Size effects in thin sheet metal forming

T A Chang¹, A R Razali¹, N A I Zainudin¹ and W L Yap¹
¹Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

E-mail: cta_wen@hotmail.com

Abstract. Negligible factors in bulk materials, such as grain-size effects, have proven inappropriate to be neglected for micro-forming processes. Studies had shown that material behaviour varies greatly with the increasing of the scale in the micro-forming world. Therefore, in every micro-forming-related process, especially in micro-stamping, studies and analyses of each material used for the process have to be considered as indispensable in order to be able to understand their behaviour and to be able to correlate their behaviour with the process. Uniaxial tensile-testing experiments have been carried out to determine the strip’s properties, behaviour and its correlation with the feeding process in micro-stamping/micro-sheet-forming application. Based on the results of the uniaxial tensile-test experiments conducted, the flow stress was found to decrease with the decrease of the strip thickness and vice versa, due to the size/scale effect. A surface model was used to explain the findings.

1. Introduction
Desire for better quality of life, good health and high working efficiency has been one of major drives to the innovation of many products hence, new products models were invented, for instance netbook, handheld computers and cars, emerging of new products such as smart mobile phones, MP3 player, ultra-thin flat-screen displays, as well as new medical instruments/implants. Dramatic changes of the global, economic development maps and demand for global market of the said micro-products during last 15 years have significantly influenced how the manufacturing is organized and implemented. It was estimated that micro-products industry through evolvement of miniaturization concept would bring more than 1.5-3.5billion dollars trade within five years [1-4].

Nevertheless, differ from conventional manufacturing process which is seen more mature and stable, theory of micro-manufacturing process is seen immature enough for industrial transformation or even 24/7 application. A lot of issues have been addressed by researchers around the globe covering the manufacturing methods and processes [5-13]. Not only issues on the machineries and tooling aspect to be tackled and dealt accordingly, challenging issues such as material behaviors also have to be well-versed in order to guarantee total success.

When feature size of a part is reduced smaller than 1mm, a so-called size effect came up and made the knowledge in terms of empirical and analytical know-how of conventional forming process cannot be directly applied in micro-forming world. A lot of efforts has been done and proved that material behavior in micro-scale is different from macro-scale. The purpose of this research is to study and understand the influence of the size effects on material behavior. Then the material behavior is discussed with a view to the micro-stamping material handling process.
2. Equipment and Materials

2.1. Tensile Testing Machine
Universal testing machine made by Instron was used to measure the material’s mechanical properties. The machine has various ranges of working tension and compression load; 0-2.5, 0-5, 0-10, 0-25, 0-50kN with resolution of 1N. Maximum actuator stroke is at ±50mm with actuation speed of up to 5000mm/min. The screw grips measures 60 mm wide and 55 mm deep and can hold material as thick up to 10mm and as thin as micron range thickness.

2.2. Electron Backscattered-Diffraction (EBSD)
Efforts made elsewhere [14-16] have revealed that the use of EBSD is proven as an excellent tool for quantitative metallographic. The effort also has revealed that capability of EBSD analysis which is not only limited to grain size determination, but also there are a number of important microstructural parameters may be determined through the analysis which is not obtainable from any conventional light microscopy.

EBSD analysis also may reveal more number of grain count compared to conventional light microscopy methods. This in turn leads to better microstructural analysis range that covers analysis from the smallest to the biggest grain size. Consequently, this leads to better and more accurate grain size measurement, deviation and aspect ratio.

2.3. Tensile Testing Specimen
Tension test first require the preparation of a test specimen typically from sheet coil. The specimens were prepared according to ASTM E8M specification and cut by using wire cut process. This cutting process is favored in order to avoid burry edges which may have potential to initiate crack during testing. Three types of specimens were used, 50µm and 100µm thick carbon steel and 50µm stainless steel strips and prepared with the similar size to one another.

3. Procedures
Uniaxial tensile test is the simplest and most convenient method and is used to determine material properties for particular temperature and strain-rate specifications. Tensile tests are mostly used to test the materials which are to be used in mechanical structures in which the materials deflect elastically or undergo low levels of plastic deformation. Mechanical properties analyses on thin sheet metal had received vast studies worldwide covering some popular engineering material [4, 17]. 15 specimens of each strip (50µm and 100µm thick carbon steel and 50µm thick stainless steel strips) were tested and stress-strain curve for each strip was plotted and discussed.

Apart of determination of mechanical properties through uniaxial testing which was conducted on each strip, measurement of grain structure is also important because grain size does have an influence on the material mechanical properties [17]. Therefore electron backscattered-diffraction analysis was conducted on each strip with a view to determine grain orientation, boundaries, shapes and sizes. The EBSD system used was an Oxford Instruments/HKL Nordlys detector. The polished samples were mounted at 70degrees to the horizontal and were examined in a Zeiss Supra 40 FEGSEM at 20kV with a beam current of about 2nA.

4. Results
Brittle materials such as 50µm and 100µm thick carbon-steels do not have a yield point, and do not strain-harden. This means that both ultimate and breaking strength of each material are the same. The stress–strain curves for both the thin and thick carbon-steel strips are shown in figure 1(a) and figure 1(b). Typical brittle materials such as these carbon-steel strips show little plastic deformation. One of the characteristics of the failure of carbon-steel strips failure is that the two broken parts can be reassembled to produce the same shape as that of the original component.
From the figures, it was obvious that the flow stress–strain curves vary greatly with the sheet thickness. For carbon-steel strips, with the decrease of the thickness, flow-stress decreases. The testing also revealed that less deformation was observed where none of the tested carbon-steel strips had significant plasticity deformation, hence no region of obvious plastic deformation was observed. The strips, however, were believed to fracture during elastic deformation, which was indicated by an almost linear stress–strain curve.

Differently to the case for stainless-steel strip (SS50) in figure 1(c), significant plastic deformation was observed in the given recorded stress–strain curves, as shown in figure 1(c) the strip was seen to be more ductile and possibly plastically-deformed before fracture. However, less force was required to result in fracture and failure. Table 1 shows the calculated modulus of elasticity for all of the strips tested.

![Stress-Strain curve for a) CS50, b) CS100 and c) SS50.](image)

**Figure 1.** Stress-Strain curve for a) CS50, b) CS100 and c) SS50.

### 4.1. EBSD Results

Inspection by conventional light-microscopy at 500x magnification as illustrate in figure 2(a) revealed a bluish martensite region as well as cementite content in the 50µm carbon-steel strip (CS50) due to the heat-treatment process. Quenching of the strip has resulted in some of the carbon content being formed into iron carbide. Iron carbide, also known as cementite (white spots), usually measures less than 1µm and increases the mechanical properties of the strip. Figure 2(b) shows grains coloured by size with the darker/red coloured being the larger grain size for 50µm carbon-steel strip. Although no specific shape may be used to define the grain, the grain was defined as areas enclosed by boundaries. A step-size of 0.05µm was used to create a reasonably clear resolution for accurate indexing of the
microstructure. This step-size covers an image-mapping area of 30x35µm. Based on the analysis of the mapped image, there were 3404 counted grains. The smallest and largest measured grains were 0.0564µm and 5.2757µm, with an average of 0.4028µm. The numbers of small grains were seen to be dominating the microstructural pattern and no specific and uniform grain shapes were observed. This suggests that the previous deformed-grain (due to hot-rolling) might be reformed/reshaped due to the tempering process. A large aspect ratio was observed also, where each grain on average has an aspect ratio of 2.2288 and a maximum of 12.2060. A large and slender aspect ratio may cause the microstructure to become weak and less resistant to external forces.

Figure 3(a) shows an image of a photomicrograph of a 100µm thick carbon-steel strip (CS100) under light microscopy at 500x magnification. This technique may be found useful as a fast way to reveal the type of process that has been undergone by the strip material. Although this technique was unable to reveal greater numbers of grains than EBSD was capable of, the technique has proven able to identify irregularity-content of the strip. White spot on the image was identified as cementite, which may cause an increase of the strength and brittleness of the strip. The presence of cementite on this strip was observed to be twice as much as for the CS50 strip.

An EBSD microstructure-mapping image of CS100 strip is shown in Figure 3(b). A similar scanning-step as that for CS50 was used to observe the microstructure. A similar number of pixels were used to ensure that a broad and wide image would be captured, using the same total mapped area of 30x35µm. 6438 grains was successfully mapped with a grain-size average of 0.2661µm, the smallest and largest grains being 0.0564µm and 3.2762µm, respectively. The number of grains revealed was found to be twice many when compared with the number for CS50. This indicates that the CS100 microstructure was very dense and also consists of many tiny grain-sizes, smaller than those for CS50. This was confirmed by the average grain-size obtained throughout the examination, which revealed that CS100 grains were 34% smaller than CS50 grains. An almost similar maximum aspect ratio as that for CS50 was found for CS100, which was a 12.3760. However, the average aspect ratio for CS100 was found to be slightly smaller than for the thinner carbon-steel strip, which was 1.8331. Due to the smaller aspect ratio, the grains might be able to stay close to each other, resulting in a very dense grain pattern.

Mapping of 50µm thick stainless-steel strip (SS50) using conventional light-microscopy at 500x magnifications in figure 4(a) shows many grains, which were heavily deformed due to the hot-rolling process. Nevertheless, the image from this technique was seen to be unable to show important microstructural information such as grain boundaries and clear distribution of neighbouring grains. Due to the larger grain size that may be obtained from a stainless-steel specimen, a large scanning step may be used to map and index its microstructure. 5618 grains were successfully mapped and indexed in figure (4b) with an average grain size of 0.7698µm, which was larger than that for the tested carbon-steel strips. The minimum and maximum indexed grain-size was 0.2820µm and 20.2870µm, respectively. Due to the grains being heavily deformed, a large part of the mapped area could not be indexed, hence a large number of blanks were observed on the image. In order to obtain a clear view of grain boundaries and orientation, the mapped image was split into two images. Both of these images represent the indexed grain size, which is <1µm and >1µm. The analysis also reveals that SS50 has many larger grains compared to carbon-steel and has the greatest grain aspect-ratio of 19.7060. This has resulted in a lesser grain density, which may be affecting its mechanical properties (table 1).
Figure 2. a) CS50 at 500x magnifications, showing iron carbide/cementite (white colour) and b) EBSD microstructure mapping image of CS50 strip.

Figure 3. a) Light-microscopy image of CS100 strip at 500x magnification with cementite shown (white colour) and b) EBSD microstructure-mapping image of CS100 strip.

Figure 4. a) Light-microscopy image of SS50 strip at 500x magnification and b) EBSD microstructure-mapping image of SS50.
5. Discussions

5.1. Size Effect and Material Stress–Strain Relation

Studies had demonstrated that the flow stress of thin sheet-metal decreases compared to that of its bulk material due to the size effect, and decreases proportionally with miniaturization [17, 18]. Commonly, there are two categories of the size effect that can be investigated: the grain-size effect and the feature-size effect.

Many investigations have been conducted elsewhere [19, 20] and have shown that sheet metals of different grain sizes show different mechanical properties. The grain-size effect was already known to follow the Hall–Petch equation, which topic has been elaborated upon elsewhere [21]. This equation simply states that a material with a greater grain size has less strength compared to one which has a smaller grain size. This effect is purely reliant on the average grain-size of the material and is mostly dominant in macro-scale material. Although the tested strips were very thin, due to their relatively large width and length, they can still be considered as macro-scale material. According to the EBSD results conducted on all of the strips, the stainless-steel strip (SS50) were found to have a greater grain size, followed by that of the 50μm-thick carbon-steel strips (CS50), and finally that of the 100μm-thick carbon-steel strips (CS100). Good agreement of the results achieved between those for EBSD and those for tensile testing have established and confirmed the effect of varying grain size. The least flow-stress was observed with SS50, which in turn has the larger grain size, this being followed by CS50 and finally CS100. This is because when a material of greater grain size is deformed, dislocations are easier to move compared to the situation with a smaller grain size. Less force is required and a lesser number of grains have made a larger grain-size material prone to fail a lot more quickly than would a smaller grain-size material.

Moreover, feature size also has a significant effect on a material’s flow stress. The decrease of flow stress with the decrease of sheet thickness may be explained by the so-called surface-model, as depicted in figure 5. This model was used to describe the correlation between flow stress and miniaturization and has been popularly validated elsewhere [4, 22, 23]. According to the model, the grains located at the free surface are less restricted than are the internal grains. This in turn leads to the surface grains being subjected to less hardening, and having a lower resistance against deformation, because dislocations move through the grains during deformation and pile-up at grain boundaries, but not at the free surface. With the decrease of strip thickness, the share of surface grains increases, hence lower flow stress. On the other hand, thicker sheet, in this case 100μm carbon-steel strip, the share of surface grains decreases and this in turns leads to a relatively higher flow stress compared to that for thinner strip.

Figure 5. Grain distribution in a material section of different material/feature size.
Table 1. EBSD and Young’s Modulus of the tested strips.

|                  | CS50     | CS100    | SS50    |
|------------------|----------|----------|---------|
| Count grain, N   | 3404     | 6438     | 5618    |
| Mean (µm)        | 0.4028   | 0.2661   | 0.7698  |
| Minimum (µm)     | 0.0564   | 0.0564   | 0.2820  |
| Maximum (µm)     | 5.2757   | 3.2762   | 20.2870 |
| Standard deviation (µm) | 0.3980 | 0.3072   | 1.0114  |
| Grain aspect ratio |         |          |         |
| Mean             | 2.2288   | 1.8331   | 2.0039  |
| Minimum          | 1.0000   | 1.0000   | 1.0000  |
| Maximum          | 12.2060  | 12.3760  | 19.7060 |
| Standard deviation |         |          |         |
| Young’s Modulus (GPa) | 69     | 70       | 60      |

6. Conclusions
Based on the experiments conducted, the following conclusions are drawn:

i. Tested thicker carbon steel strip has the smallest grain size, followed by the tested thinner carbon steel strip and finally stainless steel strip.

ii. The thick carbon-steel strip has the greatest modulus of elasticity (stiffness) followed by the thinner carbon-steel strip and finally the stainless-steel strip.

iii. It may be concluded that thicker carbon steel strip has the stiffer characteristic compared to the thinner carbon and stainless steel strip.

References
[1] Zhao J, Qin Y, Razali A, Yip A L K, Fei Z, Hot-embossing of polymeric micro-tubes. 7th International Conference on MicroManufacturing; 2012.
[2] Razali A R, Qin Y 2013 Procedia Engineering 53 665-72
[3] Qin Y 2006 Journal of Materials Processing Technology 177 8-18
[4] Lai X, Peng L, Hu P, Lan S, Ni J 2008 Computational Materials Science 43 1003-9
[5] Razali A, Qin Y, Harrison C, Brockett A, Investigation of feeding devices and development of design considerations for a new feeder for micro-sheet forming. 6th International Conference on Manufacturing Research, ICMR 08; 2008.
[6] Razali A, Qin Y, Zhao J, Harrison C, Smith R 2011 Journal of Manufacturing Sc. & Engineering 133 061025
[7] Qin Y, Brockett A, Ma Y, Razali A, Zhao J, Harrison C, et al. 2010 The International Journal of Advanced Manufacturing Technology 47 821-37
[8] Qin Y, Ma Y, Harrison C, Brockett A, Zhou M, Zhao J, et al. 2008 International Journal of Material Forming 1 475-8
[9] Razali A, Qin Y, Harrison C, Zhao J 2009 Journal of Advanced Manufacturing Technology
[10] Zhao J, Brockett A, Razali A, Qin Y, Harrison C, Ma Y 2010 Steel Research International 81 1185-8
[11] Qin Y, Razali A R, Zhou M, Zhao J, Harrison C, Nawang W, et al., Dynamic Characteristics of a Micro-Sheet-Forming Machine System. Key Engineering Materials; 2012: Trans Tech Publ.
[12] Jie Z, Yip A L K, Yi Q, Razali A, Fei Z-c 2012 *Transactions of Nonferrous Metals Society of China* **22** s214-s21
[13] Law A R J Z F, Yi Q 2011 *Journal of Plasticity Engineering* **6** 015
[14] Mingard K, Roebuck B, Bennett E, Gee M, Nordenstrom H, Sweetman G, et al. 2009 *International Journal of Refractory Metals and Hard Materials* **27** 213-23
[15] Wagner F, Allain-Bonasso N, Berbenni S 2011 *Materials Characterization* **62** 681-3
[16] Klocke F, Hensgen L, Klink A, Mayer J, Schwedt A 2014 *Procedia CIRP* **13** 237-42
[17] Peng L, Hu P, Lai X, Mei D, Ni J 2009 *Materials & Design* **30** 783-90
[18] Anand D, Kumar D R 2014 *Procedia Materials Science* **6** 154-60
[19] Dong X, Hong X, Chen F, Sang B, Yu W, Zhang X 2014 *Materials & Design* **64** 400-6
[20] Kim J, Golle R, Hoffmann H 2010 *Materials Science and Engineering: A* **527** 7220-4
[21] Mahabunphachai S, Koç M 2008 *International Journal of Machine Tools and Manufacture* **48** 1014-29
[22] Peng L, Liu F, Ni J, Lai X 2007 *Materials & design* **28** 1731-6
[23] Vollertsen F, Niehoff H S, Hu Z 2006 *International Journal of Machine Tools and Manufacture* **46** 1172-9