ZANCO Journal of Pure and Applied Sciences
The official scientific journal of Salahaddin University-Erbil
https://zancojournals.su.edu.krd/index.php/JPAS

ISSN (print):2218-0230**, ISSN (online):** 2412-3986**, DOI: http://dx.doi.org/10.21271/zjpas**

RESEARCH PAPER

EFFECT OF COATING ON THE SPECIFIC PROPERTIES AND DAMPING LOSS FACTOR OF ULTEM 1010

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A B S T R A C T:

The dynamic analysis of the fused deposition modeling (FDM) products is one of the most important topics in investigation of 3D manufacturing nowadays. The purpose of this paper to present the dynamic properties of FDM parts made from ULTEM 1010 with different coating layer thicknesses. The coating process consists of two stages: physical vapor deposition (PVD) to pre-coat the samples with a thin layer of Cu and Cr to prepare samples for the next step, electroplating different layer thickness Cu an outer layer of Ni. COMSOL Multiphysics software is used for finite element analysis of the models for free and forced vibration. The results showed an increase in ultimate tensile strength and Young's modulus with increasing coating thickness. The effect of different coating layer thickness on the natural frequency and damping loss factor was studied. The scanning electron microscope was used to investigate the coating layers in tensile specimens after failure.

KEY WORDS: ULTEM 1010; Fused Deposition Modeling; Physical Vapor Deposition; Electroplating; Damping Loss Factor;
DOI: http://dx.doi.org/10.21271/ZJPAS.33.2.10
ZJPAS (2021) , 33(2);105-116 .

1. INTRODUCTION :

3D printing of polymers is widely used as a new cost-effective, efficient technology to produce a complex geometry structure (Singh, 2011, Bikas et al., 2016). In order to increase the quality and the flexibility of the prototype made by 3D printing the material properties must be improved. One of the methods to increase the strength of 3D parts is electroplating with different metal layers on the printed materials (Yang et al., 2015, Kannan and Senthilkumaran, 2014, Saleh et al., 2004). (Wang and Inman, 2013, Liu et al., 2017) mentioned that one of the essential properties that must be considered with increasing the strength of 3D printed parts is vibration suppression. Early mechanical failure by resonant vibration excepted in structures with lower damping. Therefore, stiffness and damping study of the systems are essential during the strengthening process of materials. (Taylor et al., 2018) studied the mechanical properties of ULTEM1010 to investigate of flexural behavior of ULTEM 1010. Different storage modulus and damping loss factor was presented by (Reichl and Inman, 2018), for various types of 3D printed materials. (Cuan-Urquizo et al., 2019, Mohamed et al., 2016, Bellini and Güçeri, 2003, Domingo-Espin et al., 2014) demonstrated the effect of the process condition on dynamic properties of the 3D printed product by FDM process using the theoretical model and experimental work. Many researchers have reported studies of the theoretical and empirical investigation of damping properties and natural frequencies of materials. They presented the effect of different parameters such as Poisson's ratio and modulus of elasticity on the natural frequencies and damping loss factor (Vitaliy et al., Vergassola et al., 2018, Al-Jumaily and Jameel,

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Article History:
Received: 26 / 10/2020
Accepted: 07/11/2020
Published: 18 /04 /2021

2000, Xu and Deng, 2016, Chirikov et al., 2020, Abbasloo and Maheri, 2018, Mohammed, 2017).
(Ge et al., 2020), studied the damping properties of a 3D printed photopolymer. They used impact loading that was caused by extreme damping. (Gietl et al., 2018), investigated 3D printed parts' damping properties measured and compared with the manufacturer's values. They use the COMSOL Multiphysics software to design samples by predicting eigenvalues or bending modes for cantilever beams.
This work present the effect of coating on the samples of ULTEM 1010 manufactured by fused deposition modeling. The mechanical properties were obtained from the tensile test for all models. The data from the experimental work used in the COMSOL Multiphysics software for determining the damping loss factor of the coated samples. The vibration tests were performed for pieces of the base material to validate the COMSOL Multiphysics software results.

2. EXPERIMENTAL METHODOLOGY

ULTEM 1010 samples for tensile and vibration tests were manufactured using a fused deposition manufacturing process by the 3D-Fabrica company (Turkey). Fifty tensile test specimens were made in x and y directions according to ASTM D638 type v. The beams with a dimension of 300×20×5 mm were produced for vibration analysis test. The experimental part of this study includes five experiments.

- First, the coating processes were performed on the sample groups, as indicated in Table 1. The coating process consists of two stages spattering physical vapor deposition (PVD) to pre-coat samples with thin layers of Cr(30nm) and Cu(200nm) and electroplating of the models with different layer thickness Cu and an outer layer of 2μm Ni. The PVD process and electroplating were performed by the FHR Centrotherm group and Galvanoform Companies in Germany.
- The second experiment was the tensile tests. A tensile test machine type "Karmmrath & Weiss Dortmund" with 10 kN capacity was used to perform tensile tests.
- In the third experiment, a field emission gun scanning electron microscope was used to study the specimens' coating layer. All second and third experiments were conducted at Freiberg University-Germany.
- The fourth and fifth experiments were free and forced vibration analysis of the provided samples. An impact hammer type 8206 B&K and an exciter type 5961 B&K were used to carry out free and moved vibration tests. An accelerometer type 4507 B&K and load cell type 8230 B&K used to measure acceleration and force. Then all data transmitted through a Module type 3560 B&K for analyzing as shown in figure 1.

Table 1. Sample sets for coating process

Thickness of coating (μm)		No of specimens		
Cu layer	Ni layer	x-direction	y-direction	z-direction
0	0	5	5	5
100	2	5	5	0
150	2	5	5	0
200	2	5	5	0
250	2	5	5	0

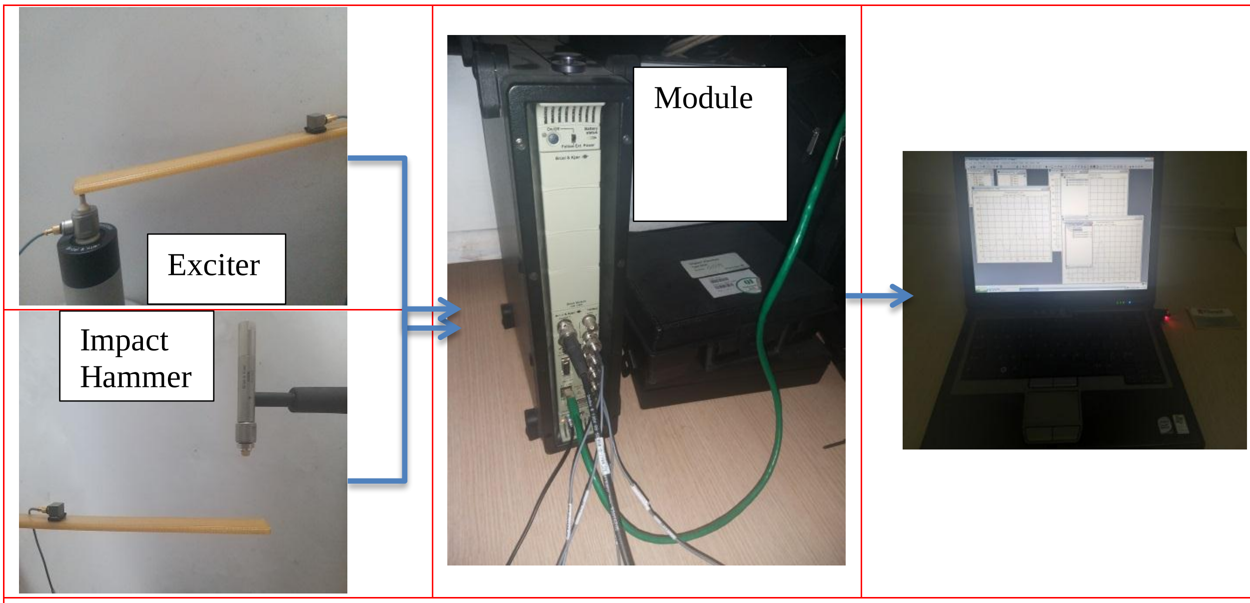

Figure 1 The experimental setup of a beam in free and forced vibration

3. FINITE ELEMENTMODELING

The finite element modeling FEM was performed using the COMSOL Multiphysics software for free and forced vibration analysis. A beam of 300mm long, 20mm width, and 5mm thickness with geometry properties of total surface area $0.015m^2$ and center of mass (0.15, 0.01, 0.0025)m was created. The material properties were obtained from the experimental procedure for ULTEM 1010. Eight thousand two hundred sixty-eight elements with 41415 degrees of freedom were made in the beam's meshing, as shown in figure 2. The left end of the beam was constrained to satisfy the cantilever beam's boundary condition. A nodal force applied on the free end of the beam with a frequency variation of 0.1 Hz/Sec during forced vibration analysis. The damping loss factor was obtained from the results using the half-power bandwidth method.

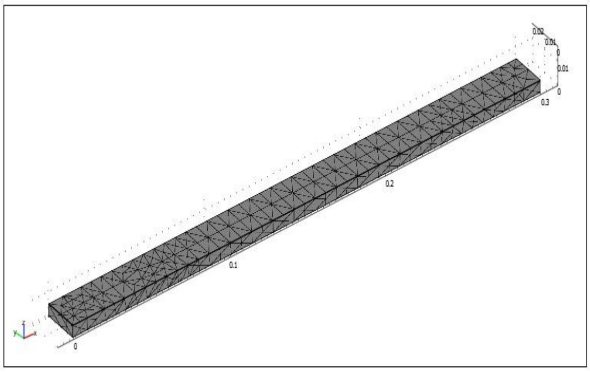

Figure 2.a The finite element model of a beam in COMSOL multiphysics software

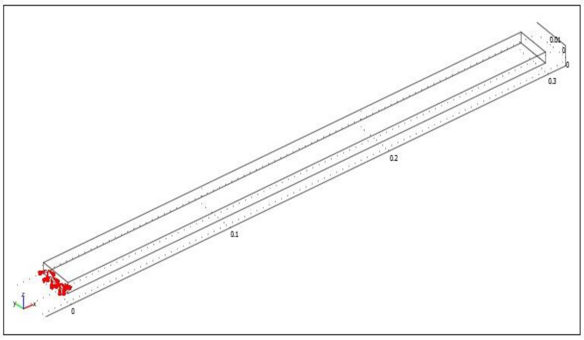

Figure 2.b The boundary condition of a beam in COMSOL multiphysics software

4. RESULTS AND DISCUSSION

Figure 3 shows the stress-strain diagram for ULTEM 1010 samples made by fused deposition modeling in x, y, and z-directions. It resulted from the stress-strain charts that the strength in x and y-directions were high in comparison with the samples made in the z-direction. The production of parts in the z-direction is more time-consuming and costly than the manufacturing in the x and y-directions.

The stress-strain diagrams for the coated samples were shown in figures 4 and 5 for the models made in x and y-directions, respectively. Ultimate tensile strength, modulus of elasticity, Poisson's ratio, and ductility can be obtained from the stress-strain diagrams for all cases. The five samples were electroplated for each coating thickness then tested.

The coating thickness layer's effect on the ultimate tensile strength of ULTEM 1010 is presented in figure 6. The results were conducted in the increasing of maximum tensile strength with an increasing layer thickness of Cu. The strength of ULTEM 1010 was increased by 175% for samples made in the x-direction and 162% for models in the y-direction, where the pieces coated by 250 µm Cu and 2µm Ni.

Figure 7 illustrates the effect of electroplated thickness on Young's modulus. The modulus of elasticity increased with the increasing of coating layers. The largest value of coating layer thickness resulted in the highest modulus of elasticity.

The scanning electron microscope images for the tensile tested samples' fracture surface are shown in figure 8. Good adhesion between the layers and the base materials that effected in high strength of the coated pieces can be observed. Also, it was apparent that the thickness of copper and nickel layers decreased due to the plastic deformation when indicated the high ductility of the coated samples in comparison with the base material ULTEM 1010.

Table 2 presented Young's modulus's values, and Poisson's ratio was obtained from the tensile test. These results were used for the finite element modeling in the COMSOL Multiphysics software. Damping loss factor (DLF) was determined using the half-power bandwidth method. The natural frequency must be determined firstly in the procedure of calculating the damping loss factor. In the COMSOL Multiphysics software, Eigen-frequency solution was used to find the natural frequency of all samples. The natural frequency obtained from the experimental impact hammer test was used to validate the COMSOL Multiphysics software results. The natural frequencies for base materials were brought in practical tests were 13.7 and 14 Hz for samples made in x and y-direction, respectively. These results agreed with the COMSOL Multiphysics software results, 13.4 and 13.6 Hz, for the models in x and y-directions. Frequency response solutions used to determine the damping loss factor in the COMSOL Multiphysics software — the data from the COMSOL Multiphysics software transferred to MATLAB the damping loss factor calculated using the half-power bandwidth method.

The results from forced vibration in the experimental method obtained and damping loss factor calculated in the same way used in finite element modeling in the COMSOL Multiphysics software. The damping loss factor for the base material ULTEM 1010 obtained from the COMSOL Multiphysics software was 0.004418 for samples made in the x-direction and 0.006096 for the models in the y-direction. The damping loss factor for the same material obtained in experimental tests was 0.004599for samples in the x-direction and 0.006475 for models in the y-direction. By comparing the results, a good agreement between the results from COMSOL Multiphysics software and experimental work can be observed. Table 3 shows the coated samples obtained from the COMSOL Multiphysics software for all models in x and y-directions. Damping loss factor increases for the coated pieces concerning the base material illustrated in figure 9. These results showed that the samples with a thickness of 150µm copper had the highest percentage value. Damping loss factor depended on mechanical properties such as modulus of elasticity, Poisson's ratio, and materials density. The variation of all aspects during the coating process caused in the most considerable value for samples with a 150µm copper thickness.

Table 2. Modulus of elasticity and Poisson's ratio for different samples.

The thickness of Cu coating (μm)	E-x direction (MPa)	E-y direction (MPa)	υ-x direction	υ-y direction
100	3215	3346	0.424	0.476
150	3912	3570	0.497	0.515
200	4121	4176	0.551	0.543
250	4319	4582	0.565	0.565

Table 3. First and second lateral frequencies from the COMSOL Multiphysics software.

Thickness of Cu coating (μm)	f1-x direction (Hz)	f1-y direction (Hz)	DLF-x direction	DLF-y direction
100	12.7	13.1	0.011142	0.007687
150	13.4	13.4	0.028687	0.011769
200	12.9	12.7	0.009147	0.008008
250	12.6	12.9	0.005302	0.008271

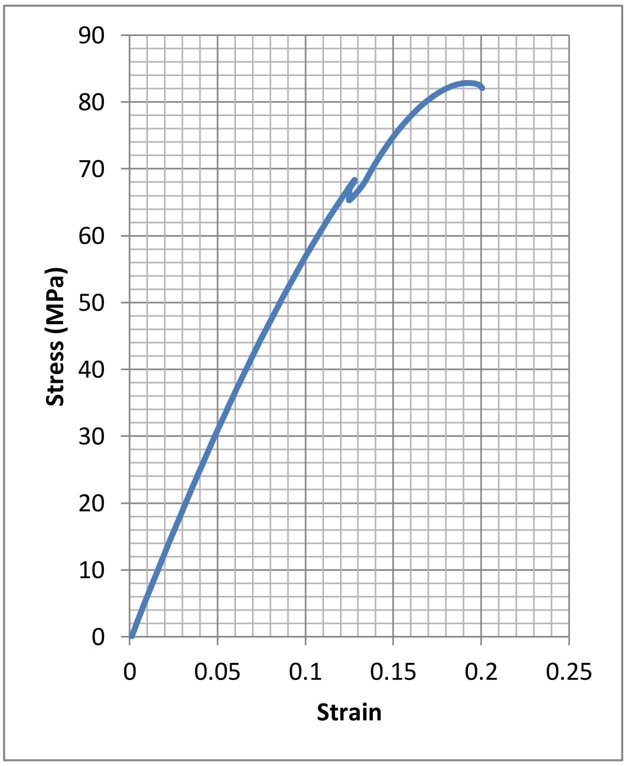

Figure 3-a. Strain-stress diagram for uncoated samples made in the x-direction.

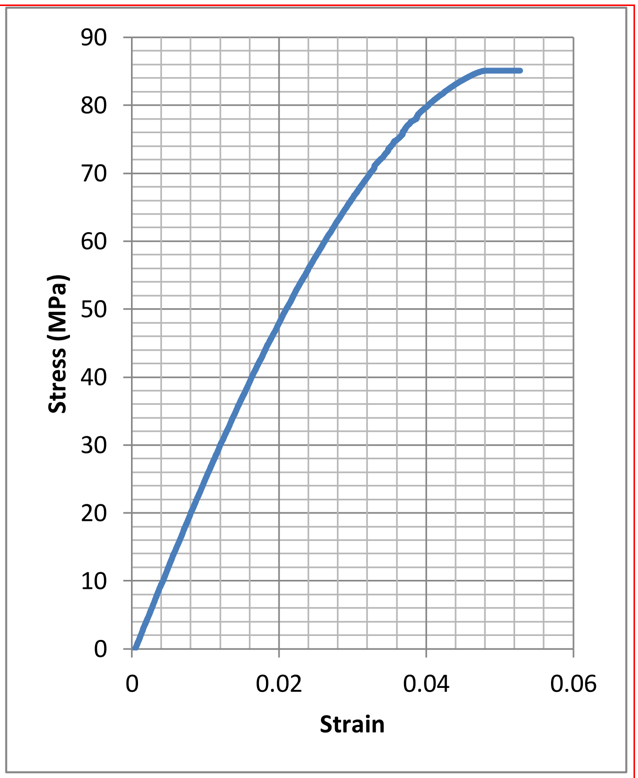

Figure 3-b. Strain-stress diagram for uncoated samples made in the y-direction

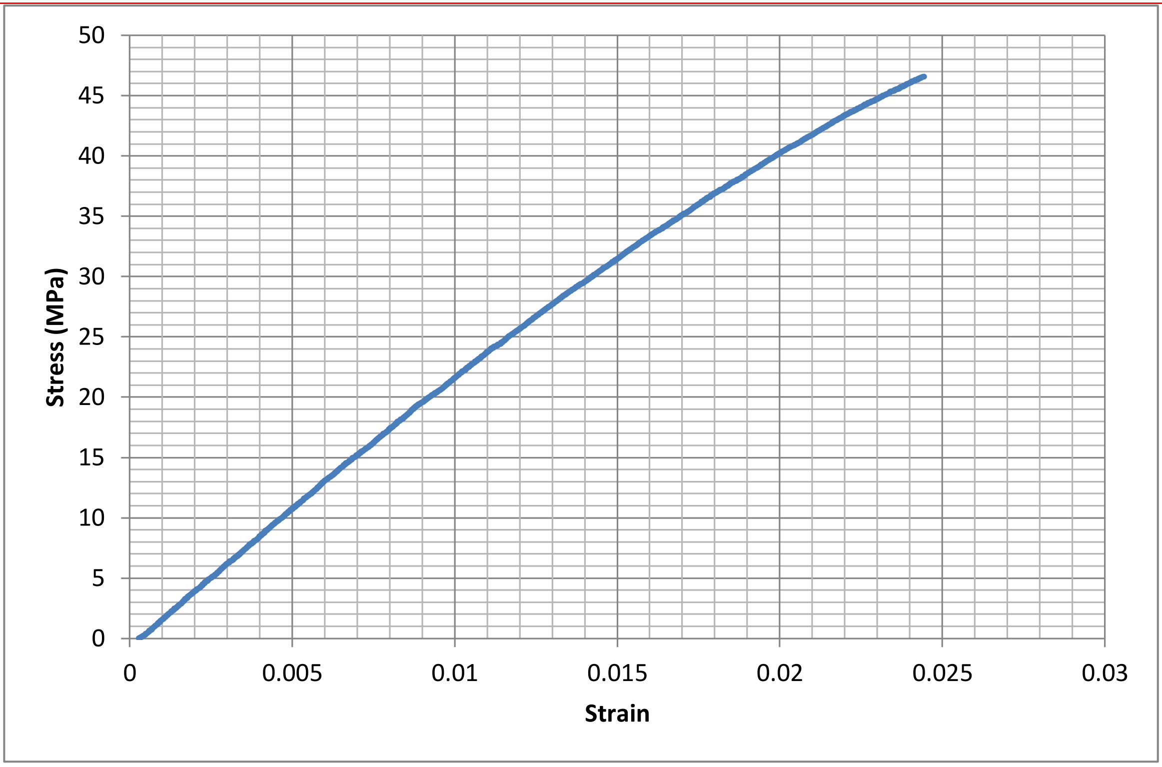

Figure 3-c. Strain-stress diagram for uncoated samples made in the z-direction

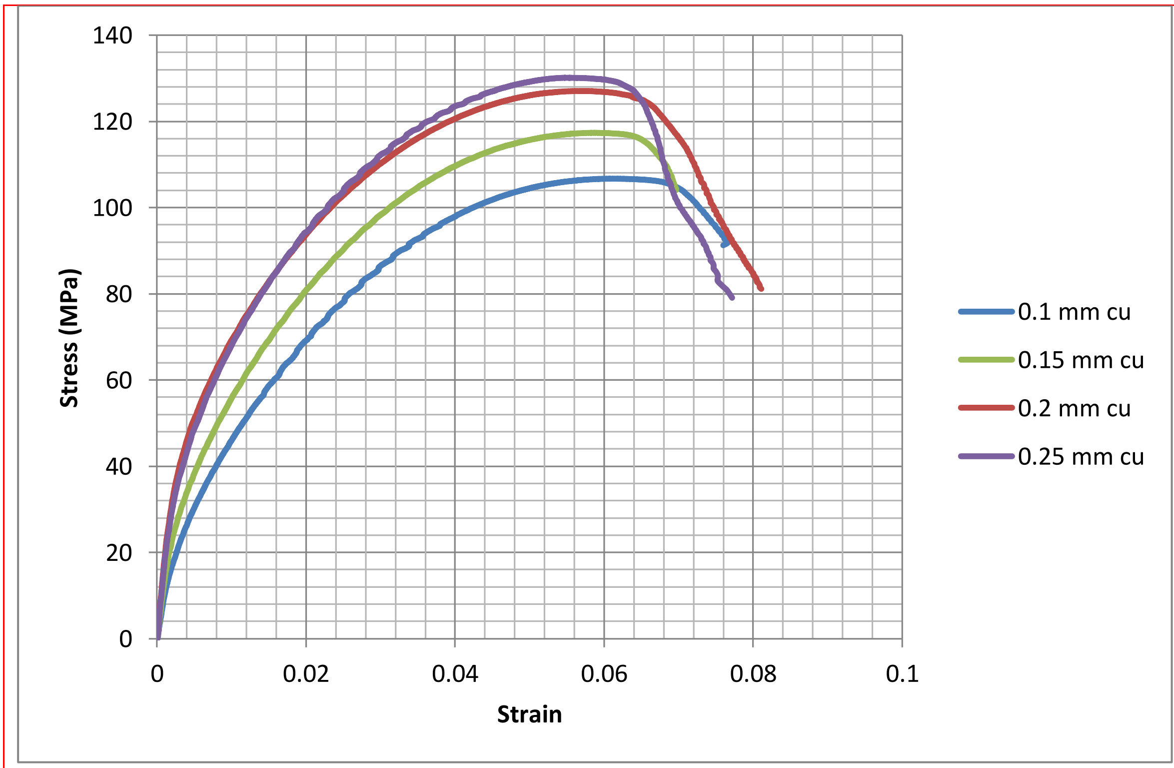

Figure 4. Strain-stress diagram for coated samples made in the x-direction

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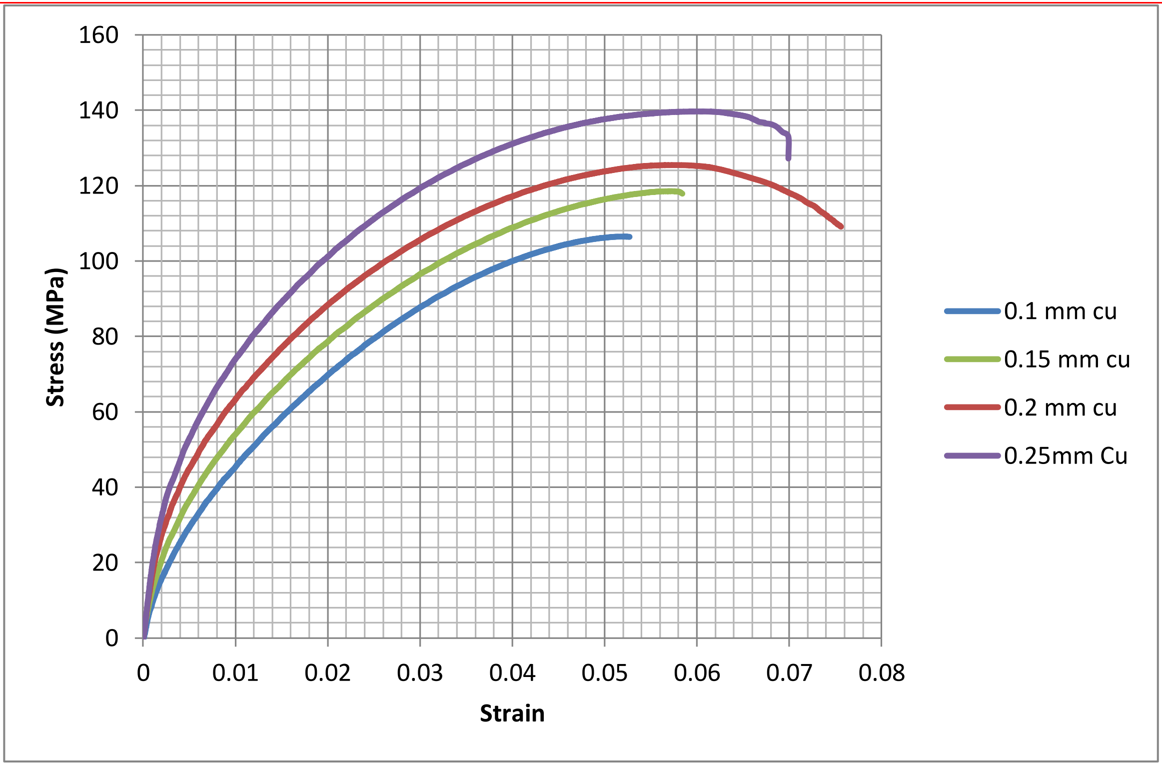

Figure 5. Strain-stress diagram for coated samples made in the x-direction.

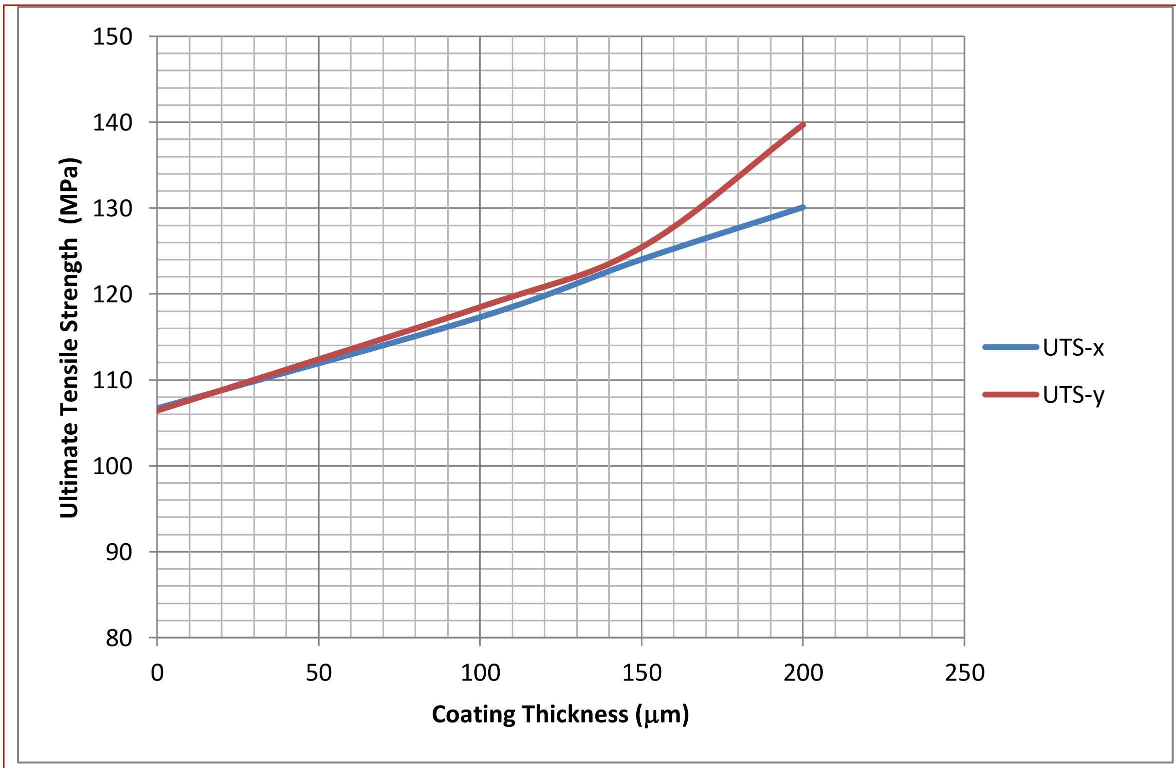

Figure 6. Ultimate tensile strength of samples with different coating thickness made in x and y-direction

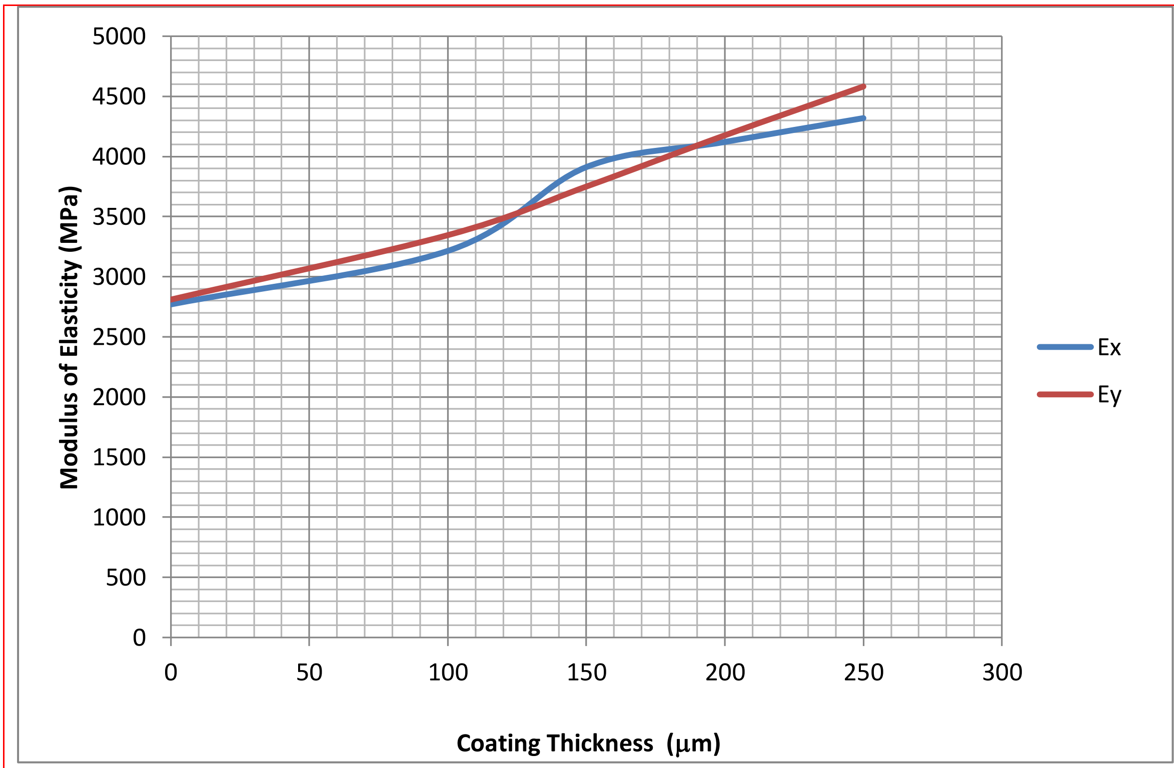

Figure 7. Modulus of elasticity for samples with different coating thickness made in x and y-direction

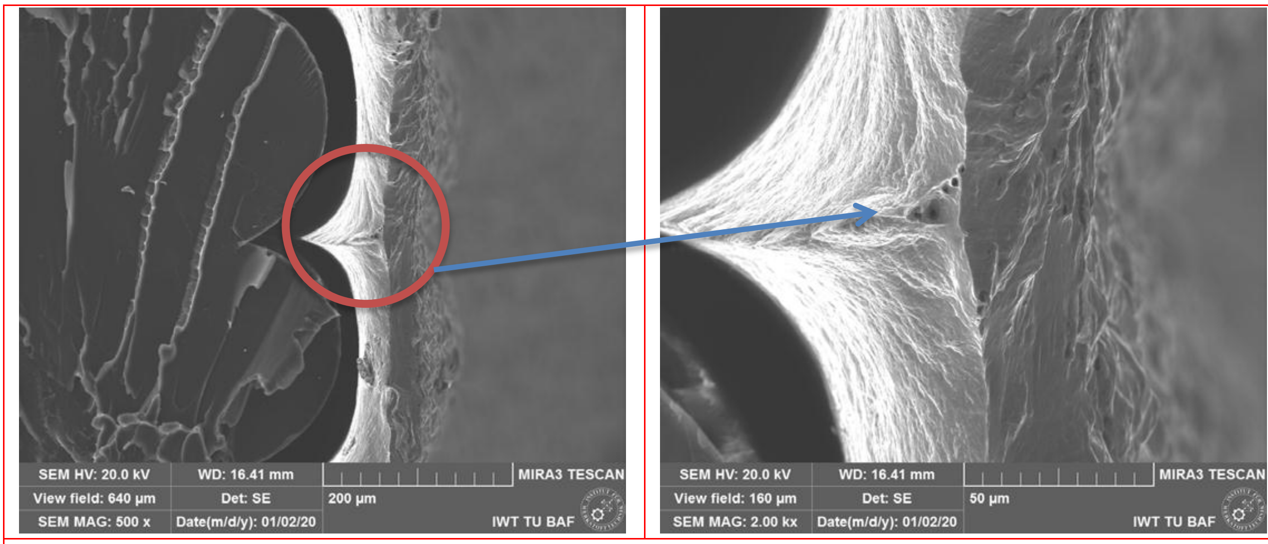

Figure 8-a. SEM image of the ULTEM 1010 coated with 100 μm Cu and 2 μm Ni.

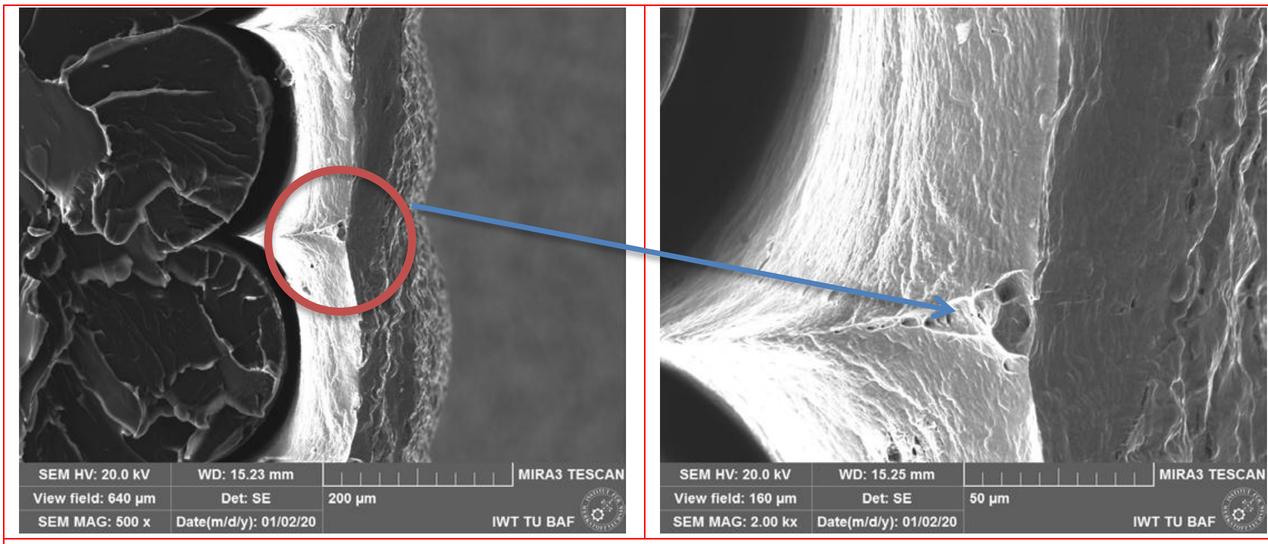

Figure 8-b. SEM image of the ULTEM 1010 coated with 150 µm Cu and 2 µm Ni.

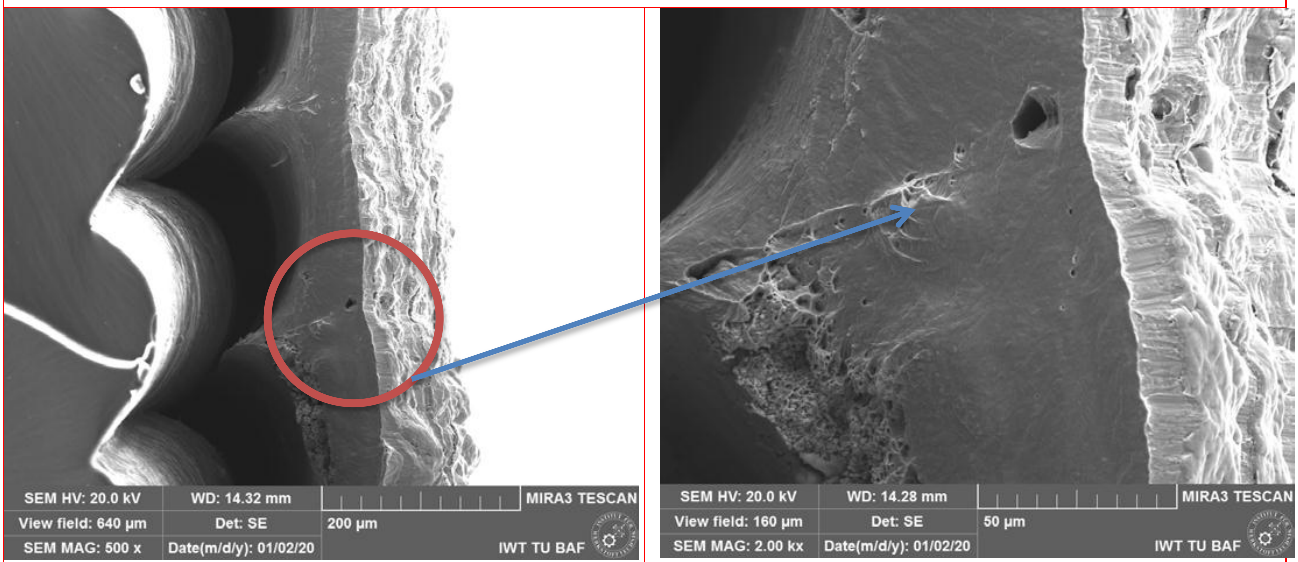

Figure 8-c. SEM image of the ULTEM 1010 coated with 200 µm Cu and 2 µm Ni.

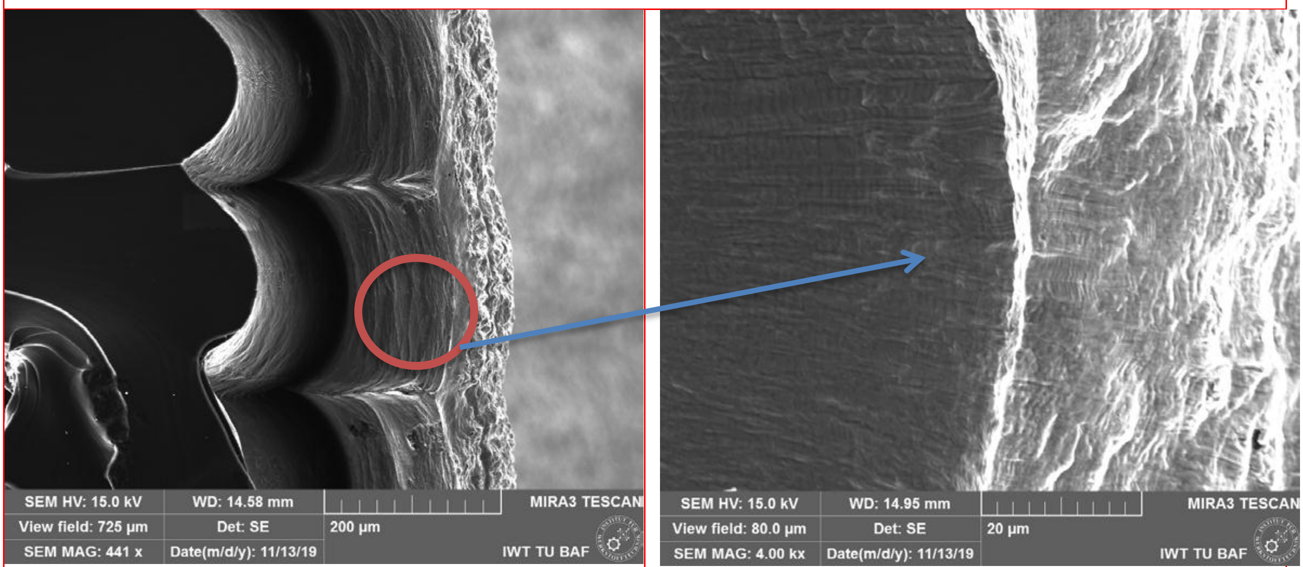

Figure 8-d. SEM image of the ULTEM 1010 coated with 250 µm Cu and 2 µm Ni.

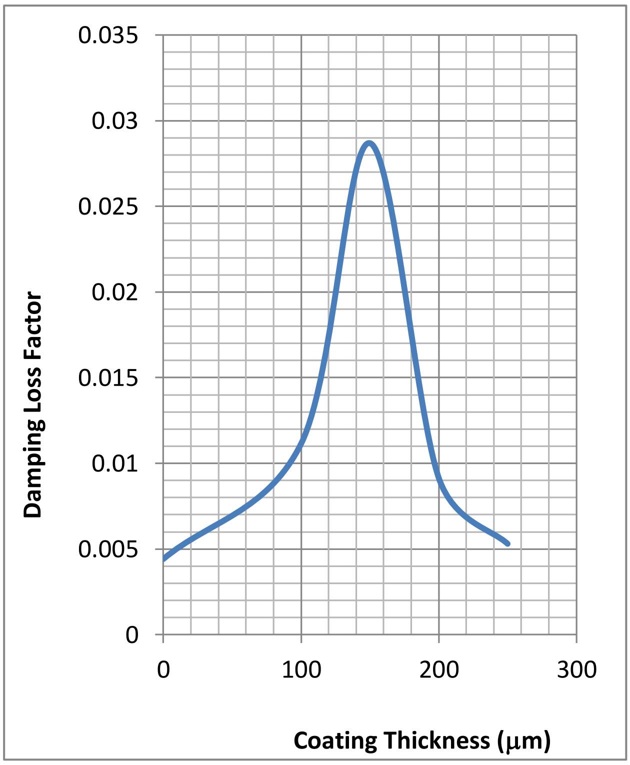

Figure 9.a Damping loss factor of coated samples made in the x-direction.

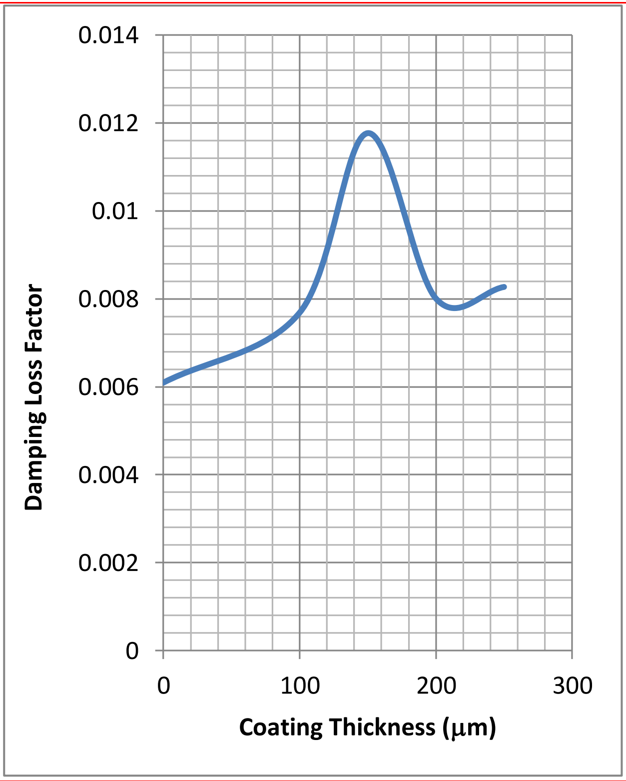

Figure 9.b Damping loss factor of coated samples made in the y-direction.

Figure captions

Figure 1 The experimental setup of a beam in free and forced vibration

Figure 2-a The finite element model of a beam in COMSOL

Figure 2.b The boundary condition of a beam in COMSOL multiphysics software

Figure 3-a. Strain-stress diagram for uncoated samples made in the x-direction.

Figure 3-b. Strain-stress diagram for uncoated samples made in the y-direction.

Figure 3-c. Strain-stress diagram for uncoated samples made in the z-direction.

Figure 4. Strain-stress diagram for coated samples made in the x-direction.

Figure 5. Strain-stress diagram for coated samples made in the y-direction.

Figure 6. Ultimate tensile strength of samples with different coating thickness made in x and y-direction.

Figure 7. Modulus of elasticity for samples with different coating thickness made in x and y-direction.

Figure 8-a. SEM image of the ULTEM 1010 coated with 100 µm Cu and 2 µm Ni.

Figure 8-b. SEM image of the ULTEM 1010 coated with 150 µm Cu and 2 µm Ni.

Figure 8-c. SEM image of the ULTEM 1010 coated with 200 µm Cu and 2 µm Ni.

Figure 8-d. SEM image of the ULTEM 1010 coated with 250 µm Cu and 2 µm Ni.

Figure 9-a. Damping loss factor of coated samples made in the x-direction.

Figure 9-b. Damping loss factor of coated samples made in the y-direction.

5. CONCLUSIONS

The results of tensile tests for the specimens of ULTEM 1010 manufactured by FDM were conducted in low mechanical properties in z-directions in comparison with x and y-directions. Therefore, the study performed on the samples in x and y-directions. PVD process was used to pre-coat the models with thin layers to prepare for electroplating materials with Cu and Ni layers. The tensile tests resulted in the highest ultimate tensile strength and modulus of elasticity for the layer thickness of 250 µm Cu and 2µm Ni. The data from the tensile tests used in the COMSOL Multiphysics software analyzed free and forced vibration to find the natural frequencies and damping loss factor. The maximum damping loss factor was obtained for the thickness of 150µm Cu and 2µm Ni. A comparison between the COMSOL Multiphysics software results and experimental tests showed a good agreement between the works.

Acknowledgments

The authors are grateful to the Freiberg University-Germany and Salahaddin University - Erbil for supporting this work.

Conflict of interests

The author declares that they have no competing interests.

Funding

The author declares that this paper does not have any funder.

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