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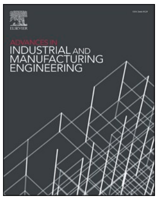

Development of a portable Universal Testing Machine (UTM) compatible with 3D laser-confocal microscope for thin materials

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ABSTRACT

The tensile test always delivers an in-depth understanding of true stress-strain relationship. However, it is not easy for the researchers to understand and evaluate the tensile properties of micro-specimens. This paper presents a research work aiming at the design and manufacturing of a small universal test machine (UTM) for measuring the mechanical properties of the miniaturised samples. The newly developed machine is sensitive to small loads and permits to obtain the stress-strain curves for thin materials. This portable UTM consists of a stepper motor, a load cell, a linear variable differential transformer (LVDT), a load cell amplifier and a data acquisition system. Copper based small and thin (50 μm) tensile test samples were tested on this machine at room temperature, and the calculated results were compared with the test results derived from a commercial UTM (METEX - 1 kN) to justify the validation of the developed apparatus. The obtained mechanical properties are in good agreement with the values obtained from a commercial UTM. To confirm the possibility of in-situ micro-observation, the surface roughness analysis has been conducted on the developed apparatus for pure copper foils under 3D laser-confocal microscope. Finally, it is concluded that this kind of testing apparatus could be manufactured within a manageable budget.

1. Introduction

Today in this modern world of miniaturization, the demands of complex and high-performance micro-metallic parts are increasing day by day. Micro metal forming is a correct and relevant approach to manufacture the micro-scale metallic parts (Kals and Eckstein, 2000). With the fabrication of micro-scale parts, it becomes essential to do the engineering design and analysis, for which the stress-strain relationship is needed (Jiang et al., 2017). The tensile test is the most significant method to study out the stress-strain relationship of material and it is broadly used due to its high degree of flexibility and economic advantages (Razali and Qin, 2013). The universal testing machine (UTM) is the most common equipment used for tensile testing (Jeswiet et al., 2008). This type of traditional testing machines are relatively heavy and typically installed in a laboratory. In general, the traditional testing machines are unable to apply the slow force on small test samples to properly replicate the actual force application (Partheepan et al., 2005a). Therefore, it is not easy to calculate the tensile properties of the small (micro-scale) samples on the traditional UTM. Moreover, the relationships between the dimensions and surface geometry in treated workpieces as well as in tools are different in macro and micro-scale, which directly affect the stress-strain relationship (Partheepan et al., 2005a; Hou and Chen, 2005a). The study of the stress-strain relationship in micro-scale samples is very important to understand the various mechanical properties (e.g. ultimate tensile strengths, young’s modulus, and poisson’s ratio) of the selected material (Ma et al., 2015).

Furthermore, the surface roughness is one of the core problems in the micro metal forming, which is mainly caused by non-uniform deformation of metal foils (Furushima and Hirose, 2018). The in-situ observations of the deformation behaviour and the surface roughness phenomena of different materials foils are very important to understand the influence of size effects in micro metal forming. For this persistence, the testing system should have the ability to perform mechanical tests of miniature and extremely small and thin specimens (Kweon et al., 2006). In the past few years, the concern about the development of miniature testing apparatus inclined the interest of researchers (Furushima et al., 2018; Partheepan et al., 2005b; Chao and Liu, 2003; Ma et al., 2002). A small disc-type tensile specimen and fixtures to hold the samples with the help of a rigid pin was recommend by Partheepan et al. (2005b) to calculate the mechanical properties of the selected materials and they used the finite element method (FEM) to check the feasibility of the sample geometry. Chao and Liu (2003) developed a ball-screw

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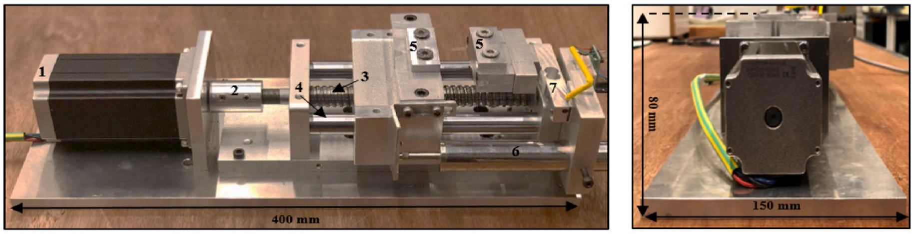


(a) Front view **(b) Side view**

Fig. 1. Overall Structure of the testing machine: (1) stepper motor, (2) coupling, (3) lead screw, (4) supported column (5) tensile test fixtures, (6) linear variable differential transformer (LVDT), and (7) Load-cell.

Table 1
Specifications of the developed UTM.

Maximum stroke	**30 mm**
Configuration	Twin column support
Mounting	Table/ground: Horizontal
Load cell	3 kg, 5 kg, and 10 kg (as required)
Electrical supply	240 v single-phase main supply
Strain-rate	0.01 mm/s, 0.02 mm/s and 0.05 mm/s (as required)
Column diameter	15 mm
Weight	5.5 kg (12 lbs.)
Operating temperature	Room temperature

guide-way testing machine with the maximum displacement and load of 100 mm and 100 kg, respectively. The machine was equipped with DC-servomotor that unable to provide low speed with high precision.

Later, Ma et al. (2002). was constructed and built a novel tensile device compatible with a scanning electron microscope (SEM). However, a lead screw is used without any guided ways which causes specimen moving during the test. An ideal uniaxial tensile testing system consisting of a closed-loop actuator, a load cell, and two grippers to hold the specimen was successfully developed by Hou and Chen (2005b). However, this established system was very complicated and expensive. Apart from this, only a few innovative small test machines are currently available in the market, but the typical budgetary limitation is big challenge to acquire those laboratory apparatuses. Therefore, it is necessary to develop a new highly precise compact testing apparatus.

To understand and optimize the idea of development of miniature testing apparatus, it is necessary to review some basic scientific facts first. Therefore, the detailed analysis of selected aspects of intensive literature concerned with miniature testing apparatus is briefly discussed and studied to evaluate the possible mechanisms. In this article, a new compact and portable UTM compatible with a 3D laser-confocal microscope is developed with an ultrahigh precision drive system and high accuracy load and displacement measurement to perform different mechanical tests with utmost control and data collection performance. The developed instrument can also be used for compression and bending analysis with appropriate fixtures and samples, but to verify the validation of the developed apparatus, these challenges are not be addressed. After developing this UTM, micro-metallic test samples made of the thin copper sheet are used to perform the actual tensile test. To verify the performance of the developed UTM, the reported results of thin copper samples are compared with the results of similar samples tested in a commercial UTM (METEX – 1 kN) using the same crosshead speed.

2. Specifications of the developed UTM

The developed UTM is designed to test small and thin specimen made of metals, polymers and metallic alloys, in the selected load range. In terms of the loading capacity of the developed apparatus, the specimen preparation and handling processes, only the thin miniaturised specimens are suitable for testing. This equipment is capable of analyzing tensile samples up to 8 cm of length. Fig. 1 shows the overall structure of the established universal testing machine and all the specifications of the developed apparatus are listed in Table 1. The general features of the developed machine are described as following.

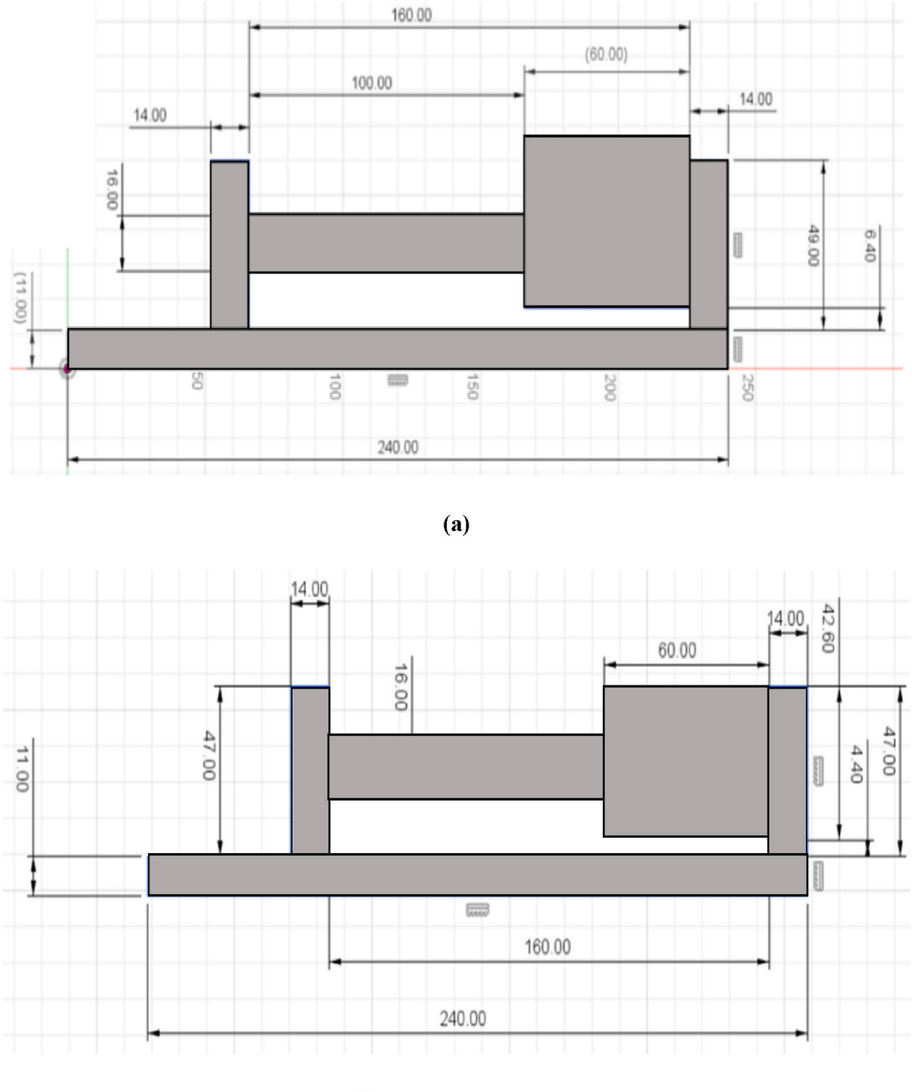
2.1. Features

- Easy to operate and control the system (e.g. emergency stop).
- Able to test miniaturised components (e.g. strain gauges).
- No hydraulic or pneumatic air supplies.
- Compatible with the 3D laser-confocal microscope.
- Easy to carry or move (portable).
- Stable design.
- Compact instrument – apparatus requires less than 0.06 m^2 of floor space.
- Able to perform micro compression and bending tests.

3. Design concept

3.1. Mechanical design

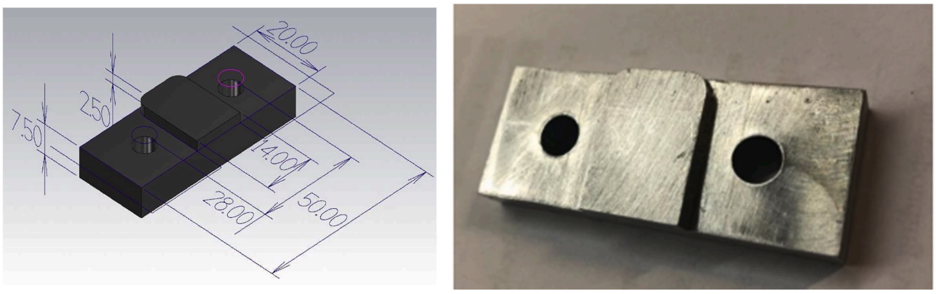
This instrument is mechanically designed to minimize the effects of load introduction in the main frame, ball screw, and the relative movement between the movable crossheads. The testing device is mainly made of aluminium alloy (Al 6061), excepting some frictional elements like the bearing and ball screw, which are made of steel (SAE 52100). After examining the previous studies (Kweon et al., 2006; Furushima et al., 2018; Partheepan et al., 2005b; Chao and Liu, 2003; Ma et al., 2002; Hou and Chen, 2005b) and conventional standard testing methods (Clothier and Shang, 2010), it is found that screw-driven mechanism is a leading technique to construct an ideal small UTM. Therefore, a small computer numerical control (CNC) linear table (model no - SFU1605) driven by a single lead screw is selected (as shown in Fig. 2a), which further attached to a stepper motor (NEMA 23 Stepper Motor 3 Nm). In order to pull the tensile samples, without torsion, the ball screw converts the stepping motor rotation into linear motion. The two feed rods in the selected CNC table provide precise linear movement of the carriage along the longitudinal axis and prevent the test samples from twisting. To make this small testing device, some modifications have done in the original specifications, such as the height of the CNC table, as shown in Fig. 2. In the next design stage, the clamps are designed to hold the dog-bone shape tensile test samples without slippage to carry out the actual testing. The specimen holder consists of two fixtures made of aluminium. The designed fixtures should be able to tightly grip the samples without breaking them at the grip faces. Therefore, the tensile test fixtures are provided in the form of male and female part to uniformly press the samples, as shown in Fig. 3a and (b). One specimen holder is attached to the load cell in order to record the load intervals, where the second clamp is moved forward and backward by a leadscrew-nut mechanism to provide enough pressure or force. All



(a)

(b)

Fig. 2. (a) Original specifications of CNC linear sliding table, **(b)** Modified specifications of CNC linear sliding table (Unit: mm).



(a)

(b)

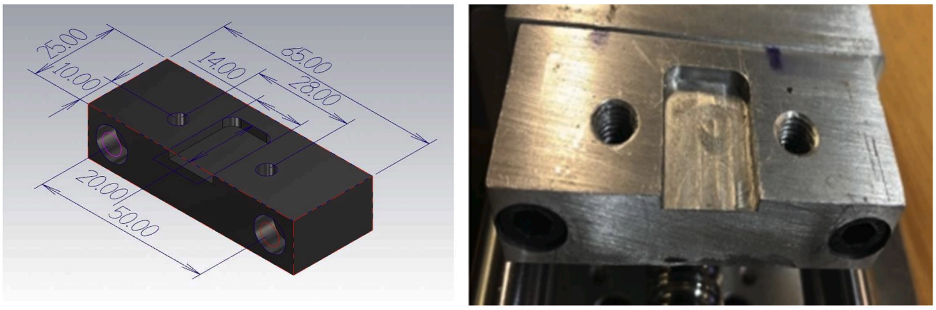
Fig. 3(a). (a) Male part of tensile fixture (unit: mm), **(b)** Actual specimen holder.

the special designed holders and fixtures were machined and manufactured on high-speed 3-axis vertical computer numerical control machine.

3.2. Electronic design

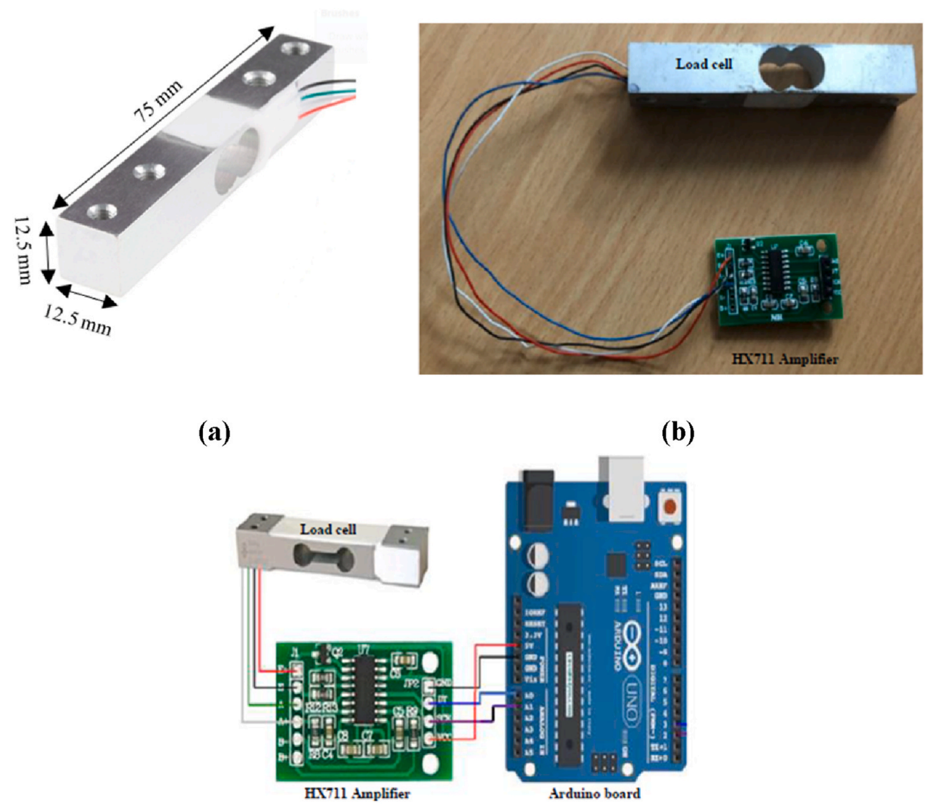
In this small testing instrument a stepper motor is used to drive the linear table with lead-screw guideway. For different test routines, it is necessary to control the both speed and position of the movable clamp, and therefore a stepper motor is used. The Control of the stepper motor is done by analogue signal generator device. With the signal generator, the speed, and rotation of the stepper motor can be easily controlled.

A miniature straight bar load cell of 10 Kg capacity is employed on the developed machine to acquire the required resolution from the



(a) (b)

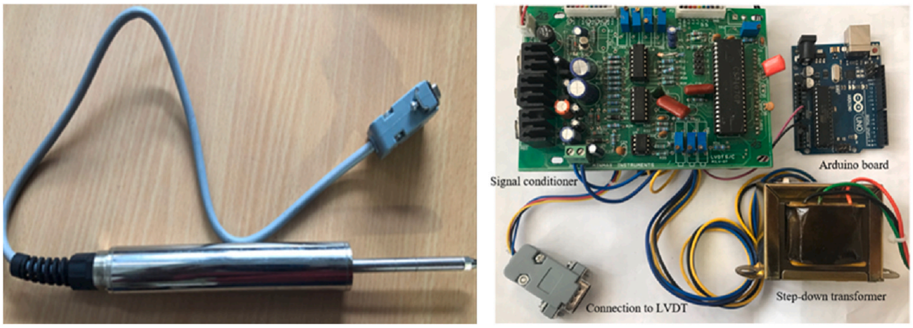
Fig. 3(b). **(a)** Female part of tensile fixture (unit: mm), **(b)** Actual specimen holder.



(a) (b)

(c)

Fig. 4. **(a)** Load cell dimensions, **(b)** Load cell with an amplifier, and **(c)** Load cell interface Arduino.



(a) (b)

Fig. 5. **(a)** A digital displacement gage (LVDT), **(b)** LVDT interface Arduino.

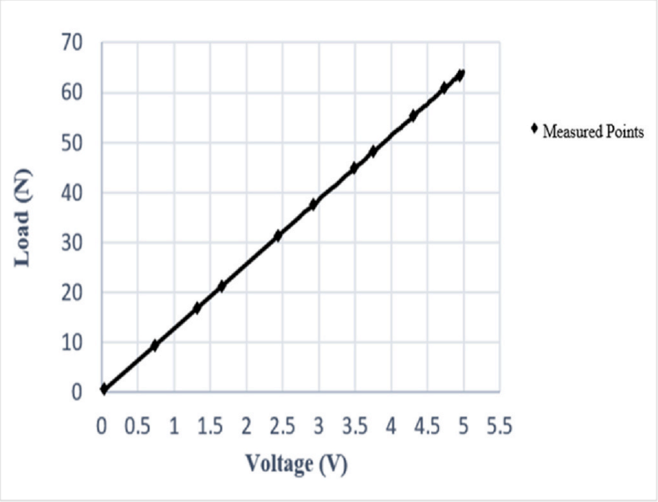


Fig. 6. Static calibration curve for the load cell.

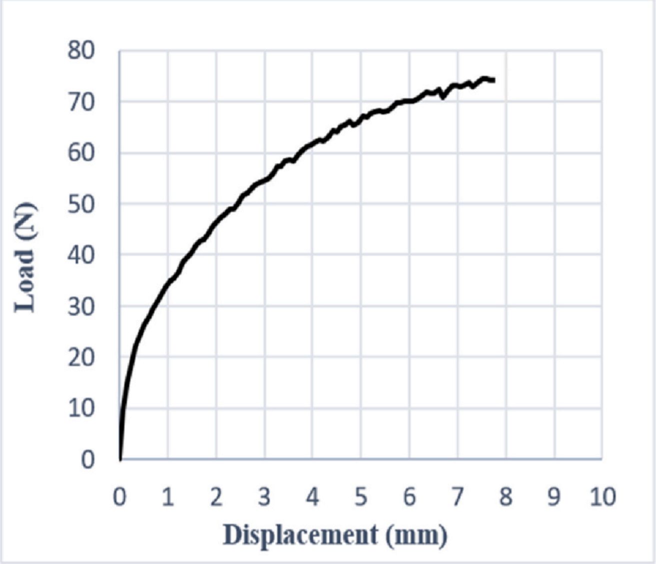


Fig. 8. Load vs displcement graph.

measurements. This miniature UTM is designed according to the different ranges of miniature straight bar load cell, for measuring the different load intervals. A HX711 load cell amplifier is used to connect the selected 10 Kg load cell with Arduino board, as shown in Fig. 4. No programming was applied for the internal registers because all the controls to HX711 were prepared through the pins. Load cell connections to the Arduino board are shown in Fig. 5b. To calculate the material strain rate, the displacement of the machine crossheads was measured with a precision digital displacement gage (LVDT) (as shown in Fig. 5) with 0.01 mm resolution and 20 mm maximum displacement. Encoder signals are required to determine the actual position of LVDT therefore the LVDT is attached to an Arduino board. LVDT connections to the Arduino board are shown in Fig. 5.

3.3. Software

Arduino contains a microcontroller, which is able to be programmed to sense and control objects in the physical world. Once all the circuits have been prepared and completed, the sketch (Arduino coding) was uploaded to Arduino board. The Arduino coding is a set of instructions that tells the board what functions it needs to perform and it can only hold and perform one coding at a time. However, to achieve high-

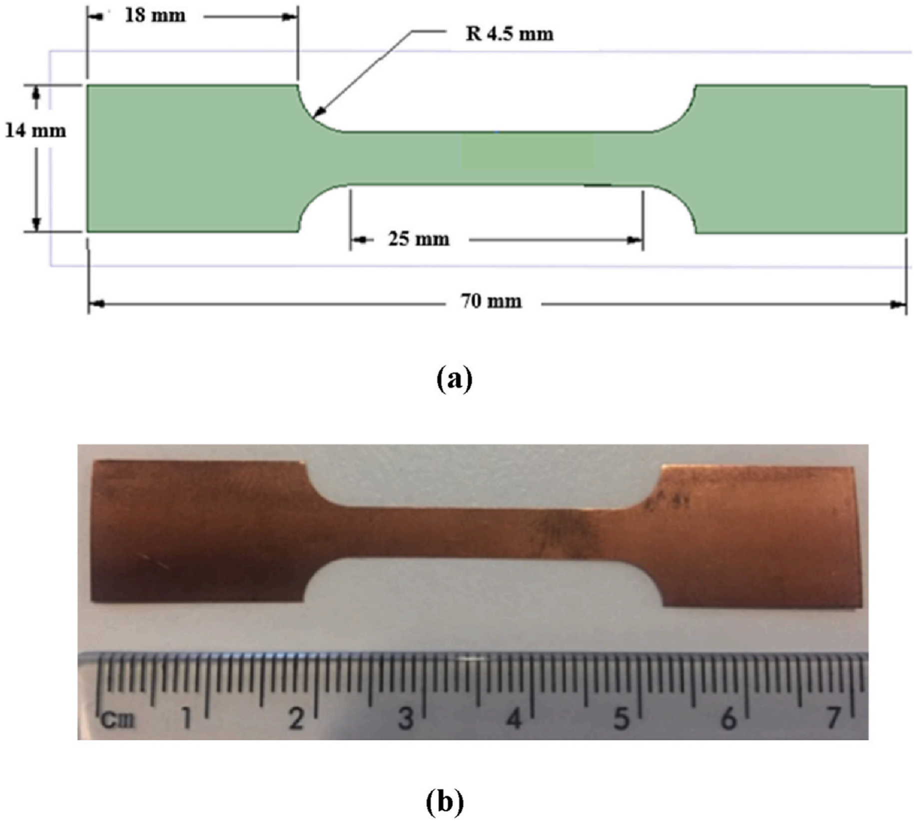


Fig. 7. **(a)** Schematic of micro tensile samples, **(b)** Actual copper specimen.

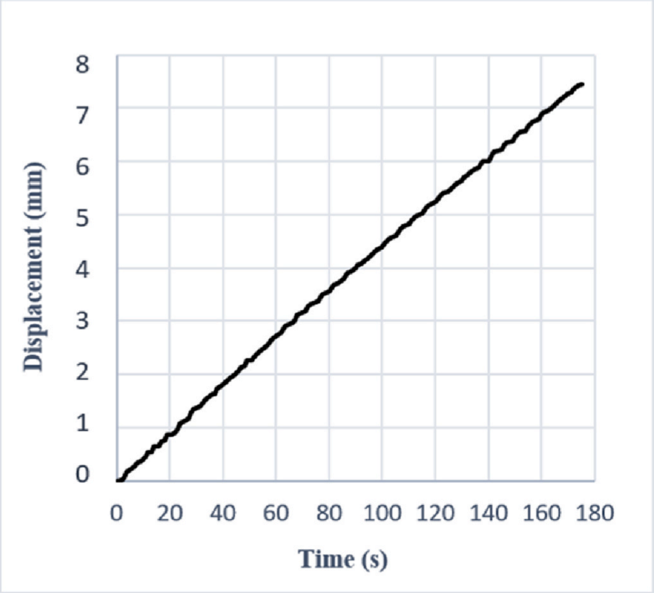


Fig. 9. Displacement vs time graph.

resolution load-displacement curves for the analyzed sample it is necessary to measure the load intervals and strain-rates simultaneously. Therefore, a new sketch was prepared and uploaded to data acquisition card (Arduino) to measure the loads and elongations at the same time. After it, the Tera-Term software was used to transfer the Arduino sensor data to excel sheet. With this process, all the parameters (applied force, displacement and time) were captured and saved in real time for subsequent examination.

4. Performance and validation

Before using this instrument for commercial purpose, the performance of the new UTM was required to evaluate. Most importantly, the calibration of the selected load cell (10 Kg) was required before attaching it to the testing instrument for conducting the actual experiment. Therefore, the calibration of the load cell was conducted by collecting data of different known applied loads (weights) and measuring its corresponding output voltage.

Fig. 6 shows the obtained linear behavior between the applied load and the output voltage as obtained from the load cell. The following equation is used to describe the relationship between applied load (P) and the output voltage (V) (Huerta et al., 2010).

$$P = 12.8366V - 0.06574 \tag{1}$$

where the applied load (P) is given in Newtons and the output voltage (V) in volts.

In order to validate the developed testing apparatus, a pure copper foil with the thickness of 50 μm was selected for actual tensile tests, the designed miniature copper sample is shown in Fig. 7. The dimensions of the tensile sample are designed according to ASTM E8/E8M. After cutting all the samples in dog-bone shape, they were annealed in order to increase the ductility. The micro tensile test samples were annealed in the NBD-O1200 vacuum tube annealing furnace. Because the samples were very small, besides vacuum condition during heat treatment, the Argon (Ar) air protection was also adopted to avoid oxidation. All the tensile tests have been performed with the same crosshead velocity (0.05 mm/s), so that the results from the newly developed UTM can be compared with the reported test results derived from a standard UTM to examine the performance.

Fig. 8 shows load-displacement curve for the analyzed copper sample measured on new UTM. Fig. 9 shows a plot of the displacement of the movable crosshead vs. time, where high stability can be observed when

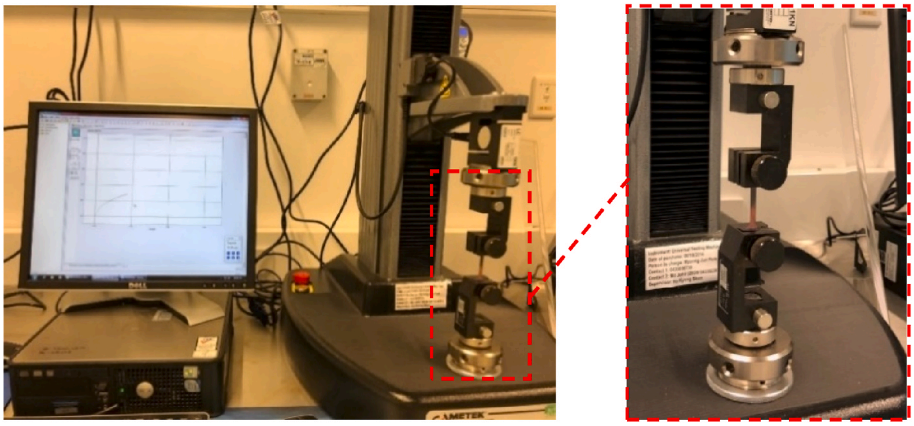


Fig. 10. Micro tensile testing on commercial UTM.

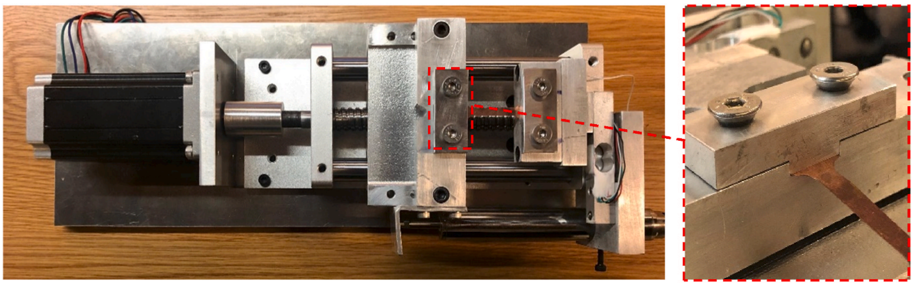


Fig. 11. Micro tensile testing on home-made UTM.

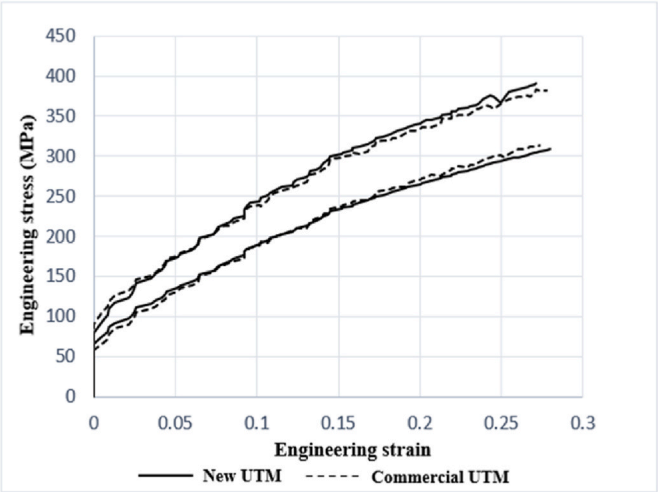


Fig. 12. Stress-strain curves obtained from commercial Instron and newly developed testing apparatus.

Table 2
Average values of a tensile test obtained from home-made UTM.

Load (N)	Extensions (mm)	Stress (MPa)	Strain
0	0	0	0
3.17	0.08	12.67	0.003
13.39	0.26	53.53	0.0104
19.58	0.44	78.33	0.017
29.78	1	119.12	0.036
39.51	1.66	158.07	0.065
49.21	2.72	196.84	0.101
60.07	4.44	240.29	0.161
65.55	5.64	262.2	0.206
70.51	7.48	282.07	0.275
69.86	8.3	279.44	0.287

Table 3
Average values of a tensile test obtained from standard UTM.

Load (N)	Extensions (mm)	Stress (MPa)	Strain
0	0	0	0
9.77	0.06	39.09	0.002
16.82	0.150	67.31	0.005
22.42	0.23	89.69	0.009
29.27	0.51	117.10	0.020
39.91	1.32	159.64	0.052
49.48	2.46	197.90	0.098
60.31	4.14	241.22	0.165
65.44	5.56	261.76	0.222
70.01	7.43	280.03	0.297
68.88	7.60	275.55	0.304

Table 4
Calculated mechanical properties.

Mechanical properties	UTS (MPa)	Yield strength (MPa)	Yield strain	Ductility (% *El*)
Home-made UTM	282.1	78.6	0.023	28.72
Commercial UTM	280	81.9	0.025	30.43
Abs. error (%)	0.72%	4.07%	8%	5.61%

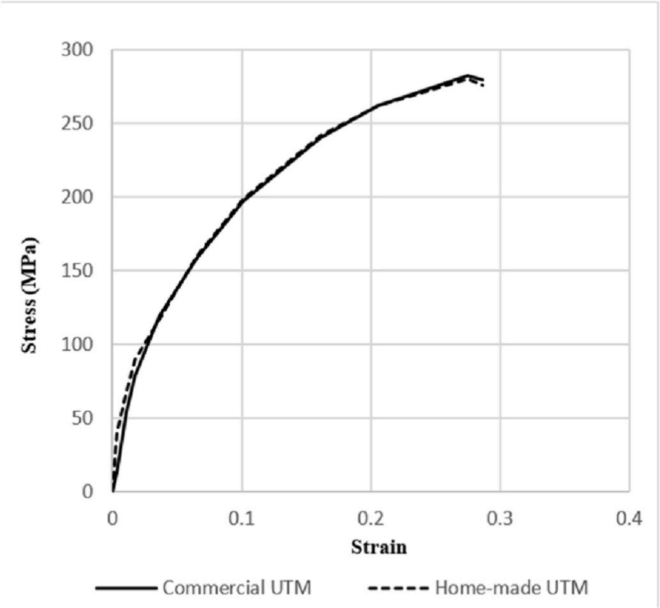


Fig. 13. Stress-strain curve obtained from commercial UTM and home-made UTM.

it moves along the drive screw with the sample gripped. This figure shows the very less mechanical noise during the crosshead movement, which means that the developed apparatus does not have additional effects, such as vibrations or speed alterations that could affect the accuracy. Fig. 10 and Fig. 11 shows the real photographs of actual tensile tests conducted on the commercial UTM (METEX – 1 kN) and home-made UTM, respectively. Fig. 12 shows the stress-strain curves of the similar copper samples as obtained from a commercial UTM and home-made UTM under similar conditions. From this figure, it can be observed the calculated values or results are quite similar, which indicate that the developed testing instrument is suitable to obtain reliable mechanical properties.

From these average stress strain values, the following mechanical properties were determined, as shown in Table 4. These results also reveal the absolute errors of measurement of 0.72%, 4.07%, 8%, and 5.61% for ultimate tensile strength, yield strength, yield strain, and ductility respectively. The apparatus is very compact in size to put under the 3D laser-confocal microscope, as shown in Fig. 14. To calculate the relative surface roughness behaviour of pure copper foil, the micro tensile test was performed on the newly developed machine under a 3D laser-confocal microscope. Where, the relative average surface roughness 'R_a' was evaluated. For the in-situ micro-observation, a large region of stretched blank surface was observed by 3D laser-confocal microscope by using high magnifying lens (5X: 0.45 μm). A constant distance was maintained between the stretched surface and the objective lens during testing.

The reported results obtained from the newly developed apparatus and standard UTM were further used to determine the absolute errors in calculated mechanical properties values. The following Table 2 and Table 3 shows the average values of tested copper sample achieved from fabricated machine and standard machine, respectively. The average stress strain values are difficult to visualize from these two tables. Hence Fig. 13 is drawn which show the stress-strain curves of tested copper sample as obtained from home-made UTM and commercial UTM. From this figure, it can be observed that the home-made UTM has a satisfactory performance, as the high stress-strain values of micro-scale metallic sample can be achieved by our machine.

Fig. 15 shows the schematic illustration of testing setup. The average surface roughness 'Ra' surface roughness was measured at the same area in four stages. The evaluated three-dimensional surface profiles of tested sample are shown in Fig. 16. Here it can be seen that the surface roughness increase with the increase of engineering strain 'ε'. From real-time examination using a newly developed compact testing apparatus, it is discovered that the fracture behaviour is mostly brought about by the concave surface that is formed by free surface roughening. Moreover,

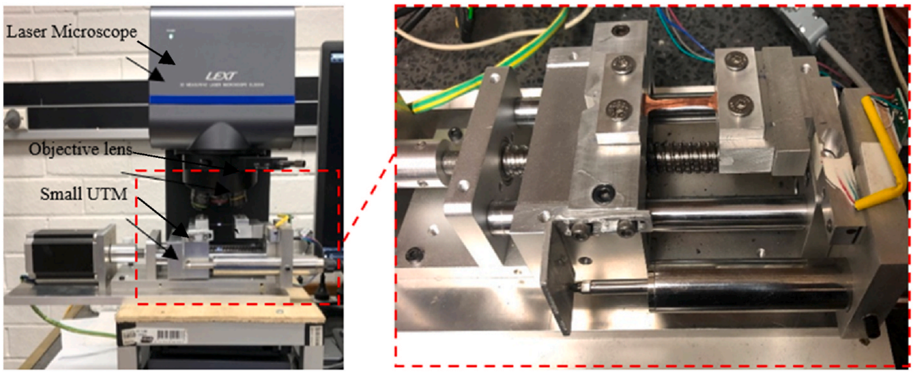


Fig. 14. The developed UTM under the laser microscope.

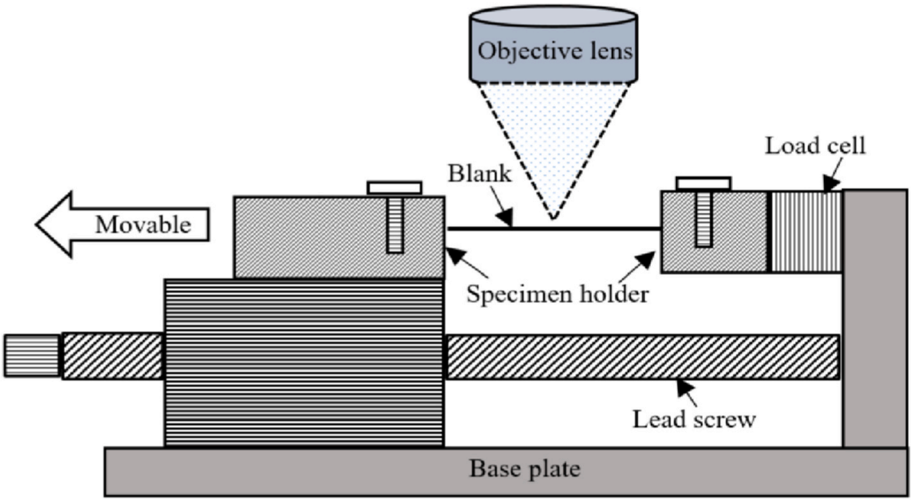
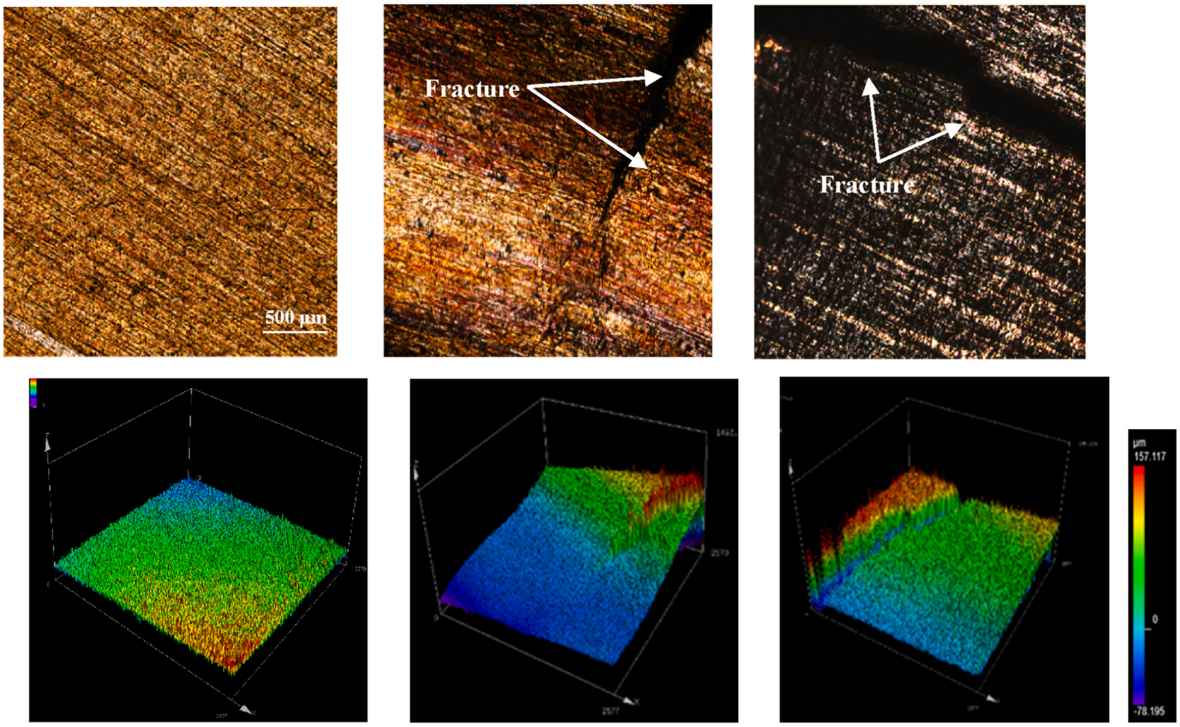


Fig. 15. Schematic illustration of testing setup.



(ε = 0.15, R_a = 8.8 μm) (ε = 0.28, R_a = 12.1 μm) (ε = 0.39, R_a = 13.4 μm)

Fig. 16. 3D surface profile of copper foil (t = 0.3 mm) obtained from laser microscope.

the fracture is mainly caused by the local necking, which occurs in a very narrow region in micro-forming. In micro forming, the surface roughening easily occurs on the free surface of the specimen because the deformation sample contains several grains. In the micro metal forming processes, the surface roughness is mostly occurred due to the crystal orientation between the grains. So, it is discovered that and the developed UTM is an appropriate device to do the surface roughness assessment on micro-metallic samples to investigate the size effects in micro metal forming, and it is an appropriate instrument to check the variation of thickness and surface irregularity.

5. Conclusion

This article described a method to design, construction and develop a portable miniaturised universal testing machine (UTM) for thin and soft materials. The design has the capability to obtain displacement as small as 0.01 mm and maximum loads of 100 N. The mechanical properties of a 50 μm thick pure copper foil were measured on this device and all the results were compared with the mean values obtained from a commercial UTM. In addition the mean values reported by newly developed machine were found in satisfactory agreement with the values obtained with a commercial UTM. The reported results and the performance of developed UTM indicate that it is an appropriate instrument to calculate reliable mechanical properties of thin and soft materials. The main advantage of this testing device is the lesser cost and smaller size compared to other commercial machines. Furthermore, an important feature of this device is the simplicity to exchange components (load cell and fixtures) according to the user requirements. This new testing system can be used on a 3D laser-confocal microscope, in order to evaluate the mechanical behavior of materials on a microscale in real time. Future efforts will address the use of this equipment to obtain the mechanical properties of other metallic materials in order to provide a better understanding of the size effects in micro metal forming. The price of this tensile test machine ranges from $1200 to $1400. The main factors that affect the cost are controller, tensile grips, and fixtures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Chao, Y.C., Liu, D.S., 2003. Gold wire and solder joint microforce testing using microforce tester. Exp. Tech. 25 (5), 37–40.

Clothier, K.E., Shang, Y., 2010. A geometric approach for robotic arm kinematics with hardware design, electrical design, and implementation. Journal of Robotics 2010.

Furushima, T., Hirose, Y., 2018. Development of in-situ observation methods of surface roughening behavior by hand-size stretching test for metal foils. J. Phys. Conf. 1063, 12130.

Furushima, T., Tsunezaki, H., Hirose, Y., 2018. Fracture and surface roughening behaviors in micro metal forming. Procedia Manuf. 15, 1481–1486.

Hou, P.H., Chen, T.Y., 2005a. An automatic tensile test measurement system for miniature specimens. Exp. Tech. 29 (4), 32–36.

Hou, P.H., Chen, T.Y., 2005b. An automatic tensile test measurement system for miniature specimens. Exp. Mech. 29 (4), 32–36.

Huerta, E., Corona Hdez, J., Oliva, A., Aviles, F., González-Hernández, J., 2010. Universal testing machine for mechanical properties of thin materials. Rev. Mexic. Fisica 56, 317–322.

Jeswiet, J., Geiger, M., Engel, U., Kleiner, M., Schikorra, M., Duflou, J., Neugebauer, R., Bariani, P., Bruschi, S., 2008. Metal forming progress since 2000. CIRP Journal of Manufacturing Science and Technology 1 (1), 2–17.

Jiang, Z., Zhao, J., Xie, H., 2017. Microforming Technology: Theory, Simulation and Practice.

Kals, T.A., Eckstein, R., 2000. Miniaturization in sheet metal working. J. Mater. Process. Technol. 103 (1), 95–101.

Kweon, H., Choi, S., Kim, Y., Nam, K., 2006. Development of A new UTM (universal testing machine) system for the nano/micro in-process measurement. Int. J. Mod. Phys. B 20 (25n27), 4432–4438.

Ma, Z., Zhao, H., Huang, H., Zhang, L., Wang, K., Zhou, X., 2002. A novel tensile device for in situ scanning electron microscope mechanical testing. Exp. Tech. 1-9.

Ma, Z., Zhao, H., Huang, H., Zhang, L., Wang, K., Zhou, X., 2015. A novel tensile device for in situ scanning electron microscope mechanical testing. Exp. Tech. 39 (6), 3–11.

Partheepan, G., Sehgal, D.K., Pandey, R.K., 2005a. Design and usage of a simple miniature specimen test setup for the evaluation of mechanical properties. Int. J. Microstruct. Mater. Prop. 1 (1), 38–50.

Partheepan, G., Sehgal, D.K., Pandey, R.K., 2005b. Design and usage of a simple miniature specimen test setup for the evaluation of mechanical properties. Int. J. Microstruct. Mater. Prop. 1 (1), 38–50.

Razali, A.R., Qin, Y., 2013. A review on micro-manufacturing, micro-forming and their key issues. Procedia Eng. 53, 665–672.