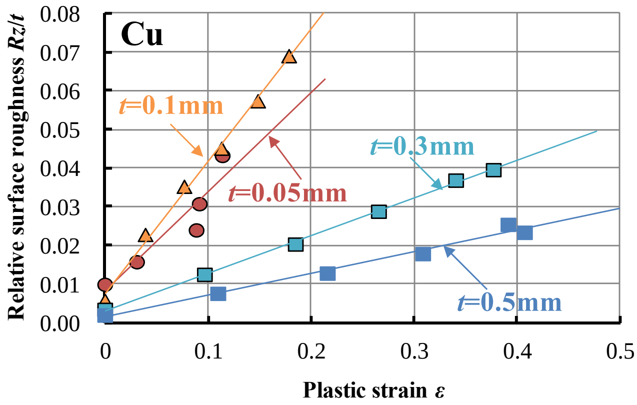
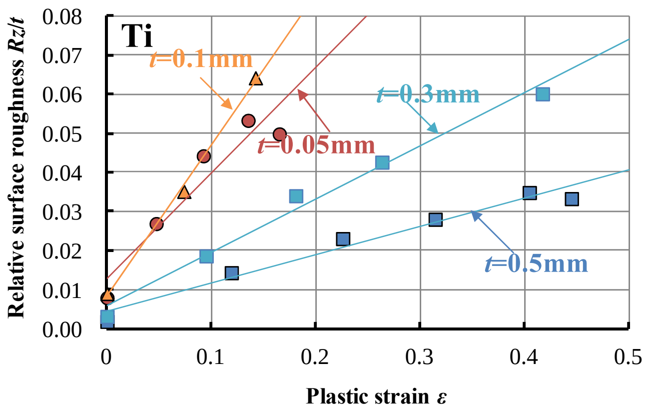


Figure 1. Effect of thickness on fracture strain in uni-axial tensile test

To clarify why the fracture strain significantly decrease with decreasing thickness, the free surface roughening on specimen surface during uni-axial tensile test was investigated. Here, we used ratio of maximum surface roughness to thickness *Rz*/*t*, because it is not always true that the surface roughness similarly decreases with decreasing thickness. The thickness *t* during deformation is calculated by assumption of volume constancy law and isotropic material. Fig. 2 shows the ratio of surface roughness to thickness *Rz*/*t* during uni-axial tensile test. The ratio of surface roughness to thickness for each material linearly increases with increasing plastic strain. In addition, most important part is that the slope of ratio of surface roughness to thickness *Rz*/*t* is completely different between sheets (*t*=0.3 and 0.5mm) and foil (*t*=0.05 and 0.1mm). Particularly, the slope of evolution of *Rz*/*t* is changing significantly from thickness 0.3 to 0.1mm. As a result, it is supposed that the decrease in fracture strain has some connections with slope of relative free surface roughening *Rz*/*t*.



(a) Pure copper

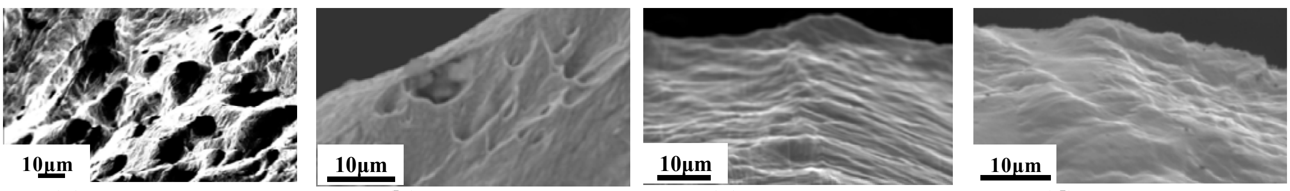


(b) Pure titanium

Figure 2. Evolution of ratio of surface roughness to thickness during uni-axial tensile deformation

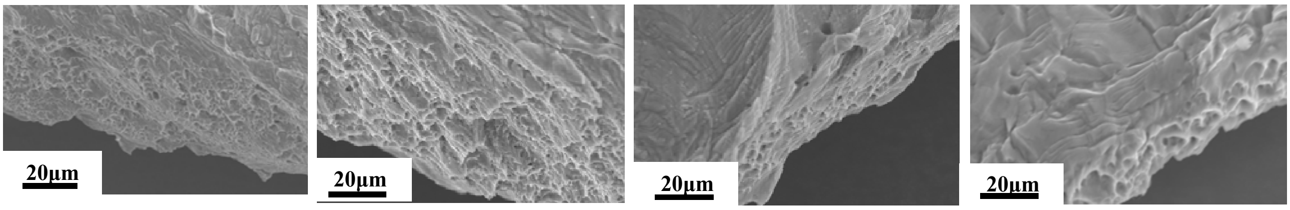
3.2. Fracture surface observation

To clarify the reason why the fracture strain changes significantly between thicknesses of 0.1 and 0.3mm, the difference in fracture mode was investigated by observing fracture surface by SEM. Figs. 3 and 4 show the SEM images of fracture surface for pure copper and pure titanium foils and sheets.



(a) *t*=0.5mm (b) *t*=0.3mm (c) *t*=0.1mm (d) *t*=0.05mm

Figure 3. SEM photographs of fracture surface for pure copper



(a) t=0.5mm (b) t=0.3mm (c) t=0.1mm (d) t=0.05mm

Figure 4. SEM photographs of fracture surface for pure titanium

In Fig. 3, some dimples on the fracture surface can be observed for pure copper sheets with thicknesses of 0.3 and 0.5mm. Meanwhile, non-dimples were on fracture surface of copper foils with thicknesses of 0.05 and 0.1mm. Generally, it is known that nucleation and growth of voids during plastic deformation causes dimple pattern on the fracture surface. Therefore, for metal sheets with relatively thicker thickness of 0.3 and 0.5mm, ductile fracture is caused by nucleation and growth of voids. On the contrary, it can be guessed that the metal foils with relatively thinner thickness of 0.05 and 0.1mm were fractured by other mechanism except nucleation and growth of voids because of non-dimple pattern on the fracture surface. These results about the existence or non-existence of dimple pattern on fracture surface between metal foils and metal sheets had some connections with significantly change in fracture strain in Fig. 1 and free surface roughening in Fig. 2. In the previous study, it was confirmed that the deep depth of surface defect purposely fabricated on the tensile specimen causes fracture at early tensile deformation stage [6]. Therefore, it would be considered that the evolution of free surface roughness causes similar effect of surface defect on the specimen. Thus, the fracture would be due to free surface roughening rather than nucleation and growth of voids inside the material.

Meanwhile, the dimple pattern can be observed for pure titanium foils and sheets with thickness of 0.05, 0.1, 0.3 and 0.5mm as shown in Fig. 4. The difference in fracture surface for pure titanium between foil and sheet cannot be confirmed seen in pure copper. Thus, it is guessed that origination of ductile fracture is not generated by free surface roughening but void nucleation and growth cause ductile fracture for pure titanium foils similar to general metal sheet, regardless the slope of relative free surface roughening is large for pure titanium foils as shown in Fig. 2. From these results, there are two fracture type of metal foils: pure titanium type with dimple pattern and pure copper type with non-dimple pattern on fracture surface.

3.3. Discussion on ductile fracture mechanism of metal foils

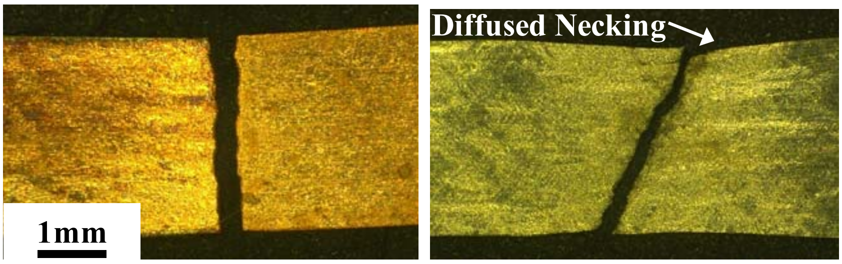
As described in section 3.1 and 3.2, it is found that the fracture type of metal foils divides broadly into two categories: existence dimple type for pure titanium and non-existence dimple for pure copper on fracture surface. To consider difference between both fracture types occurs for metal foils, we are focusing on not only the relative free surface roughening behavior and fracture surface observation described above but also basic material properties obtained from uni-axial tensile test as shown in Table 1. Material properties such as strain hardening n, K, ε_0 for each material were obtained from swift type flow stress curve as shown in Eq. (1).

$$\sigma = K(\varepsilon_0 + \varepsilon)^n \tag{1}$$

In addition, we discuss necking behavior near fracture area as shown in Fig. 5. Generally, the occurrence of necking behavior is strongly related to strain hardening exponent n [7]. it is well known that the larger n value, the larger necking strain.

Table 1. Material properties obtained from uni-axial tensile test

Material	Thickness t [mm]	n	K [MPa]	ε_0
Pure copper	0.05	0.56	671.2	0.022
	0.1	0.54	602.6	0.026
	0.3	0.46	524	0.014
	0.5	0.44	509.6	0.012
Pure titanium	0.05	0.085	533	0.015
	0.1	0.16	521.7	0.0063
	0.3	0.38	616.8	0.07
	0.5	0.33	604.1	0.05



(a) Pure copper (b) Pure titanium

Figure 5. Photographs of necking area after uni-axial tensile test

The strain hardening exponent n value of pure copper foil with thickness of 0.05mm in Table 1 was 0.56, respectively, but n value of pure titanium foil with thickness of 0.05mm was 0.085. Thus, n value of pure titanium foil is smaller than that of pure copper foil. The fracture strain of pure copper foil with thickness of 0.05mm indicates very low value as shown in Fig. 1 in spite of large n value 0.56. Additionally, it can be observed that the tensile test specimen of pure copper foil was fractured vertically to the tensile direction without diffused necking as shown in Fig. 5 (a). From these result, it is considered that the increase in the ratio of surface roughness to thickness causes inhomogeneous thickness distribution, which would lead to origination of fracture as a fracture mechanism of metal foil with non-dimple type such as pure copper. Originally, the pure copper foil with thickness of 0.05mm is supposed to indicate large fracture strain due to large n value, but fracture occurred before diffused necking because of increasing the ratio of surface roughness to thickness during deformation. Thus, it is considered that the void nucleated by occurrence of diffused necking is not growing in the specimen, and then the dimple pattern on fracture surface of pure copper foils with thickness of 0.05 and 0.1mm cannot be observed.

Meanwhile, n value of pure titanium foil with thickness of 0.05mm is extremely low value of 0.085 as shown in Table 1. Thus, it is confirmed that the necking strain indicates low level and the fracture occurs obliquely to the tensile direction as shown in Fig. 5 (b) after diffused necking. As shown in Fig. 2, the relative free surface roughening of pure titanium foils with thickness of 0.05 and 0.1mm is large as well as that of pure copper foils. However, in case of pure titanium foils with lower n value, it is supposed that the fracture occurs by necking along with metal sheet before effect of free surface roughening becomes marked. As a fracture mechanism of pure titanium foil, the occurrence of necking with lower n value is initiative of fracture of foils compared with relative free surface roughening. Therefore, the dimple pattern on fracture surface which is generated by nucleation and growing of voids after necking of pure titanium foil can be observed.

From these results, fracture mechanism of metal foil can divide broadly into two categories by the magnitude relation between the increase in ratio of surface roughness to thickness and strain hardening exponent *n* value, which would affect fracture strain level and existence or non-existence of dimple pattern on fracture surface.

4. Conclusion

In this study, the ductile fracture behavior and free surface roughening for various metal foils such as pure copper and pure titanium foils was investigated experimentally to clarify the general fracture mechanism of metal foils. As a result, the fracture type of metal foils divides broadly into two categories: existence dimple type for pure titanium and non-existence dimple type for pure copper on fracture surface. In addition, the magnitude relation between the increase in ratio of surface roughness to thickness and strain hardening exponent *n* value would affect fracture strain level and existence or non-existence of dimple pattern on fracture surface.

Acknowledgements

This research was supported by RFBR and JSPS under the Russia-Japan Research Cooperative Program.

References

[1] M.F. Fu, W.L. Chan, Geometry and grain size effects on the fracture behavior of sheet metal in micro-scale plastic deformation. Mater. Des., 32 (2011) 4738-4746.

[2] Z. Zhao, R. Radovitzky, A. Cuitino, A study of surface roughening in fcc metals using direct numerical simulation. Acta Mater., 52 (2004) 5791–5804.

[3] T. Furushima, T. Masuda, K. Manabe, S. Alexandrov, Prediction of free surface roughening by 2D and 3D model considering material inhomogeneity. J. Solid Mech. Mater. Eng. 5 (2011) 978-990.

[4] T. Furushima, T. Masuda, H. Tsunezaki, S. Alexandrov, Free surface roughening and ductile fracture of metal foils in micro metal forming. in Proceedings of the 3rd Asian Symposium on Materials & Processing (ASMP 2012) (2012) CD-ROM.

[5] T. Furushima, T. Masuda, H. Tsunezaki, S. Alexandrov, Fracture prediction in micro sheet forming using ductile fracture criterion. Steel Res. Int., Special Edition (2012) 1183-1186.

[6] T. Hiroi, H. Nishimura, The influence of surface defects on the forming-limit diagram of sheet metal. J. Mater. Process. Technol. 72 (1997) 102-109.

[7] H. Swift, Plastic instability under plane stress. J. Mech. Phys. Solids, 1 (1952) 1-18.