Bhabha Atomic Research Centre

Electron Beam Centre

Kharghar, Navi Mumbai

SUMMER INTERNSHIP REPORT

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I. ACKNOWLEDGEMENT

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We wish to express our heartfelt thanks and gratitude to our guide Mr. S. R. Ghodke, Scientific Officer, Electron Beam Centre, for his invaluable guidance and advice, without that the dissertation would not have appeared in its present shape. He motivated us at every moment during the entire training duration.

Also, we would like to take this opportunity to extend our gratitude to Mr. R. Barnwal, Mr. Mahendra Kumar and Mr. Sushanta Nayak Sir for guiding us and helping us get a practical insight and understand the concepts of the electron beam accelerators, Small Punch Test and stress distribution.

It was a great learning experience and we will try to use the gained knowledge and skills in the best possible way ahead.

We once again offer our sincere thanks to everyone who gave us their valuable time and helped us throughout in getting our project accomplished in the best possible way.

II. INDEX

1. Introduction

One of the most important tasks of a design engineer is to ascertain integrity of components during entire service life. To achieve this, one needs to know the changes in material properties of the component during operation without damaging structural integrity while removal of sample materials for testing. In case of the nuclear industry, conducting tests on ASTM standard irradiated specimens has many difficulties. Some of these are, availability of limited space in material test reactors to irradiate specimens, non-uniform gradients of neutron flux in large specimens and radiation exposure to personnel involved in post-irradiation testing. Hence, there's a need to reduce the size of irradiated specimens. The current fusion reactor materials development program also uses low volume specimens to determine mechanical properties. [1]

It is not feasible to use large volume of materials such as Diamond, Californium, etc. which are available in limited supply and radioactive materials like uranium, plutonium, etc. for testing purposes. Due to such limitations, the volume of materials available for determination of mechanical properties is extremely limited and calls for development of reliable miniaturized specimen testing methodologies. One such method is the small punch test.

Small punch test (S. P. T.) method is used to predict mechanical properties of materials using small volume to ascertain integrity of components during entire service life. Such exercise is particularly important for the components where there is a rapid change in mechanical properties of materials, viz. plants handling various chemicals, nuclear power plants, etc. [1]

Small punch test techniques using miniature – sized specimens have been investigated for header components. Small punch tests on thin disc specimens can be considered as one of the promising methods for the determination of the residual life of exposed parts of industrial plants operating at severe conditions. Due to the small specimen dimensions, the small punch test may be classified as a non – destructive method. Linear relationships have been obtained between mechanical characteristics determined from small punch test and from Universal Testing Machine. [1]

2. Problem Statement

- Several problems are experienced in the testing of materials as mentioned above in the introduction section.

- Some of them include: limited supply of material, structural integrity of components, cost or feasibility, shortage of space and many more.

- Hence there's an urging need for the development of reliable miniaturized specimen testing methodologies such as the Small Punch Test (S. P. T.).

- The project focuses on the development of a relation between material properties such as ultimate tensile stress and toughness of different copper alloys obtained from standard Universal Testing Machine and a simulation of the Small Punch Test in the ANSYS Workbench software.

- The project takes a step further by finding these relations for different copper alloys at room temperature as well at cryogenic temperatures.

3. History [1]

The first development of the small punch test was performed by Manahan and Huang. The objective was to estimate the stress – strain data of a material which is available in a very limited quantity. Baik extended the use of small punch test technique to fracture mechanics. This work created more scientific interest in the research community. Mao conducted small punch test experiments on various materials using 3 mm diameter disk having 0.25 mm thickness and also 10 mm x 10 mm x 0.5 mm specimens. The objective was to develop an empirical correlation between fracture toughness (J_{1C}) and biaxial fracture strain ($\bar{\varepsilon}_{qf}$). Estimation of fracture toughness was performed for cryogenic steels at low temperatures using S. P. T. Additionally, fracture toughness degradation was investigated on neutron irradiated 2.25Cr-1Mo ferritic steel. Further research on prediction of fracture properties using small punch test was carried out by various workers for different materials and test conditions to standardize the test. Geary performed experiments on three structural steels and one high strength offshore steel. Saucedo-Muñoz developed a fracture toughness correlation for austenitic stainless steel. Guan assessed fracture toughness in long term services CrMo low alloy steels and Rodríguez performed fracture characterization on a hot rolled API X-70 steel plate and its heat affected zone. Bulloch reported the studies of different researchers to evaluate fracture toughness (J_{1C}) correlations using biaxial fracture strain and energy. Several authors have performed small punch test (S. P. T.) and Charpy – impact test to evaluate the ductile – brittle transition temperature (D. B. T. T.). The objective was to develop an empirical correlation between the D. B. T. T. measured by the Charpy-impact test and small punch test (S. P. T.).

Hybrid methods involving experiments and numerical analysis to determine mechanical and fracture properties using small punch test were attempted by several researchers. In general, 2-D axisymmetric finite element model of small punch test specimen is employed to determine load v/s displacement diagram. Parametric studies have been carried out to determine effect of coefficient of friction between ball and specimen and other influencing parameters on the small punch test results. Authors have used G. T. N. model to study small punch test on pre-cracked specimens. The effect of variation in nucleation void volume fraction (f_N), void volume fraction at coalescence (f_C) and void volume fraction at failure (f_F) on small punch test results were also studied. Partheepan performed F. E. A. simulation of dumb-bell miniature specimen and used neural network model to evaluate fracture toughness. In recent years, several workers have tended to use pre-notched small punch test specimens.

There are several ASTM special technical publications (S. T. Ps.) dealing with the S. P. T. that provide a comprehensive overview of the development of the S. P. T. for the evaluation of material mechanical and fracture properties. These publications include ‘The Use of Small-Scale Specimens for Testing Irradiated Materials S. T. P. 888’, ‘S. P. T. Techniques Applied to Nuclear Reactor Vessel Thermal Annealing and Plant Life Extension S. T. P. 1204’, ‘Small Specimen Test Techniques: 4th Volume S. T. P. 1418, 5th Volume S. T. P. 1502 and 6th volume 1576’.

4. The Small Punch Test

4.1. Description of the test:

Simulations of a mechanical test have been carried out in the ANSYS software on small disc shaped test pieces (Ø3 mm x 0.25 mm) of different copper alloys by means of the application of a mechanical load applied to one surface of the test piece by means of a spherical ball, made of material (Tungsten Carbide, WC) having high toughness value (around 400 Brinell Hardness Number or HBN), driven by flat punch in order to investigate its response to the load. The response of the specimen to the applied load is recorded to predict the material properties from room temperature (295 K, 21.85 °C) to cryogenic temperatures (4 K, -269.15 °C). Such a mechanical testing scheme is known as small punch test method which is abbreviated as 'S. P. T.'. This is used to investigate the material properties like: (a) Fracture Toughness and (b) Ultimate Tensile Strength (S_{ut}).

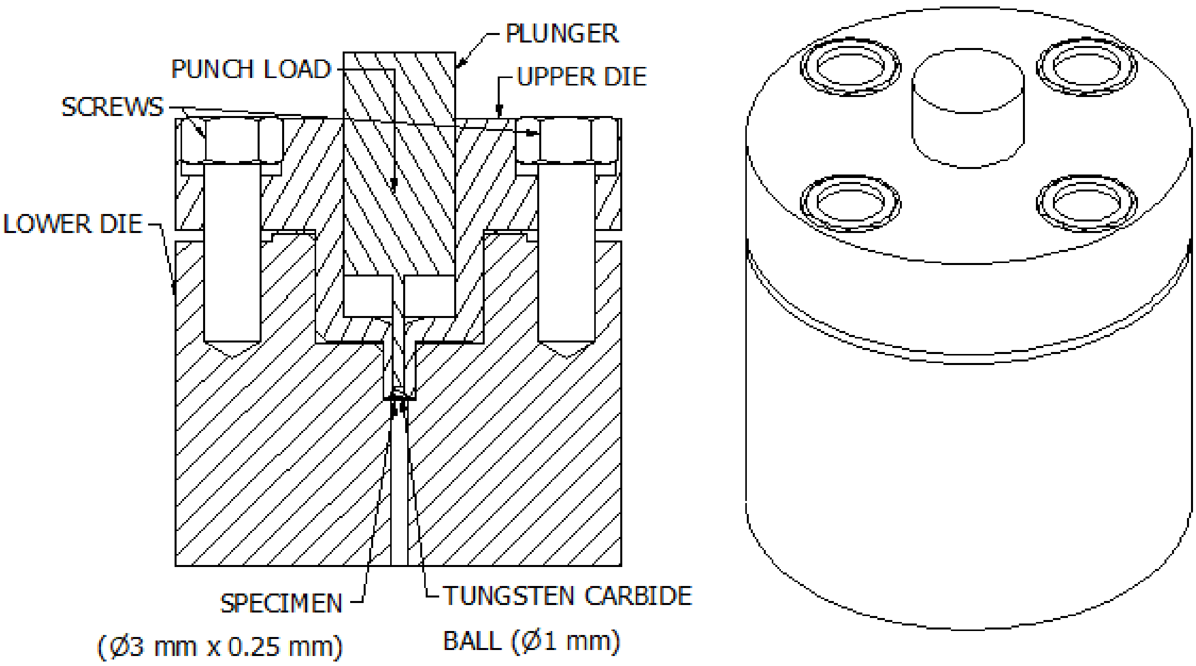


Figure 1: Configuration of the Small Punch Test.

As shown in figure 1, the configuration of the S. P. T. fixture assembly is composed of the following components: i) a lower die, ii) an upper die, iii) a spherical ball and a punch or plunger which is used to drive the spherical ball. A variety of S. P. T. fixtures and specimen have been reported [1 – 3]. The two main types of specimen used in analysis are: i) S. P. T. specimen & ii) pre – notched S. P. T. (p-SPT) specimen. The specimen types used for the analysis in this project are S. P. T. specimen. The same S. P. T. fixture could be used for both types of specimens. The most popular S. P. T. fixture and specimen geometry was proposed by Manahan and Baik [1]. The design of S. P. T. fixtures and specimen geometries of Manahan and Baik have been used by various researchers to predict mechanical and fracture properties of the material [1]. Mao has major contribution to small specimen technology for prediction of mechanical and fracture properties of the materials using same design of S. P. T. fixture [3]. The table 1 [1] shows different types of reported small punch test (S. P. T.) specimen and die configuration. The S. P. T. fixture assembly has two major important dimensions (a) bore diameter (d_2) of the lower die and (b) bore diameter (d_1) of the upper die or diameter (d_1) of the spherical ball [1].

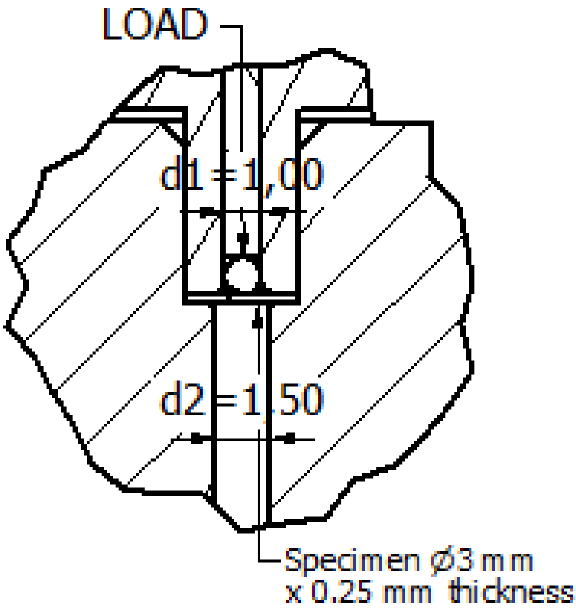


Figure 2: Detailed view of S. P. T. Fixture.

Other notable design factors of S. P. T. fixture are the fillet radius (r*) of the lower die, clamping area and specimen dimensions. According to the C. E. N. code of practice on 'small punch test method for metallic materials' a fillet radius (r*) of 0.2 mm is recommended for 3 mm diameter disk specimen [1]. Additionally, the hardness of the S. P. T. fixture should be enough for mechanical tests. A hardness of spherical ball should not be less than 55 HRC is recommended in so as not to be deformed during the test, hence a tungsten carbide ball is used for analysis with a hardness value of around 400 HBN.

The S. P. T. specimen can be either disc or square shaped in configuration. Table 1 shows that most authors have used the size of S. P. T. specimen which ranged from as large as 10 mm in diameter with 0.5 mm thickness to a specimen size of 3 mm in diameter with 0.25 mm in thickness. Figure 3 shows orthographic views of the specimen used in our analysis.

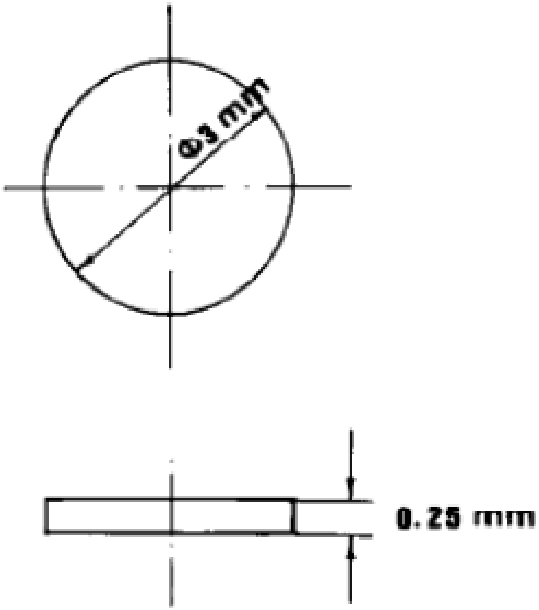


Figure 3: S. P. T. specimen details.

Table 1: Different types of reported small punch test (S. P. T.) specimen and die configurations.

Reference	S. P. T. specimen dimensions (mm)	S. P. T. die dimensions (mm)
Manahan [1]	Ø = 3; t_0 = 0.25	d_2 = 1.5; d_1 = 1
Baik [1]	10 x 10 x 0.5	d_2 = 3.4; d_1 = 2.4
Mao [2]	Ø = 3; t_0 = 0.25	d_2 = 1.5; d_1 = 1
Mao [2]	10 x 10 x 0.5	d_2 = 3.4; d_1 = 2.4
Misawa [1]	10 x 10 x 0.25	d_2 = 4; d_1 = 2.4
Rasche [1]	Ø = 8; t_0 = 0.5	d_2 = 4; d_1 = 2.5
Garcia [4]	10 x 10 x 0.5	d_2 = 4; d_1 = 2.5

4.2. Load – Displacement regimes [1]:

The small punch test is generally performed at crosshead speed of 0.2 mm/min. The alignments of the punch and die are critical in minimizing anisotropy effect caused by eccentricity and misalignments while performing the actual test. To reduce this effect during the test, three important considerations are adopted for planer isotropic deformation of the specimen during S. P. test: (a) the die axis of symmetry must be coincident with punch axis of symmetry, (b) precision tolerances must be given among punch, lower and upper die and (c) the thickness of the specimen should be approximately constant at any point on the S. P. T. specimen.

The S. P. test should incorporate an accurate loading and displacement measurement system. There are three ways to measure displacement: (a) direct measurement of punch displacement from machine, (b) measurement of punch displacement using clip gauge and (c) measurement of central deflection on opposite side of the S. P. T. specimen using linear variable differential transducer (L. V. D. T.).

As a result of the small punch test, the load – displacement data and fracture of the S. P. T. specimen to a corresponding region have been presented in figure 4. The standard load – displacement curve has been divided into five regions for ductile materials. The experimental results of S. P. T. specimen have been simulated to analyse the pattern of deformation numerically by Onat’s perfect rigid plastic model. During large deformation of S. P. T. specimen, the small punch specimen is elastically deformed in region I, which has been verified by loading and unloading up to the point of departure.

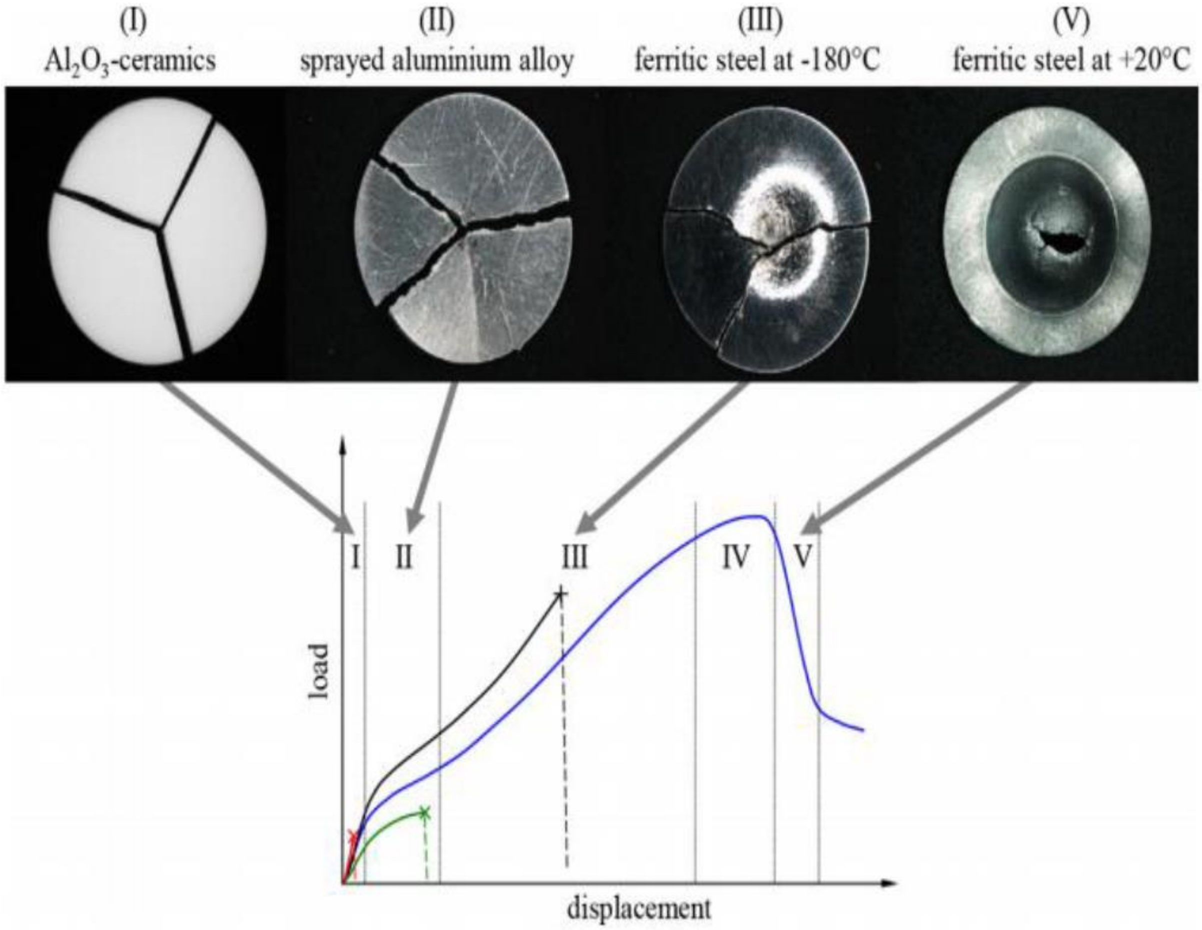


Figure 4: Schematic LDCs of specimens showing different stages of deformation at the moment of fracture. Failure points and curve shapes reflect the toughness behaviour. It ranges from purely brittle (technical alumina ceramics) to fully ductile (ferritic pressure vessel steel).

In region II, it was found that the deformation of the S. P. T. specimen was in good agreement with the plastic bending regime. In region III, the deformation of the S. P. T. specimen falls within the plastic bending and the membrane stretching (or bulging) regime where the slop increases due to work hardening during stretching. In part IV, the phenomena of geometrical softening and damage mechanism starts. On approaching the maximum load, the slope of the curve starts to decrease due to the development of failure micro–mechanisms (necking and internal cracking) in the specimen. There are two reasons for decrease in the load during deformation of the S. P. T. specimen. The first reason is through thickness thinning of the S. P. T. specimen near the punch, which corresponds to localized and diffuse necking. In this case, the small punch specimen loses its load carrying capacity gradually. However, the second reason is a final fracture of the S. P. T. specimen with subsequent through thickness and circumferential crack propagation. The experimentally measured thickness change as a function of central deflection is expressed by exponential function from:

$$\frac{t}{t_0} = e^{-\beta * \left(\frac{\delta}{t_0}\right)^p}$$

where, t, t_0, *and* δ are minimum thickness in deformed state, initial thickness and instantaneous central deflection respectively. Mao have determined the values of β and p as 0.09 and 2 respectively for the S. P. T. disk specimen having diameter Ø = 3 mm using large number of experimental data. Kulkarni have observed that S. P. T. disk specimen is having imaginary tensile specimens deforming in radial direction of the disk, as shown in figure 5.

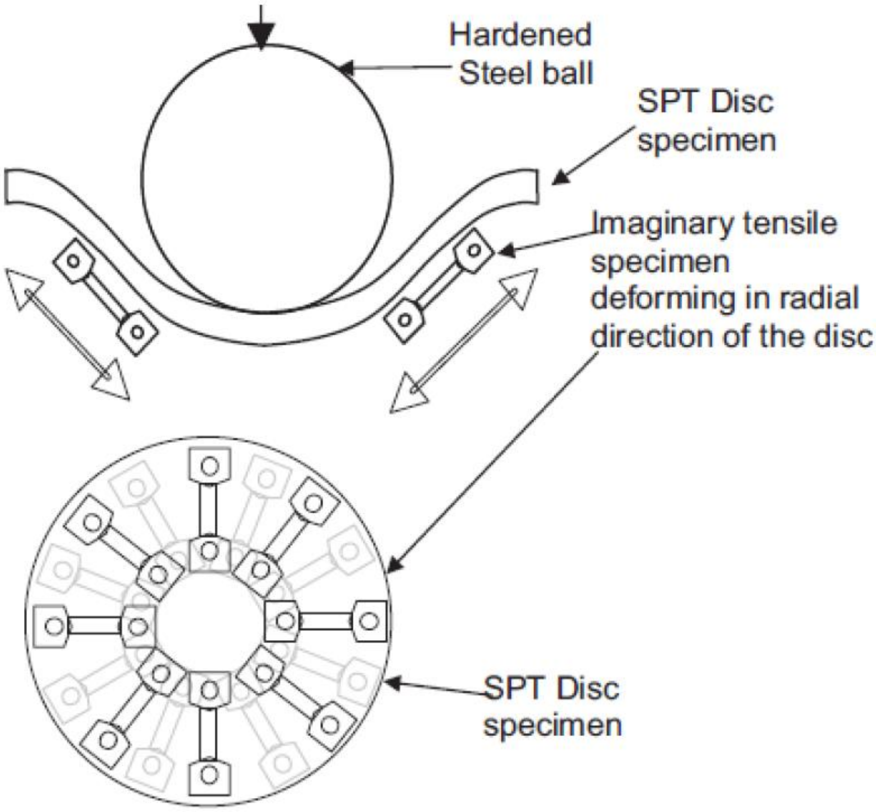


Figure 4: Schematic of SPT specimen deformation during a test compared to tensile deformation in the radial direction.

5. Objectives

The objectives of the project are:

- Understand the various fracture mechanisms and their propagation in ductile and brittle materials.

- Study of the Small Punch Test: Design and Mechanism.

- Collection of various mechanical and chemical properties of copper alloys at room and cryogenic temperatures.

- Computing the graph of True Stress vs. True Strain for the alloys.

- Computing the graph of True Stress vs. True Plastic Strain for the alloys.

- Obtaining the load–displacement diagrams for the above materials using ANSYS Workbench software.

- Obtaining a correlation for Ultimate Tensile Stress (σ_{ut}) and material Toughness between S. P. T. and Standard Tensile Test for the copper alloys.

6. Method

The methodology followed in order to complete the project was:

1. **Study:** Obtaining data (Engineering Stress – Engineering Strain curves) for various copper alloys.
2. **Digitalisation:** Digitalizing the data (Engineering Stress – Engineering Strain curves) through graph digitizing software Digitizer.
3. **Computation:** Computing True Stress vs. True Strain graphs for the materials.
4. **Post – Computation:** Computing True Stress vs. True Plastic Strain graphs for the materials.
5. **Curve – Fitting**: Using curve fitting software (such as Excel) for obtaining power law equation for the True Stress vs. True Strain graph in the plastic region (between Yield point and Ultimate point).
6. **Analysis:** This step consists of the following substeps:
    - Defining the material properties.
    - Geometry selection.
    - Defining the contacts between various geometric elements: Bounded, Frictional or Frictionless.
    - Meshing: Defining the element size over different geometric elements.
    - Boundary conditions.
    - Solution.
    - Result: Obtaining the desired load – displacement curves.
7. **Post – Processing:** Obtaining material toughness and ultimate load from the S. P. T. load–displacement diagram for the various materials.
8. **Correlation:** Obtaining a correlation in the form of an equation between material toughness and ultimate stresses (from uni-axial tensile test) and material toughness and ultimate tensile loads (from S. P. T. test).

7. Material Study

The various material properties for the following copper alloys obtained from The Copper Development Association [7] are:

1. Condition and Composition of Alloys:

Table 2: Condition and Composition of alloys.

Copper and copper alloy		Condition	Composition					Hardness	Average Grain Diameter, mm
No.	Name		Pb	Fe	Sn	Zn	Ni		
220	Commercial Bronze, 90%	Annealed, 575 °C, 3 hr.	0.005	0.01	-	10.01	-	Rf 49	0.051
230	Red Brass, 85%	Cold drawn 14%.	-	0.22	-	15.33	-	Rf 64	0.025
464	Naval Brass	Annealed, 593 °C, 1 hr.	0.09	0.02	0.63	39.71	-	Rb 57	0.036
647	Copper–Nickel Silicon	Aged, 450 °C, 2 hr.	-	0.01	-	-	1.97	Rb 98	0.025

2. Average properties of Copper and Copper Alloys at low temperatures:

Table 3: Average properties of Copper and Copper Alloys at Cryogenic temperatures.

<table>
<tr><th colspan="2">Copper and Copper Alloys</th><th>Test Temperature in K</th><th colspan="2">Elastic Properties</th><th colspan="6">Plastic Properties</th></tr>
<tr><th rowspan="3">No.</th><th rowspan="3">Name and Treatment</th><th rowspan="3"></th><th rowspan="3">Elastic Modulus 10^6 psi (5%)</th><th rowspan="3">Shear Modulus 10^6 psi (2%)</th><th colspan="4">Uniaxial</th><th colspan="2">Triaxial</th></tr>
<tr><th rowspan="2">Tensile Strength, psi</th><th rowspan="2">Yield Strength, psi</th><th rowspan="2">Elongat-ion, % in 4D</th><th rowspan="2">Reduct-ion of area, %</th><th rowspan="2">Notch Tensile Strength (KT 5.0), psi</th><th>Impact Charpy</th></tr>
<tr><th>Energy Absorbed, ft–lb</th></tr>
<tr><td rowspan="5">220</td><td rowspan="5">Commercial Bronze, 90% (Annealed)</td><td>295</td><td>15.1</td><td rowspan="5">6.59
6.97
7.24
7.37</td><td>38,500</td><td>9,600</td><td>56</td><td>84</td><td>49,900</td><td rowspan="5">112
114
112
115</td></tr>
<tr><td>195</td><td>16.4</td><td>41,800</td><td>10,200</td><td>57</td><td>80</td><td>55,600</td></tr>
<tr><td>76</td><td>17.7</td><td>55,200</td><td>13,200</td><td>86</td><td>78</td><td>69,200</td></tr>
<tr><td>20</td><td>18.0</td><td>73,200</td><td>15,600</td><td>95</td><td>73</td><td>76,300</td></tr>
<tr><td>4</td><td>18.1</td><td>68,200</td><td>15,000</td><td>91</td><td>73</td><td>78,900</td></tr>
<tr><td>230</td><td></td><td>295</td><td>14.9</td><td></td><td>40,400</td><td>13,000</td><td>48</td><td>74</td><td>53,900</td><td></td></tr>
</table>

	Red Brass, 85% (Cold drawn 14%)	195	15.8	6.55 6.77 7.06 7.20	46,500	14,000	63	79	58,500	96 82 78 76
		76	17.6		62,000	16,400	83	77	71,200	
		20	18.1		79,2006	20,900	80	75	72,000	
		4	18.2		71,000	18,300	82	71	74,900	
464	Naval Brass (Annealed)	295	14.0	5.76 5.94 6.16 6.26	63,300	31,000	37	52	74,700	38 42 38 35
		195	14.5		67,400	33,800	37	54	84,800	
		76	14.8		80,400	38,000	44	48	100,700	
		20	15.0		105,200	47,600	41	42	113,900	
		4	15.1		99,600	43,700	40	48	115,400	
647	Copper-Nickel Silicon (Aged)	295	21.4	-	112,400	105,000	15	60	189,700	110 106 109 116
		195	22.3		119,400	110,800	18	66	194,800	
		76	23.2		123,600	114,100	24	70	204,600	
		20	23.5		133,700	118,400	33	68	255,800	
		4	23.6		135,800	119,800	31	65	212,200	

8. Digitalisation

The engineering stress-strain curve diagram is obtained from the website of The Copper Development Association [7]. These diagrams are then digitalised i.e. converted into various points plot of X-Y, where X represent strain and Y represent stress. These points plotted are then used for further computation and obtaining True stress vs. True strain and True stress vs. True plastic strain curves.

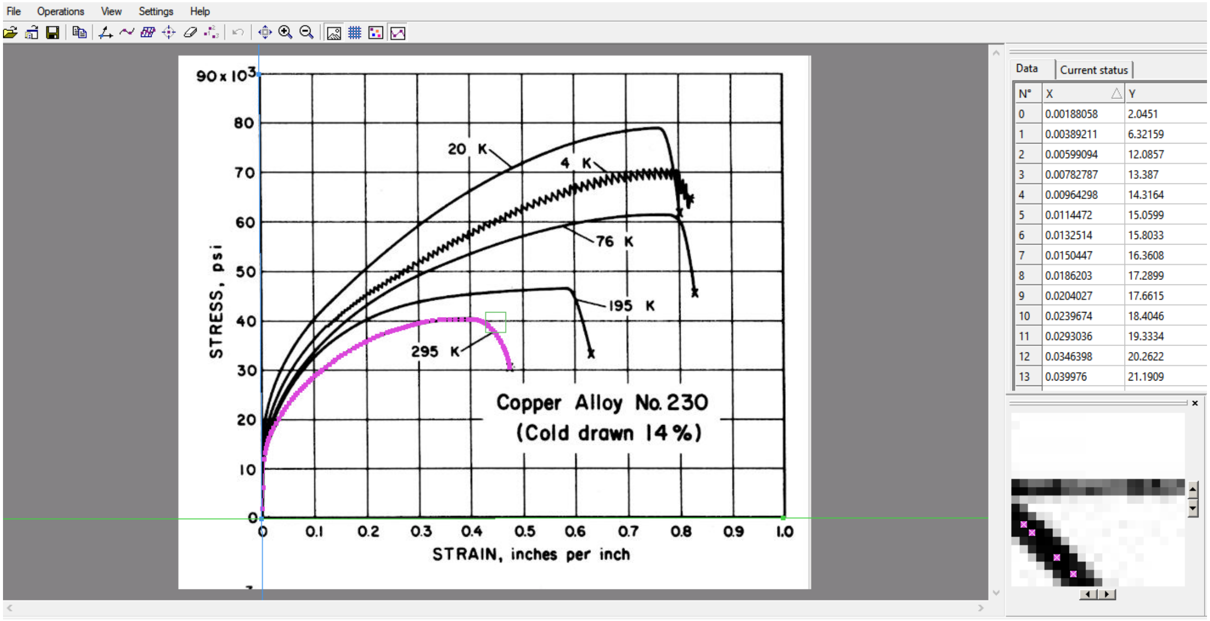


Figure 6: Illustrative example showing digitization of image and obtaining data from material C230 at 295K using the software Get Data Graph Digitizer 2.26.

9. Computation

Engineering stress is the applied load per unit of the original cross-sectional area. It is also known as nominal stress. Similarly engineering strain is the change in length per unit original length. It is also known as nominal strain.

Since for engineering strain and stress, we consider the length and cross-sectional area to be constant throughout, it is not the true one.

The True stress and True strain can be obtained by using the following equations,

$$s = \sigma * (1 + \mathcal{E})$$

$$e = \ln(1 + \mathcal{E})$$

where,

s: True stress,

σ: Engineering stress,

e: True strain &

$\mathcal{E}$: True stress.

The True plastic strain can also be found using the equation,

$$e_p = e - ({}^{s}/_{E})$$

where,

e_p: Plastic strain &

E: Young's Modulus of Elasticity.

Engineering stress-strain graphs are replotted in Microsoft Excel using data obtained from digitizer software (section 9.1). True stress vs. True strain and True stress vs. True plastic strain graphs are then computed (section 9.2 and 9.3).

Curve-Fitting in the form of power law $y = K * x^n$ is fitted on the graphs of True stress vs. True plastic strain which is shown in section 9.3.

Here,

K: Strength coefficient &

n: Strain hardening exponent.

9.1. Engineering stress vs. Engineering strain graphs:

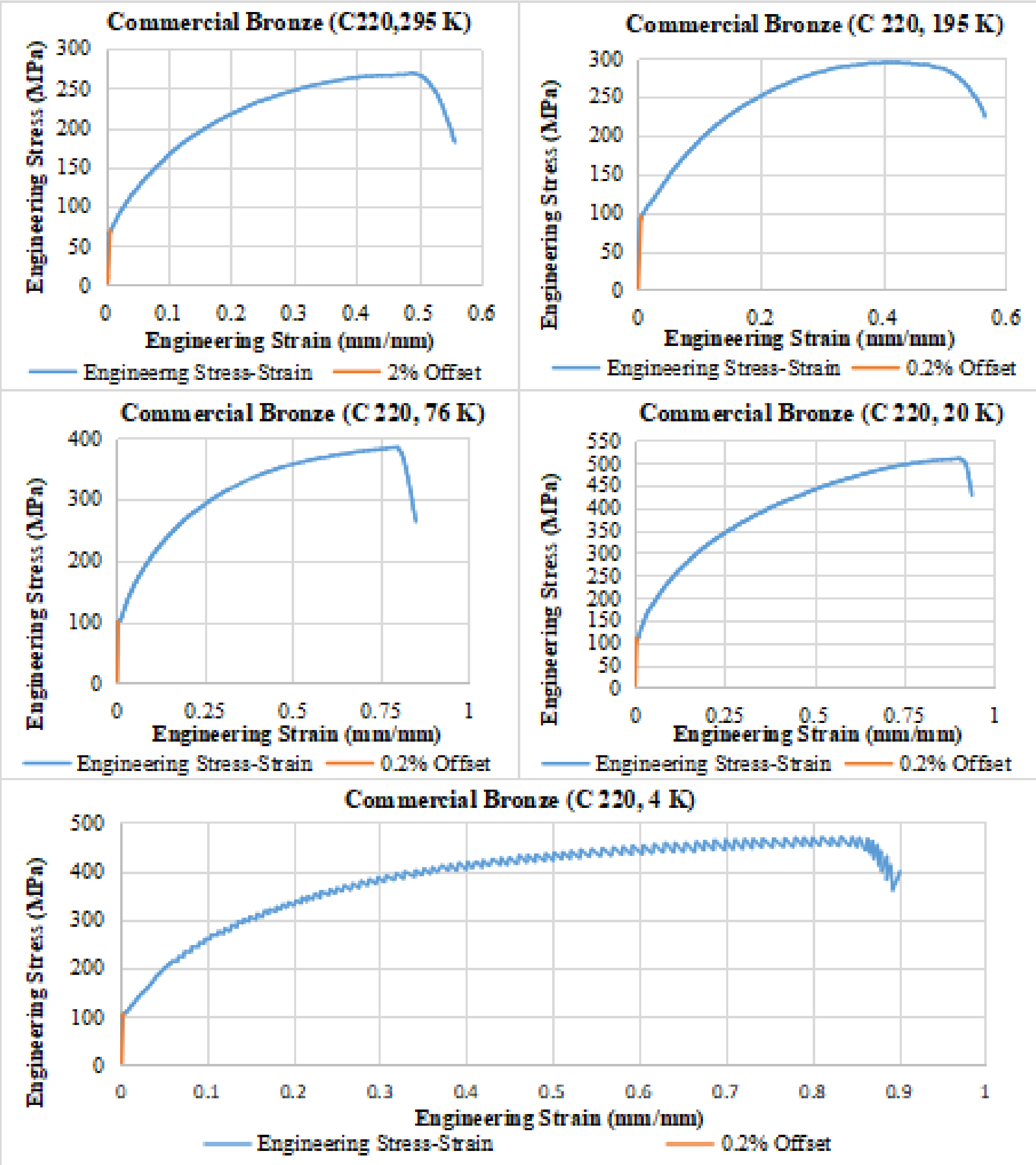


Figure 7: Engineering Stress-Strain curves for Commercial Bronze (C220) at 295K, 195K, 76K, 20K and 4K.

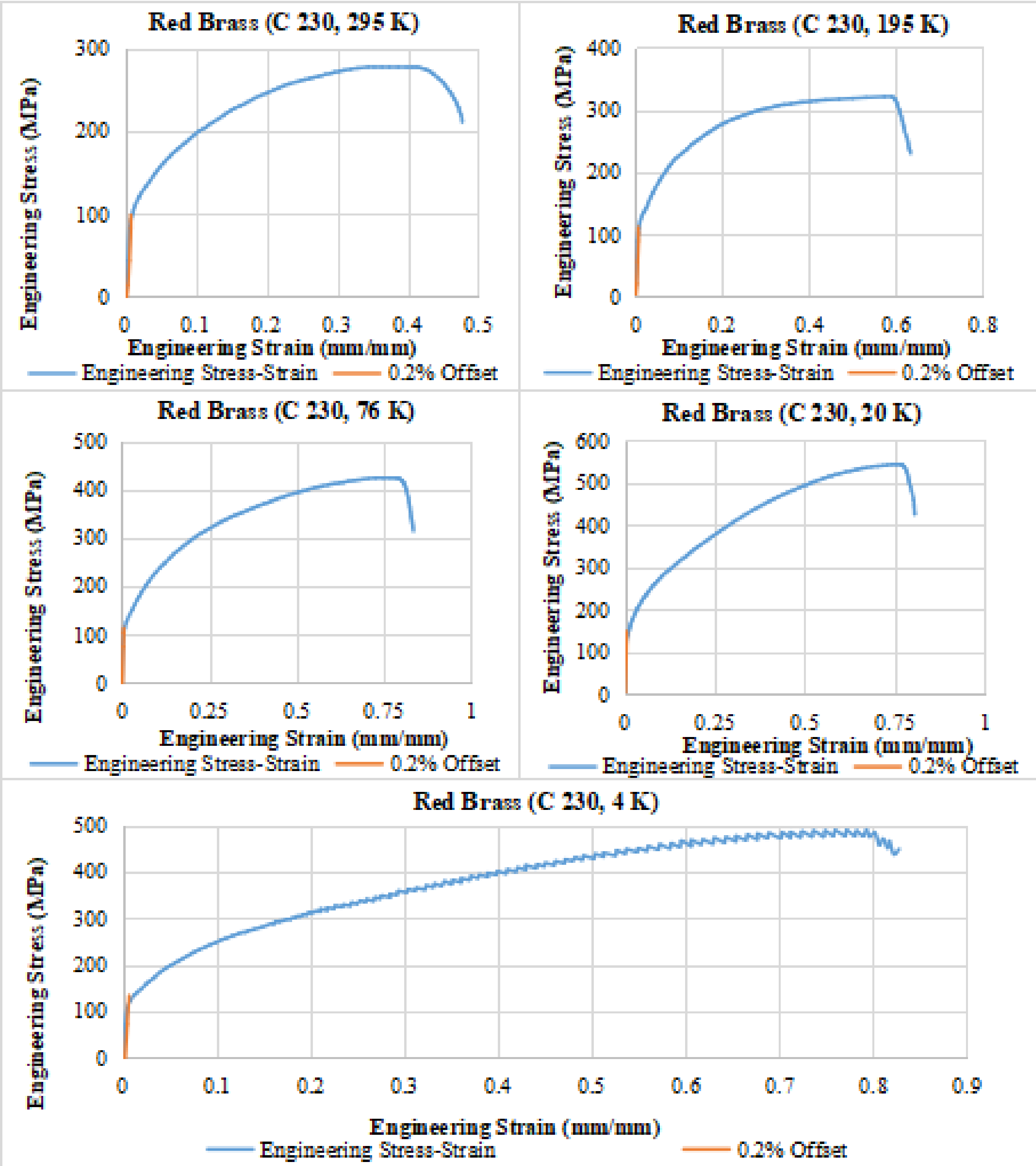


Figure 8: Engineering Stress-Strain curves for Red Brass (C230) at 295K, 195K, 76K, 20K and 4K.

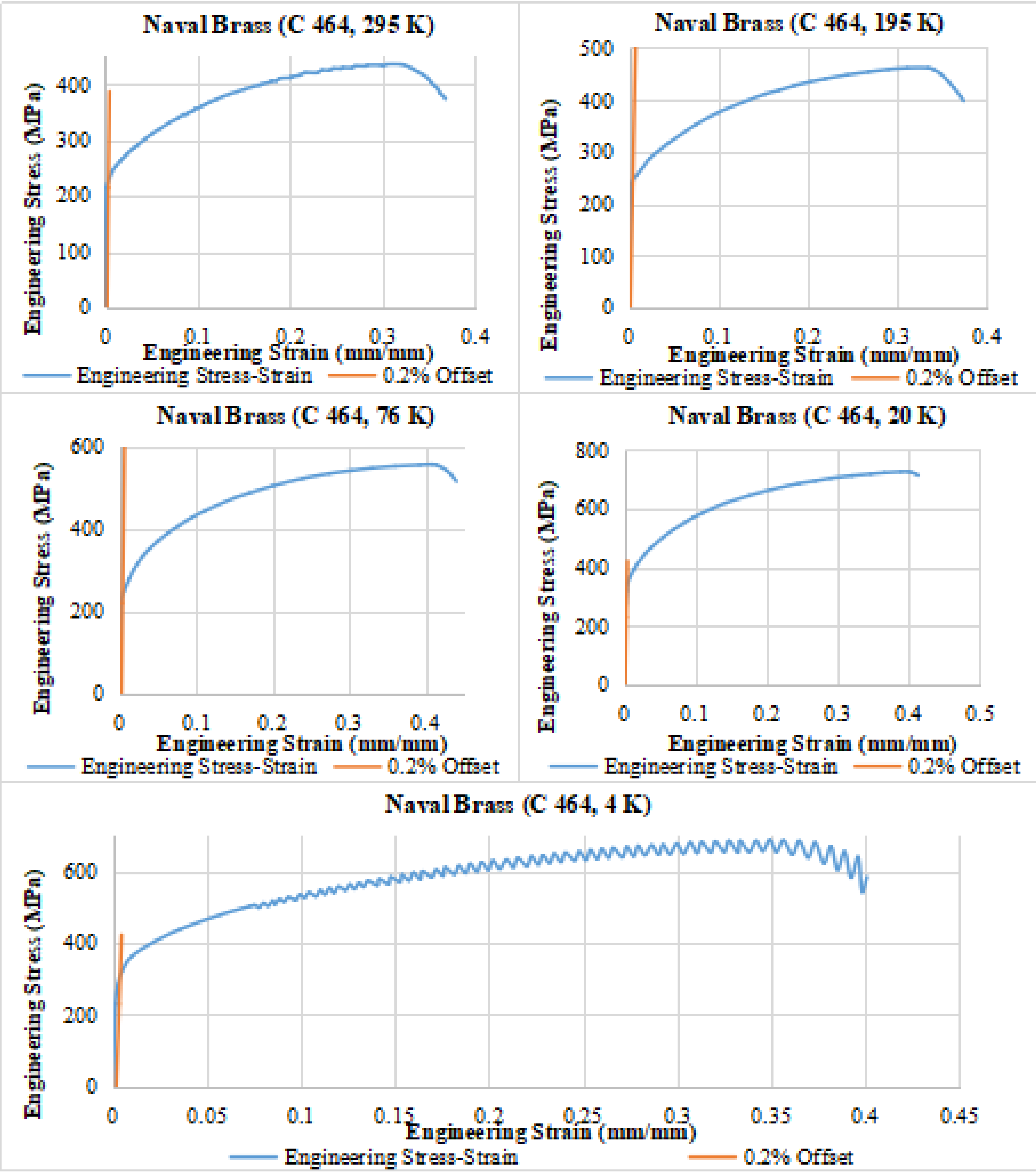


Figure 9: Engineering Stress-Strain curves for Naval Brass (C464) at 295K, 195K, 76K, 20K and 4K.

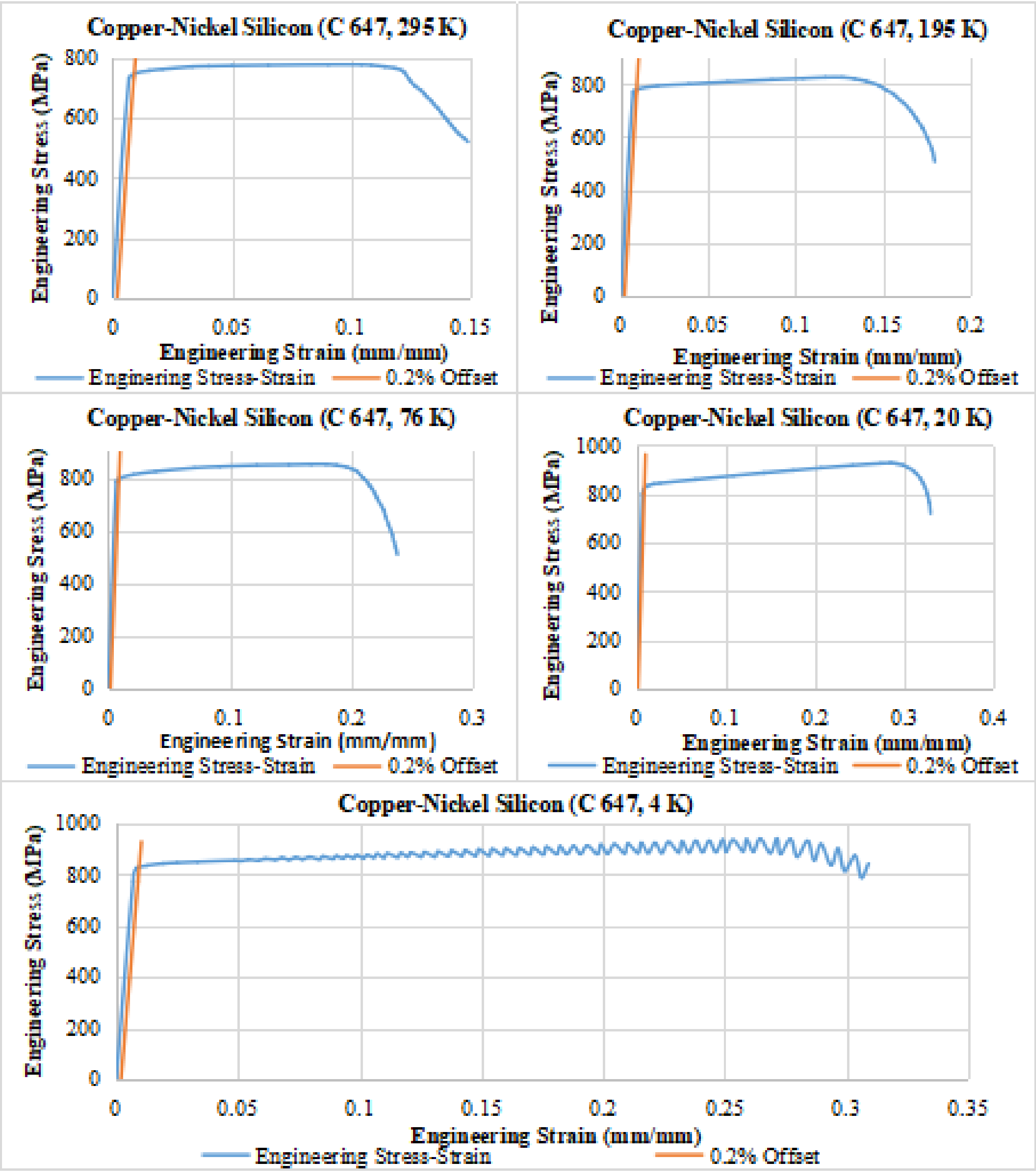


Figure 10: Engineering Stress-Strain curves for Copper-Nickel Silicon (C647) at 295K, 195K, 76K, 20K and 4K.

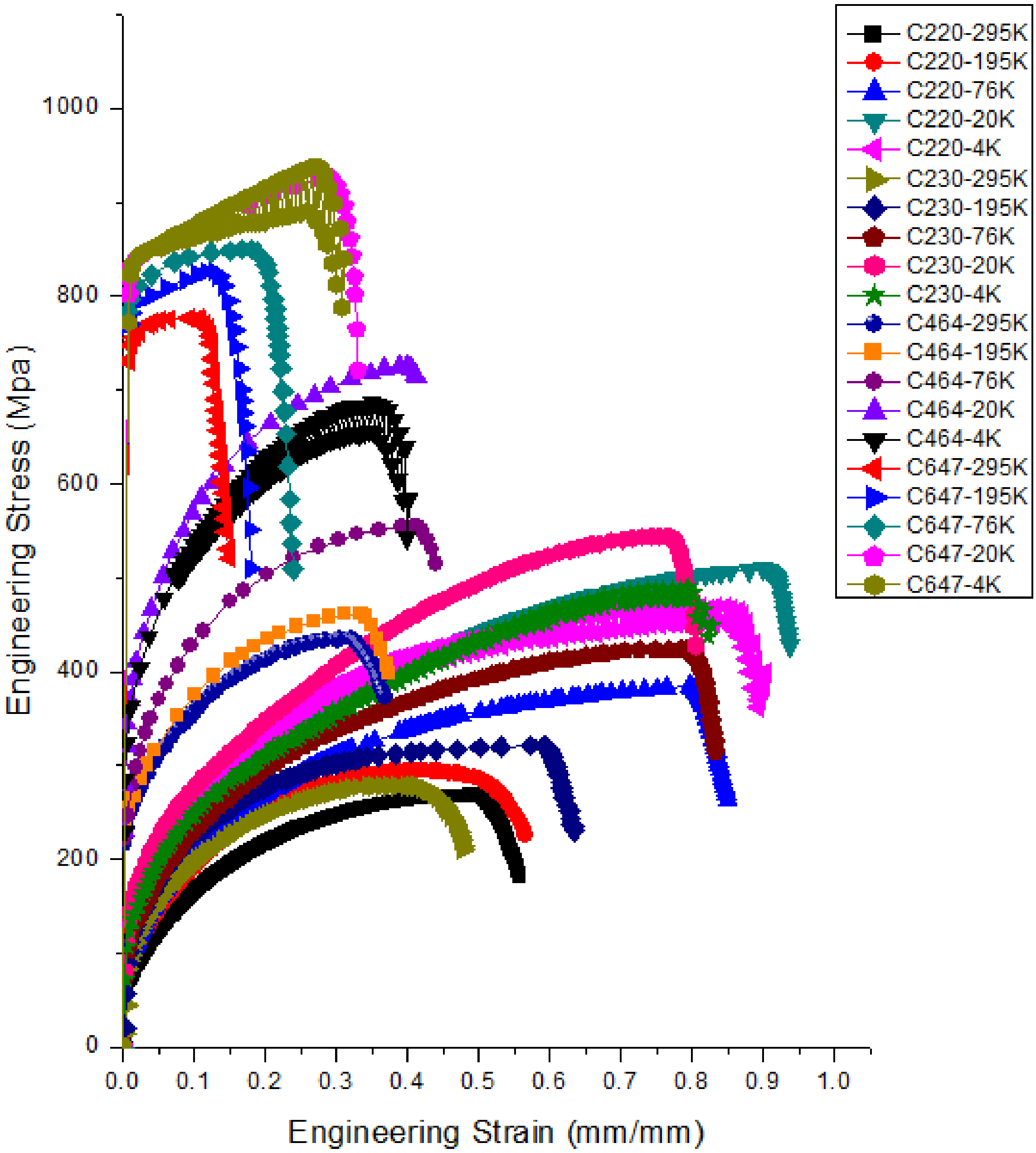


Figure 11: Combined Engineering Stress-Strain plot of C220, C230, C464, C647 at 295K, 195K, 76K, 20K, and 4K.

9.2. True stress vs. True strain graphs:

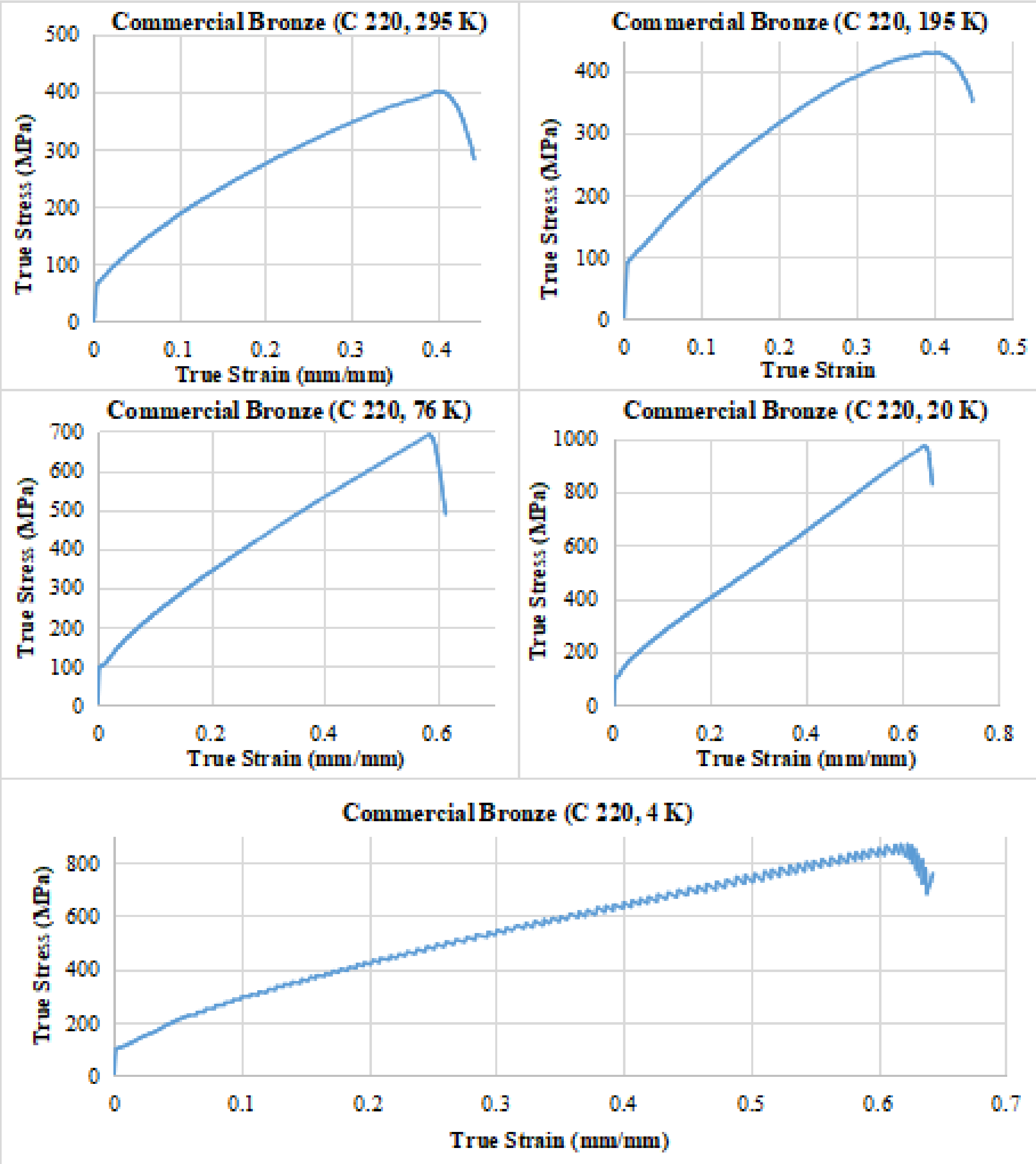


Figure 12: True Stress-Strain curves for Commercial Bronze (C220) at 295K, 195K, 76K, 20K and 4K.

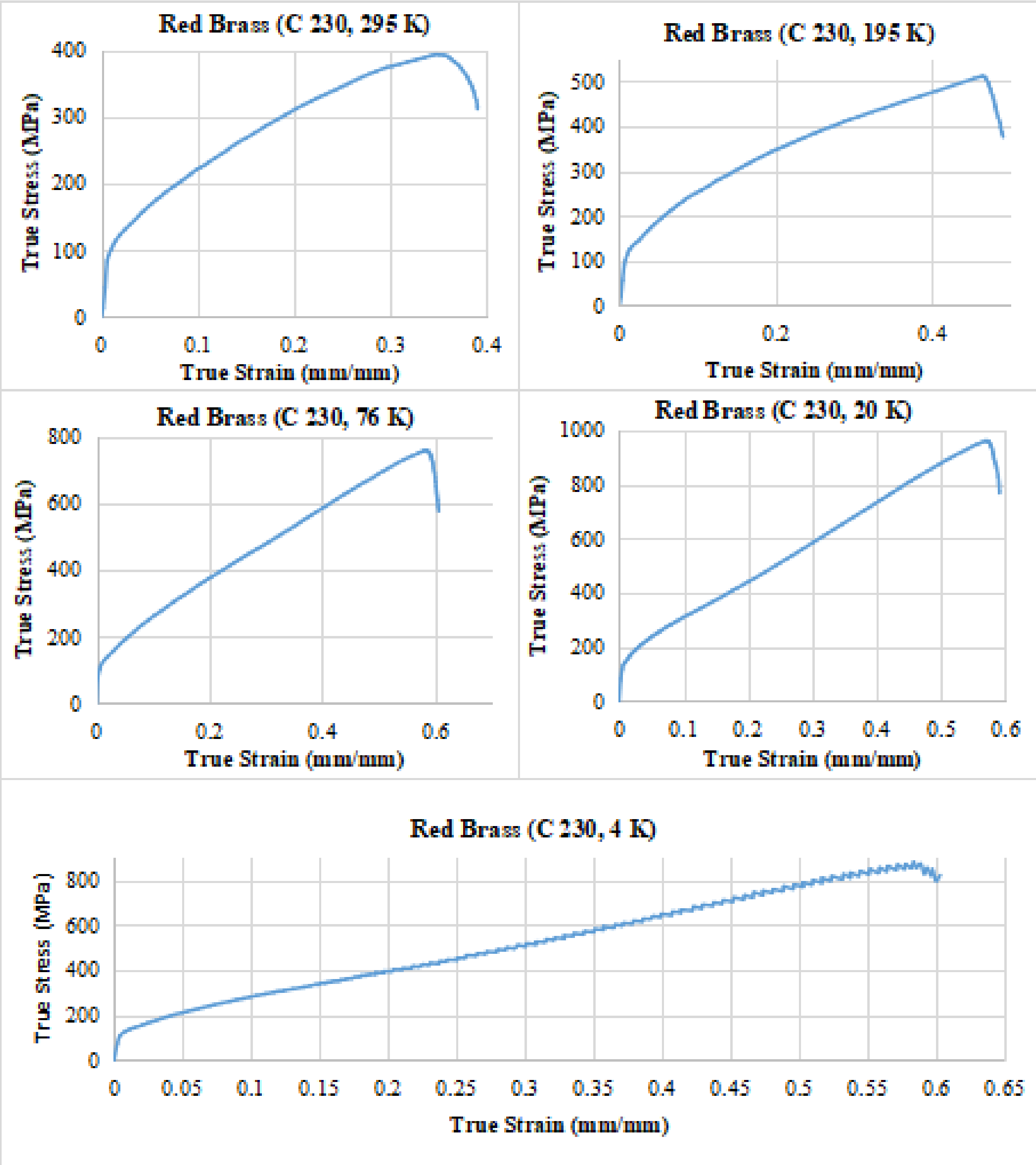


Figure 13: True Stress-Strain curves for Red Brass (C230) at 295K, 195K, 76K, 20K and 4K.

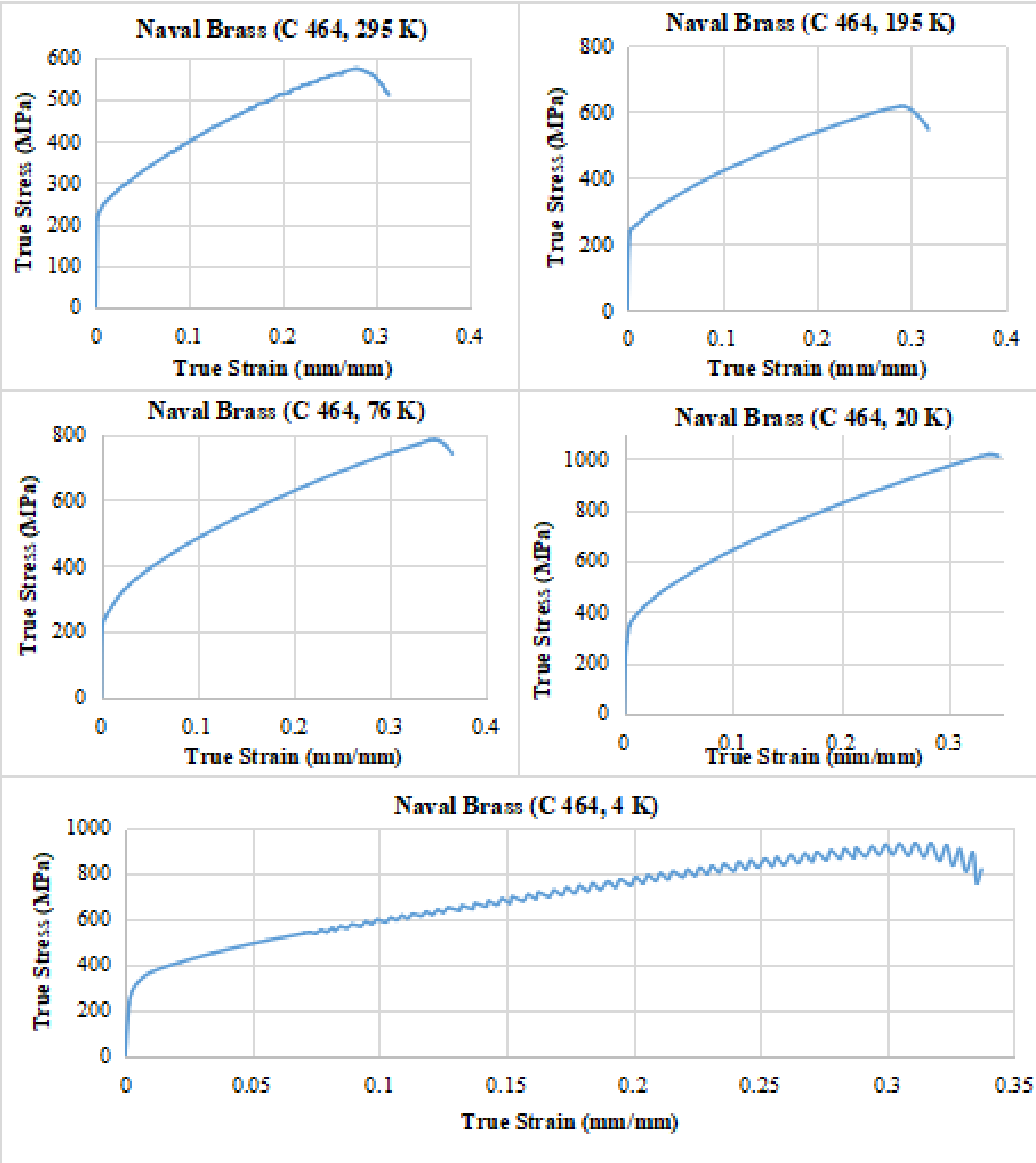


Figure 14: True Stress-Strain curves for Naval Brass (C464) at 295K, 195K, 76K, 20K and 4K.

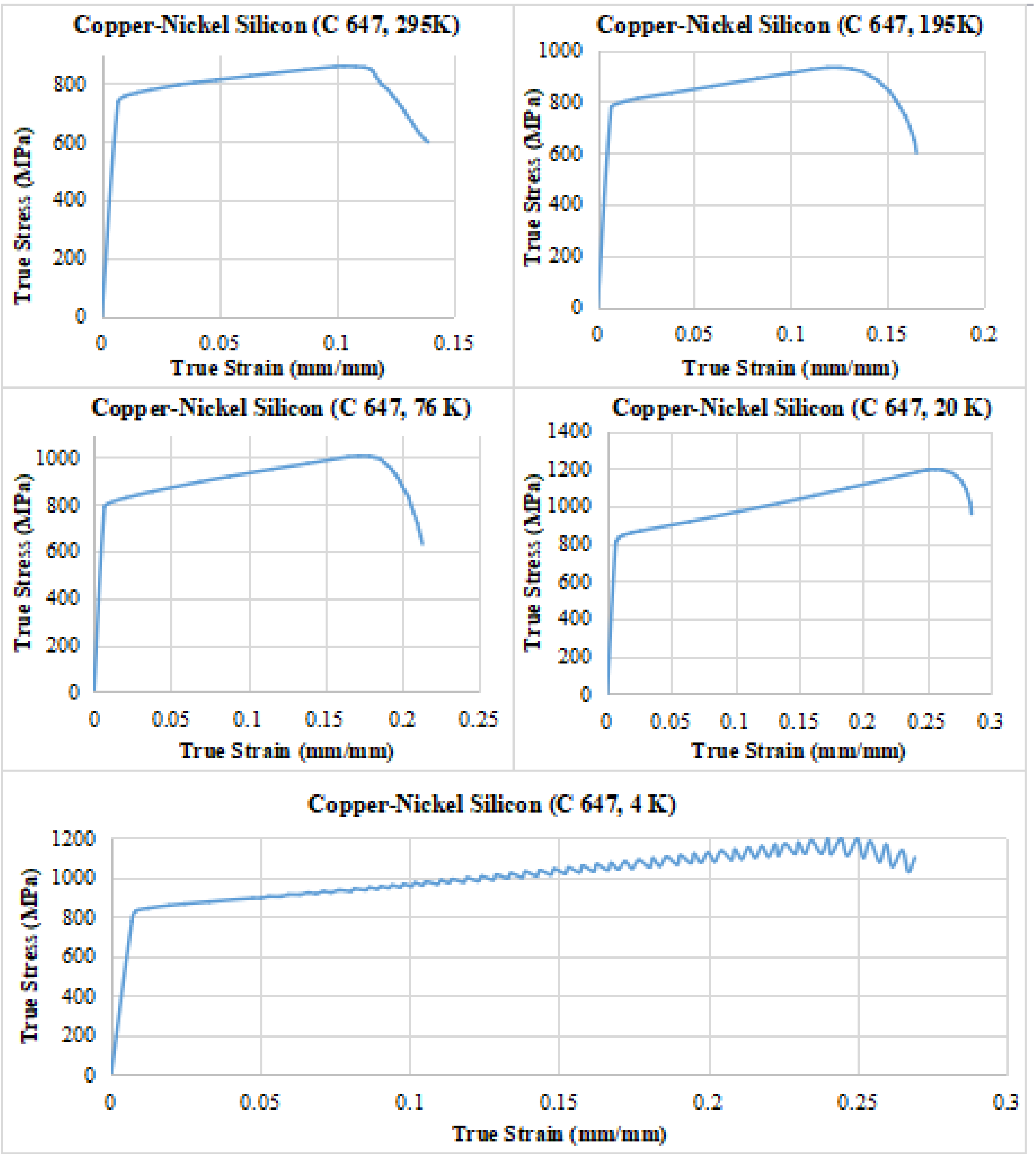


Figure 15: True Stress-Strain curves for Copper-Nickel Silicon (C647) at 295K, 195K, 76K, 20K and 4K.

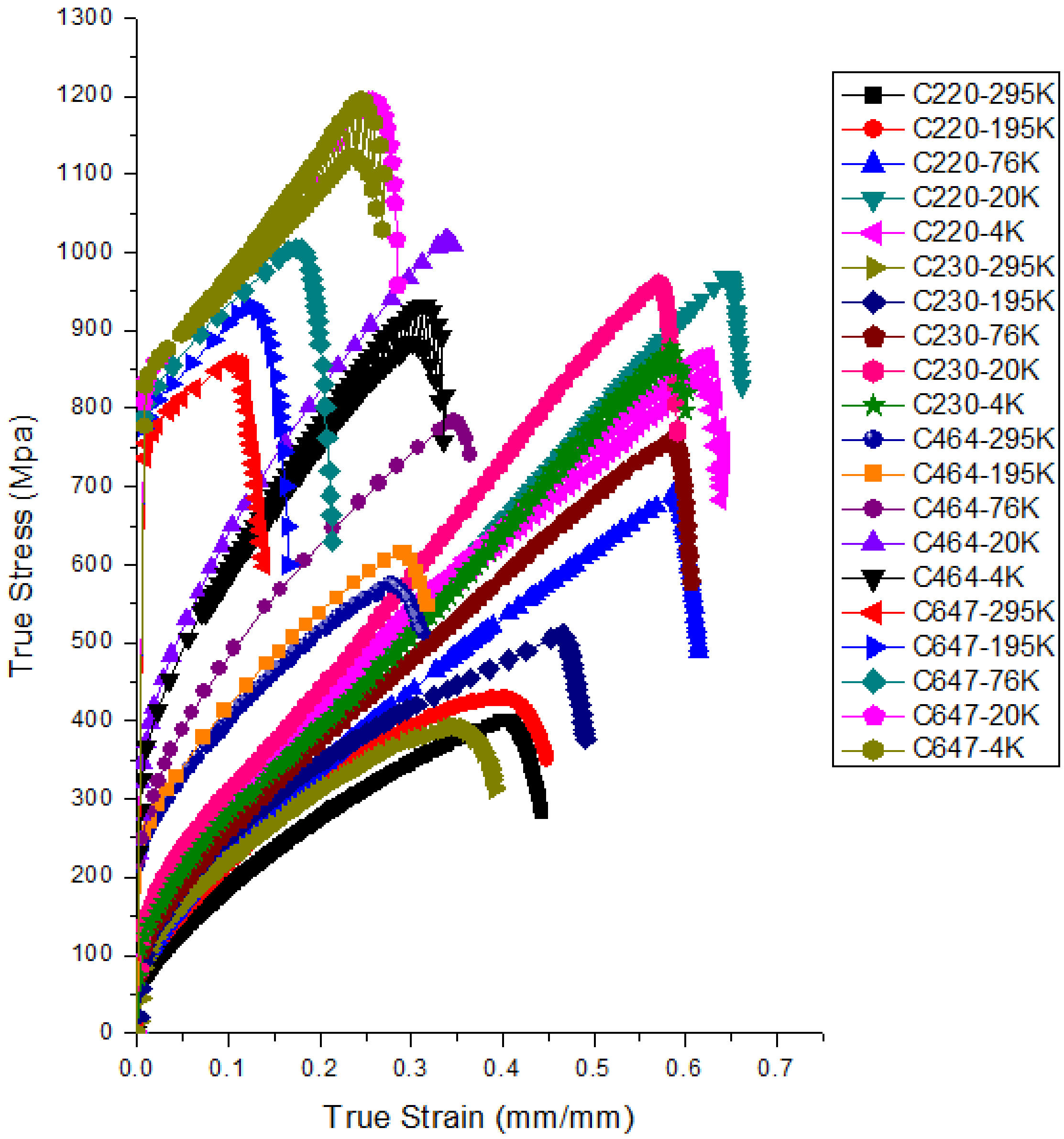


Figure 16: Combined True Stress-Strain plots for C220, C230, C464, C647 at 295K, 195K, 76K, 20K and 4K.

9.3. True stress vs. True plastic strain graphs and Curve-Fitting:

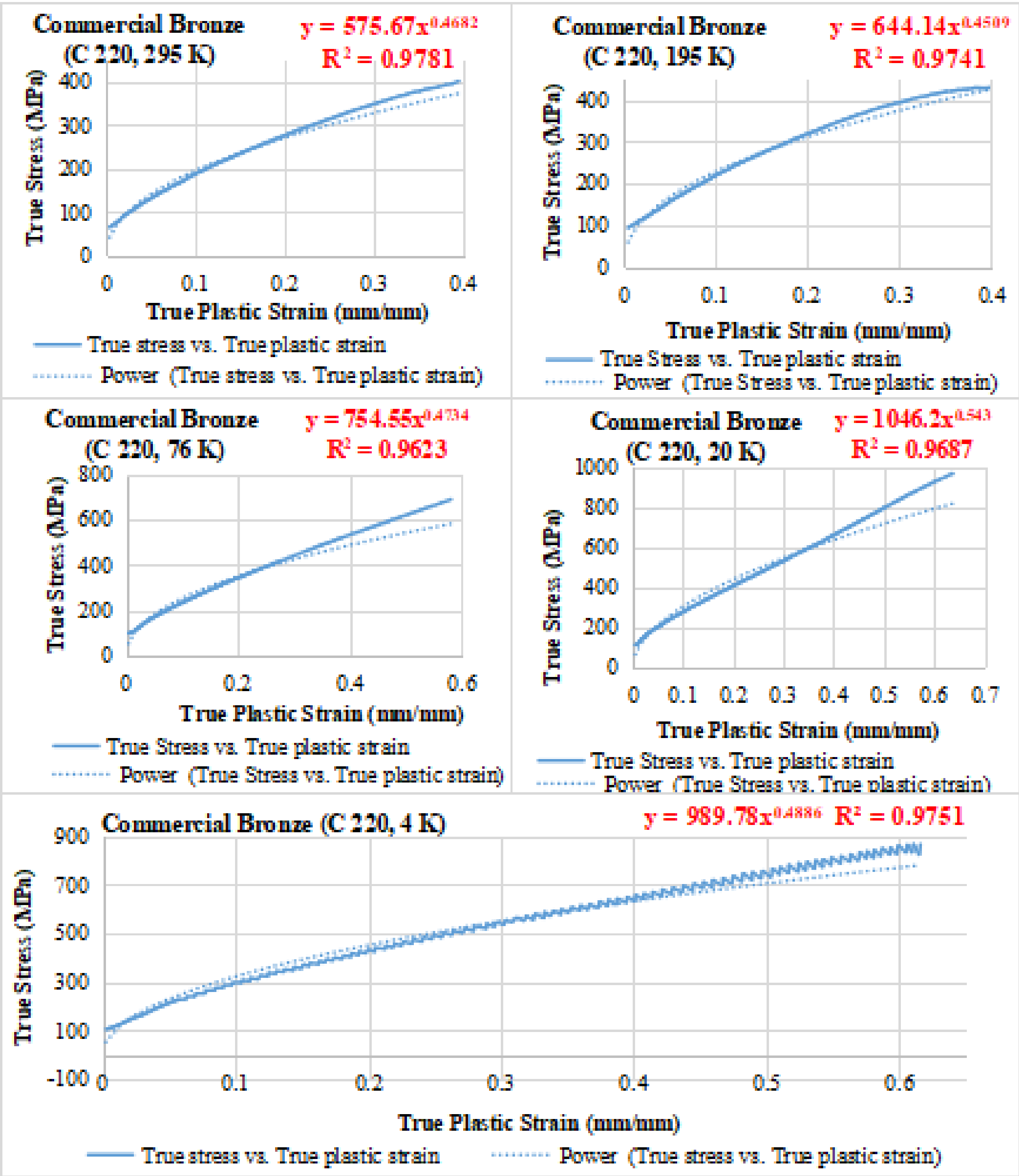


Figure 17: True Stress-True Plastic Strain curves for Commercial Bronze (C220) at 295K, 195K, 76K, 20K and 4K.

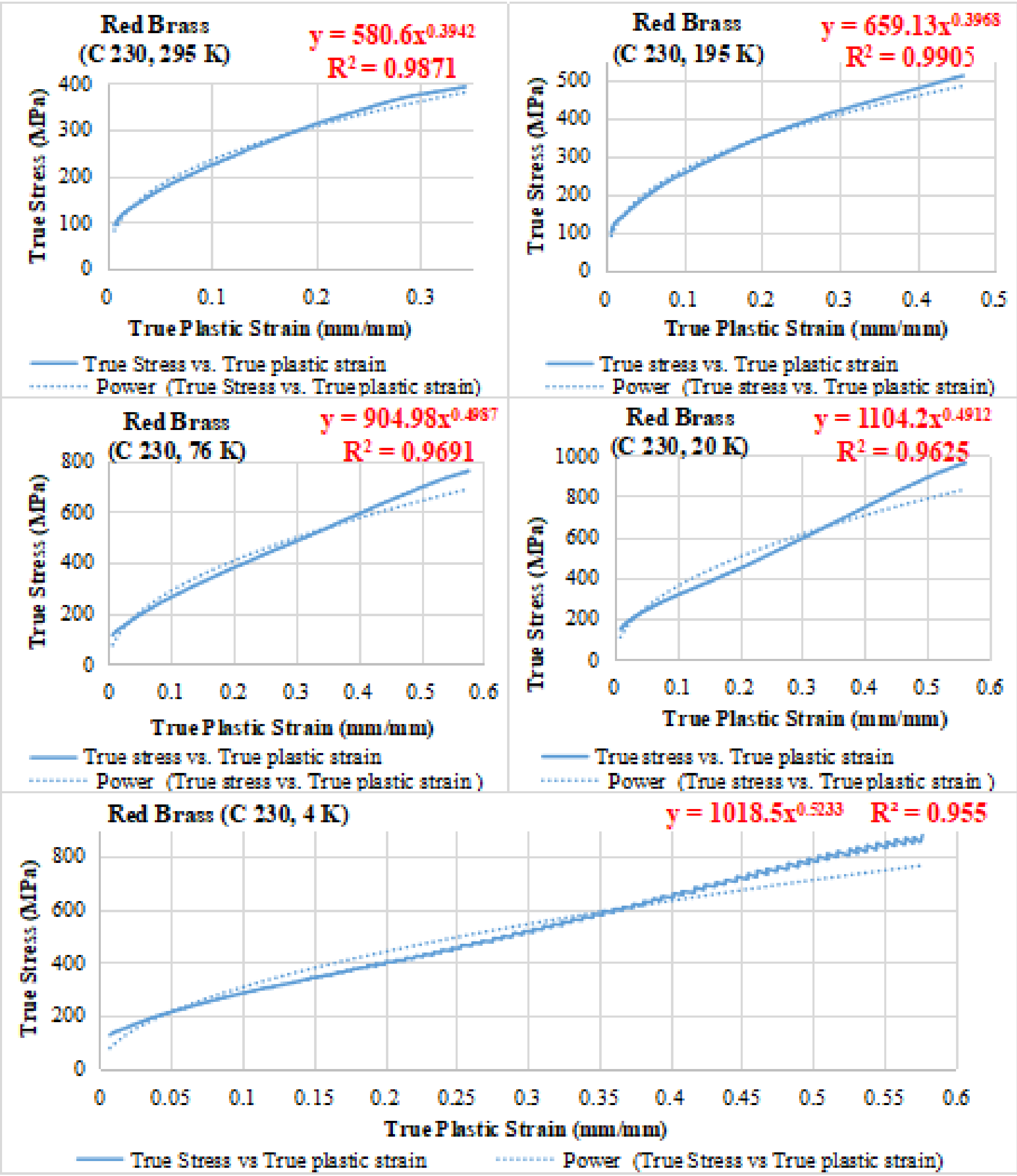


Figure 18: True Stress-True Plastic Strain curves for Red Brass (C230) at 295K, 195K, 76K, 20K and 4K.

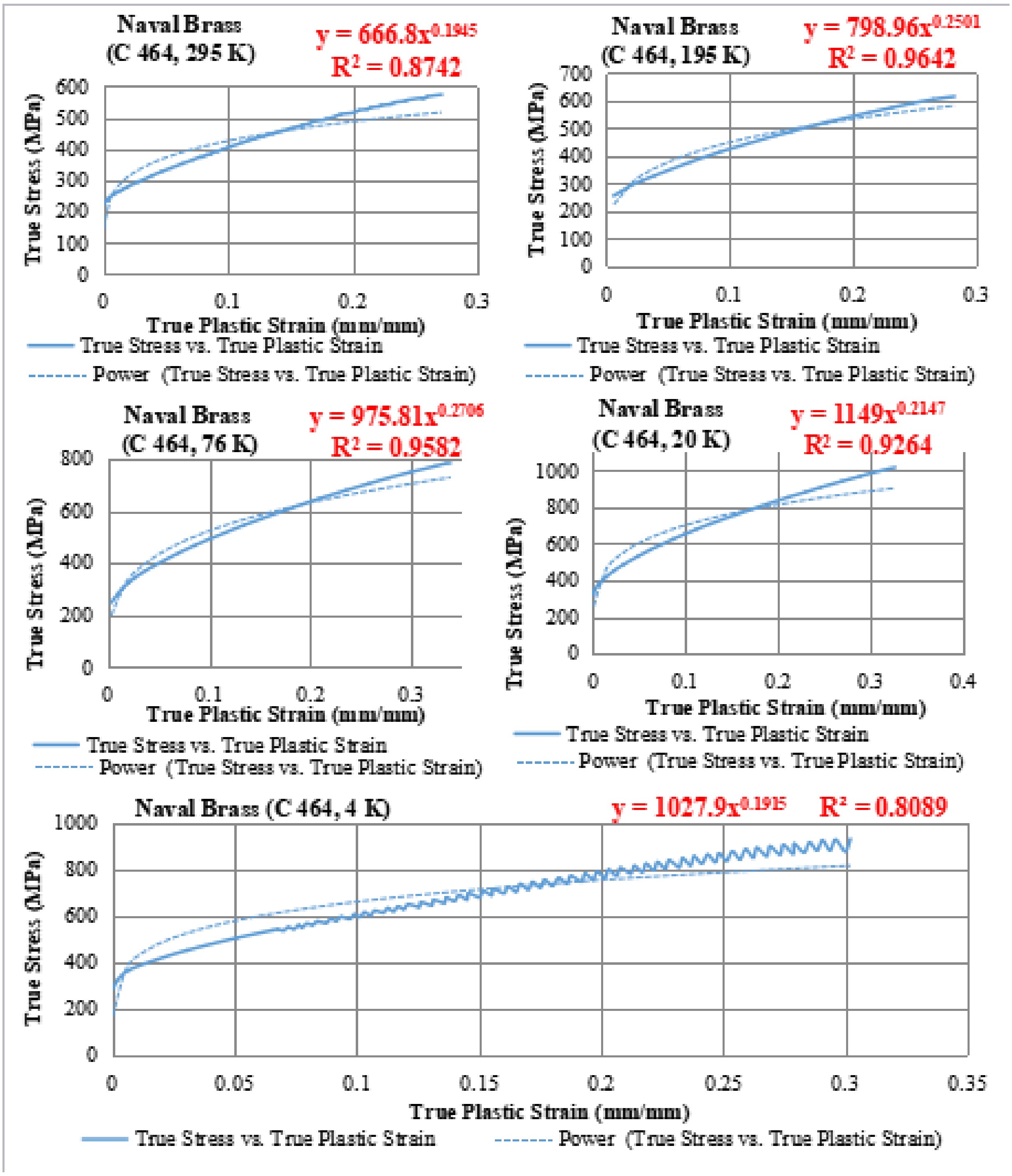


Figure 19: True Stress-True Plastic Strain curves for Naval Brass(C464) at 295K, 195K, 76K, 20K and 4K.

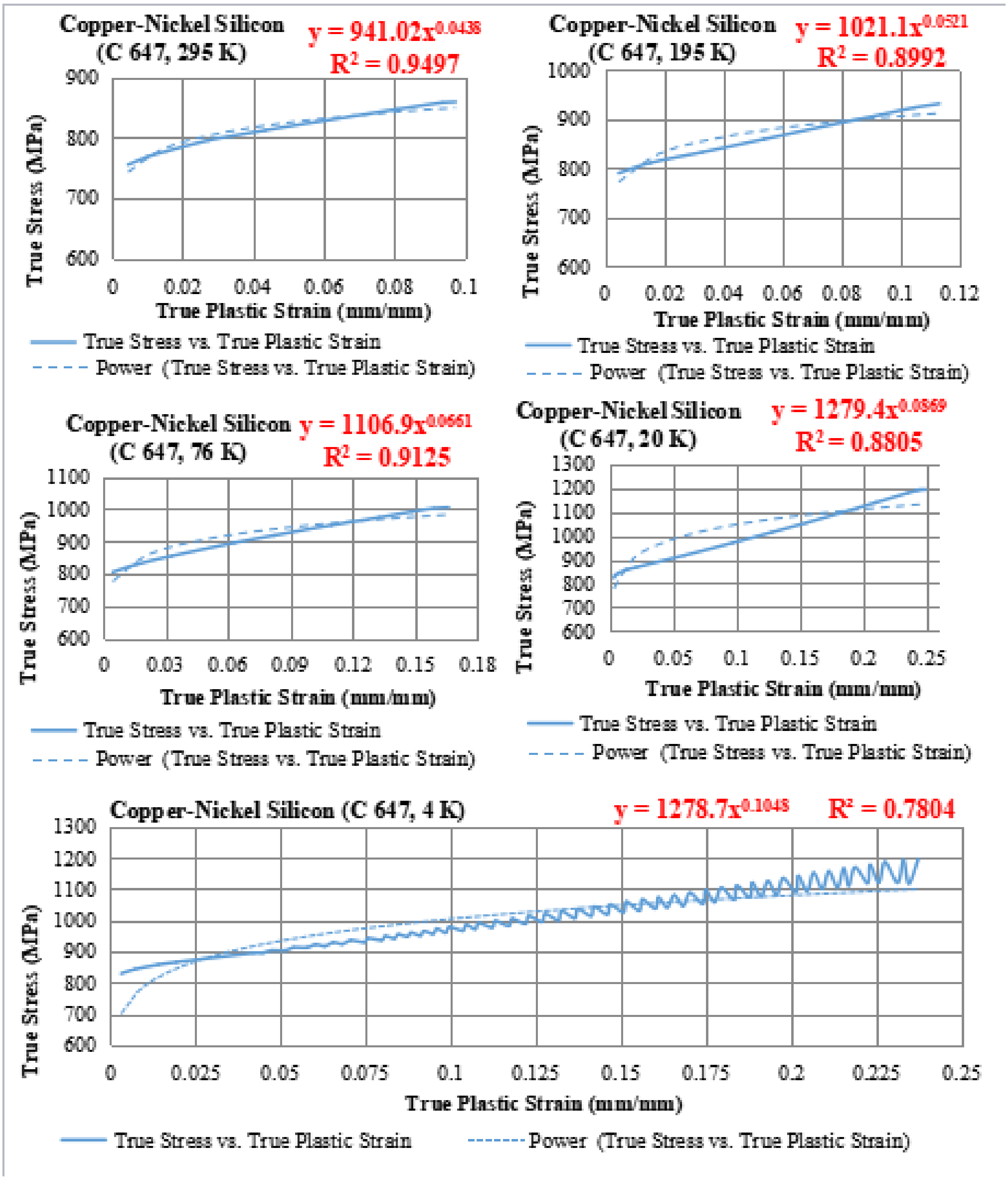


Figure 20: True Stress-True Plastic Strain curves for Copper-Nickel Silicon (C647) at 295K, 195K, 76K, 20K and 4K.

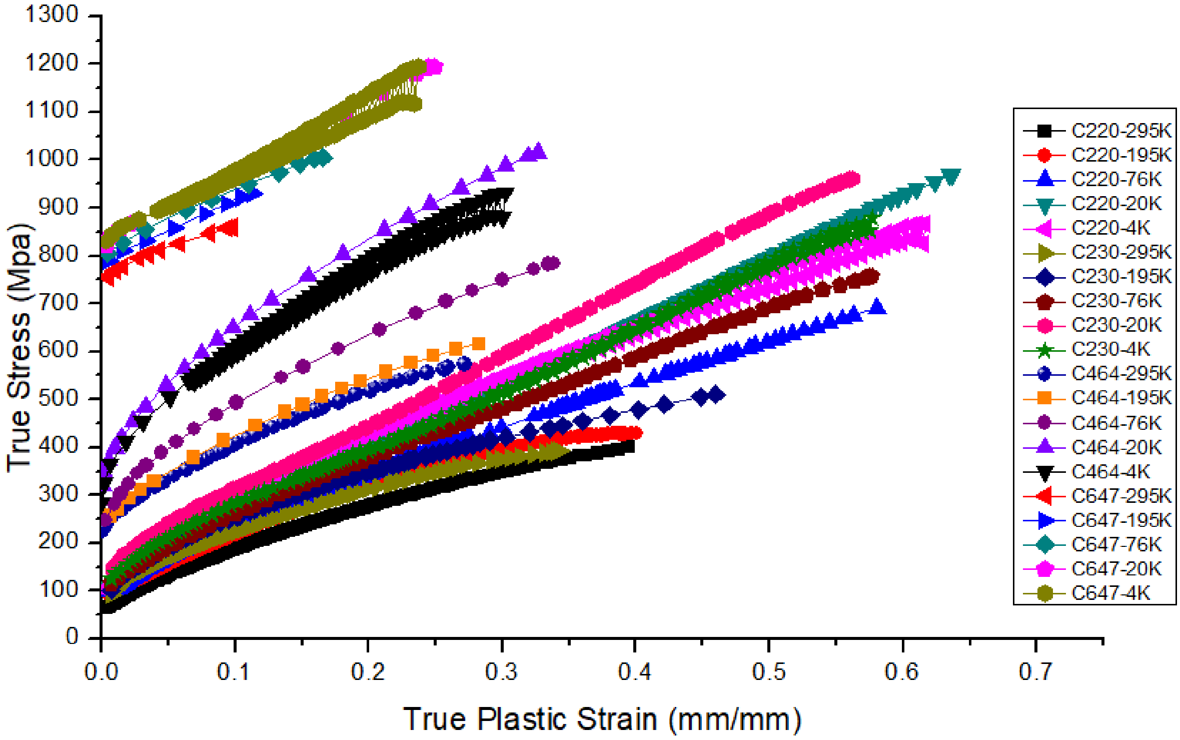


Figure 21: Combined True Stress-True Plastic Strain plots for C220, C230, C464, C647 at 295K, 195K, 76K, 20K and 4K.

10. ANALYSIS

ANSYS Workbench 18.2

Table 4: ANSYS inputs for the Copper alloys at different temperatures.

Ansys Input									
Sr. No.	**Material Name**	**Temperature (K)**	**Youngs Modulus (MPa)**	**Yield Stress (MPa)**	**Ultimate Tensile Stress (MPa)**	**Poisson's ratio (ν)**	**$\sigma = k^*\varepsilon^n$**		**Coefficient of friction (μ)**
							K	**n**	
1	C220	295	104110	66.189	269.07	0.31	575.25	0.4682	0.3
2		195	113074	70.326	294.6		644.14	0.4509	
3		76	122037	91.010	384.73		754.55	0.4734	
4		20	124105	107.55	509.75		1046.2	0.543	
5		4	124795	103.42	469.12		989.78	0.4886	
6	C230	295	102731	89.631	277.77	0.307	580.6	0.3942	
7		195	108937	96.526	321.06		659.13	0.3968	
8		76	121347	113.07	423.43		904.98	0.4987	
9		20	124795	114.1	543.93		1104.2	0.4912	
10		4	125484	126.17	489.75		1018.5	0.5233	
11	C464	295	96526	213.73	435	0.28	666.8	0.1945	
12		195	99973	233.04	461.44		798.96	0.2501	
13		76	102042	262	555.51		975.81	0.2706	
14		20	103421	328.19	725.66		1149	0.2147	
15		4	104110	301.3	685.93		1027.9	0.1915	
16	C647	295	147547	723.95	776.96	0.34	941.02	0.0438	
17		195	153753	763.94	826.16		1021.1	0.0521	
18		76	159958	786.7	849.90		1106.9	0.0661	
19		20	162026	816.34	927.94		1279.4	0.0869	
20		4	162716	825.99	938.12		1278.7	0.1048	

The Analysis is carried out in **Static Structural.**

10.1. Material Definition:

The material is defined in "Engineering Data". There are already many materials available in the ANSYS material library. Since the required copper alloys were not available, they were defined by providing certain properties of the material.

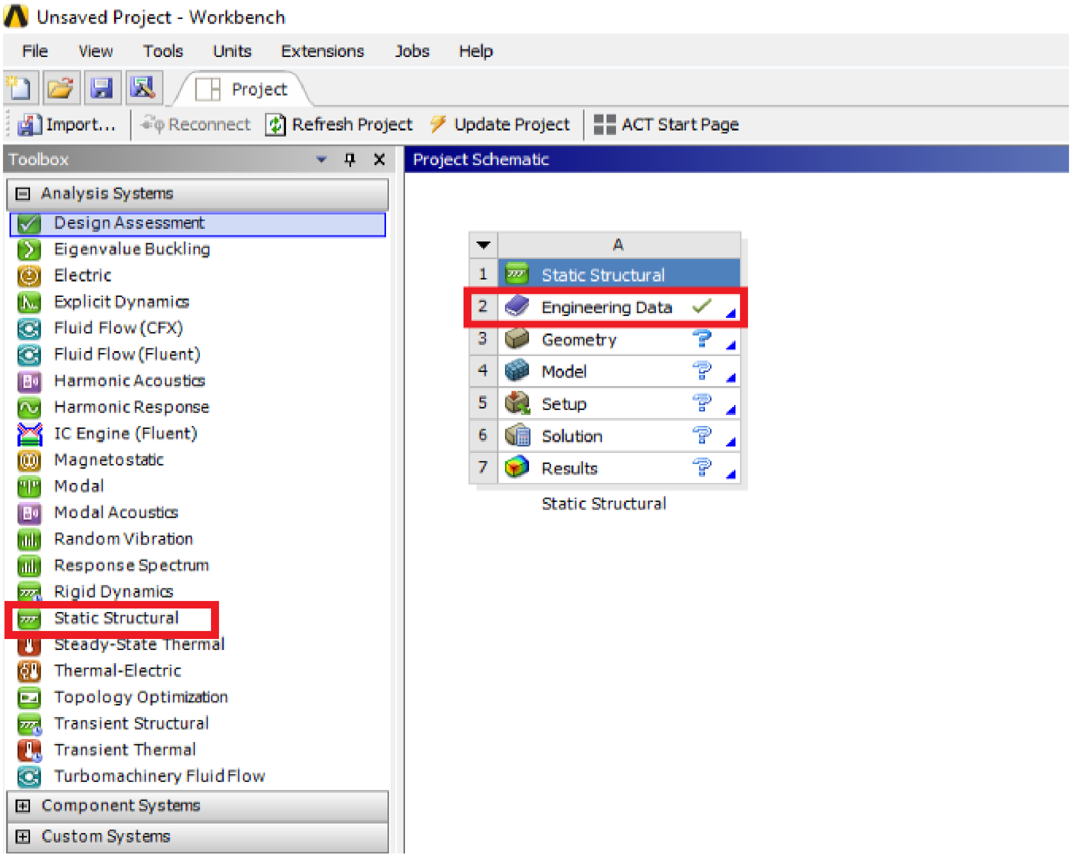


Figure 22: ANSYS Workbench opening window showing selection of Static Structural option.

During the experiment, the deformation of the specimen gets in the plastic region. Therefore, a nonlinear analysis is done. The properties needed to completely define the material of the specimens are as follows.

(i) Young's Modulus of Elasticity (E):

Young's Modulus is a mechanical property that measures the stiffness of a solid material. It defines the relationship between stress (σ) and strain (ε) in a material in the linear elasticity regime of a uniaxial deformation.

In the elastic region of the material,

$$E = \frac{\sigma}{\varepsilon}$$

It is the fundamental property of every material that cannot be changed. It is dependent on temperature and pressure however.

(ii) Poisson's ratio (ν):

It is the ratio of lateral strain to longitudinal strain. It indicates the relative change in the lateral dimensions of a component perpendicular to the direction of externally applied Load. It is denoted by Greek letter 'nu' (ν).

For illustration purpose, analysis of material C-220 at 195 K is shown.

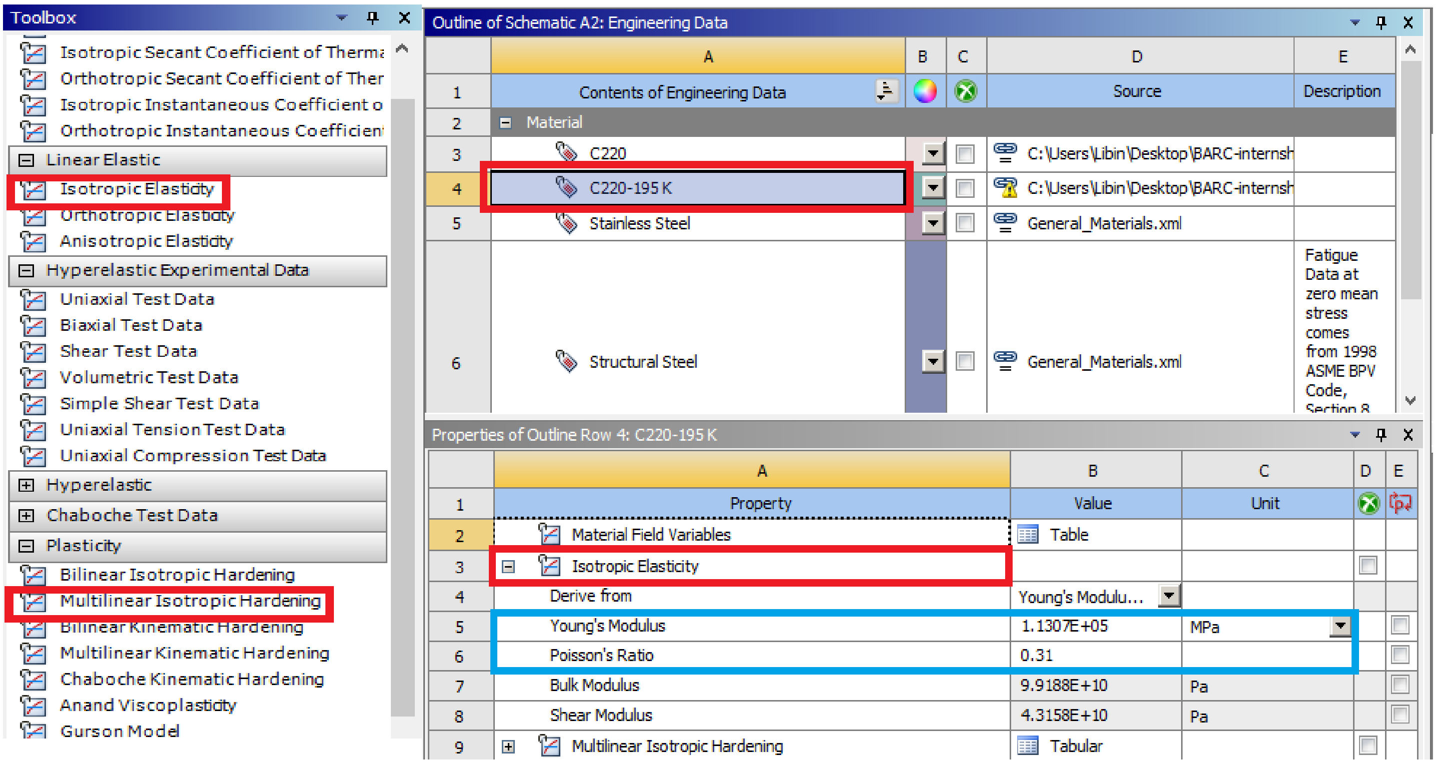


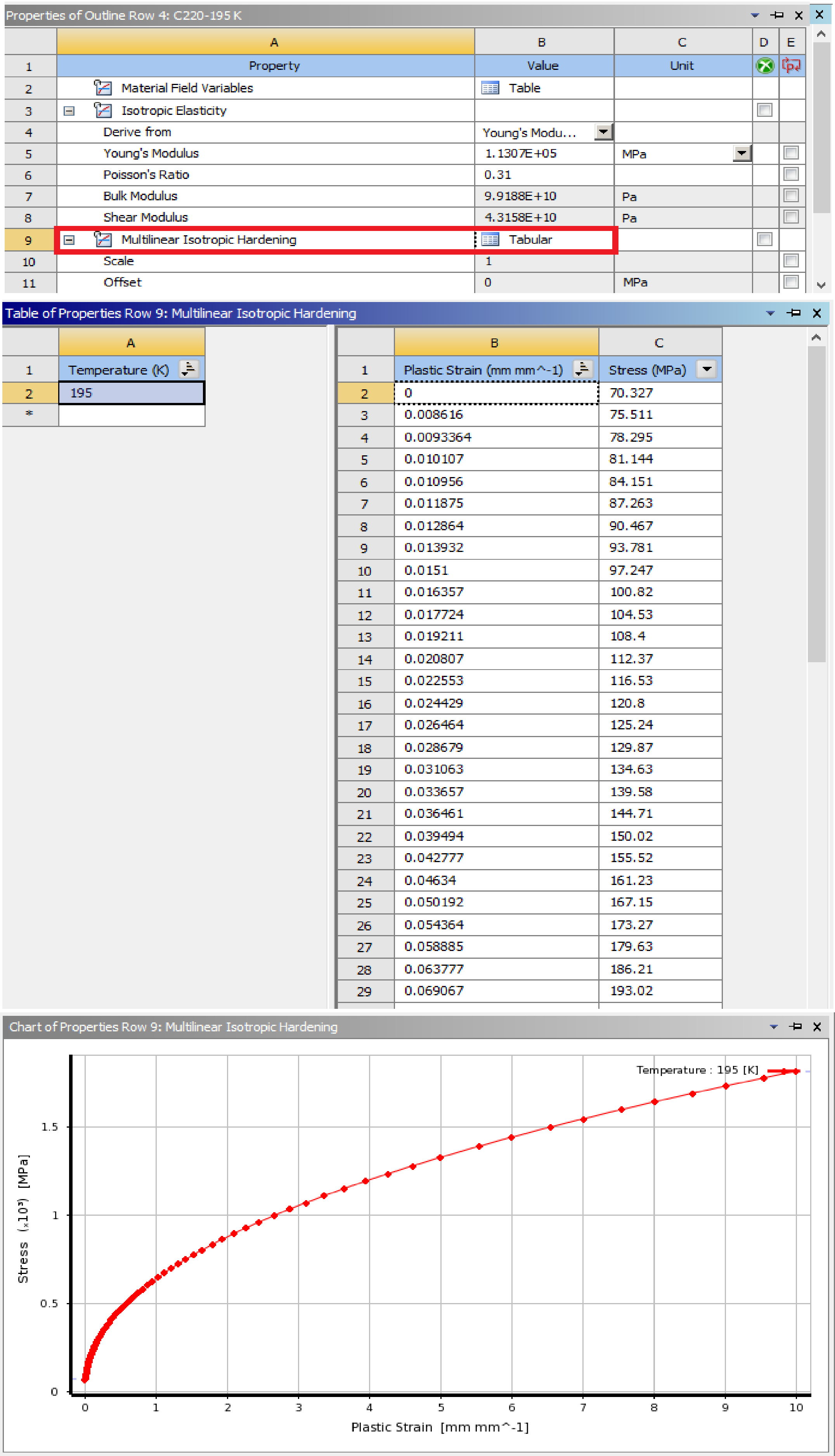
Figure 23: Illustrative image from ANSYS Workbench window showing material definition (C220 at 195K) and the engineering data input.

Linear Elastic – Isotropic Elasticity is defined by providing Young's Modulus and Poisson's ratio.

(iii) Test data (True Stress vs. True Plastic Strain):

Plasticity – Multilinear Isotropic Hardening is defined by providing a graph in the form of power law $\sigma = K * \mathcal{E}^n$. The values of K and n is obtained by curve fitting True Stress vs. True Plastic Strain curve.

Optimum strain values are chosen and corresponding stress is found out. Thus, a plot of strain vs. stress is obtained for the plastic region of the material.



	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Isotropic Elasticity				
4	Derive from	Young's Modu...			
5	Young's Modulus	1.1307E+05	MPa		
6	Poisson's Ratio	0.31			
7	Bulk Modulus	9.9188E+10	Pa		
8	Shear Modulus	4.3158E+10	Pa		
9	Multilinear Isotropic Hardening	Tabular			
10	Scale	1			
11	Offset	0	MPa		

	A
1	Temperature (K)
2	195
*	

	B	C
1	Plastic Strain (mm mm^-1)	Stress (MPa)
2	0	70.327
3	0.008616	75.511
4	0.0093364	78.295
5	0.010107	81.144
6	0.010956	84.151
7	0.011875	87.263
8	0.012864	90.467
9	0.013932	93.781
10	0.0151	97.247
11	0.016357	100.82
12	0.017724	104.53
13	0.019211	108.4
14	0.020807	112.37
15	0.022553	116.53
16	0.024429	120.8
17	0.026464	125.24
18	0.028679	129.87
19	0.031063	134.63
20	0.033657	139.58
21	0.036461	144.71
22	0.039494	150.02
23	0.042777	155.52
24	0.04634	161.23
25	0.050192	167.15
26	0.054364	173.27
27	0.058885	179.63
28	0.063777	186.21
29	0.069067	193.02

Figure 24: Illustrative image from ANSYS Workbench window showing input data for Material Isotropic Hardening of C220 at 195K.

10.2. Geometry:

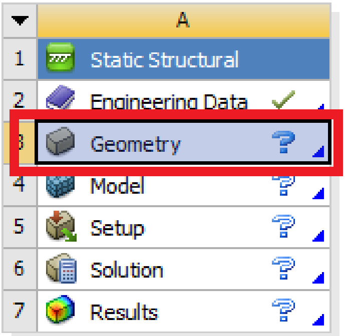


Figure 22: Starting window in ANSYS Workbench for Geometry definition.

Geometry can be modelled in ANSYS inbuilt software DESIGN – MODELER or SPACECLAIM. Geometry can also be imported as .stp, .iges file extensions. For the project analysis, geometry was modelled using AutoDesk Inventor Software and imported as .stp file.

The following is the actual geometry of the Small Punch Test:

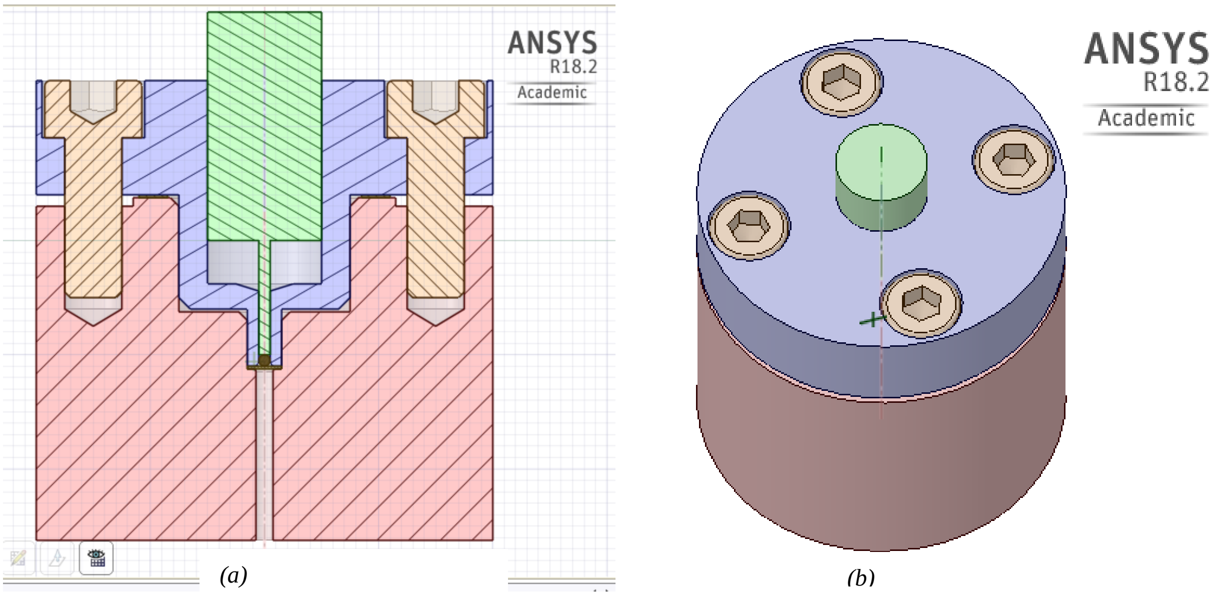


Figure 25: Small Punch Test Model in Spaceclaim (ANSYS inbuilt) - (a) Cross-Sectional view (b)Isometric View.

For analysis simplification, the setup is remodelled into a smaller size and only few dominant parts are considered.

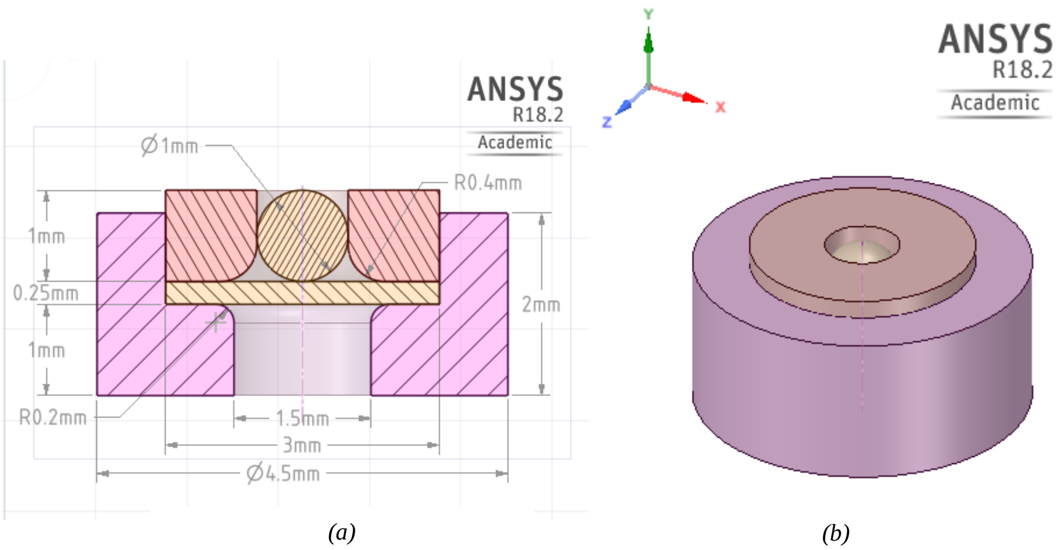


Figure 26: Reduced size of S. P. T. Model for analysis simplification - (a) Cross-Sectional View (b) Isometric View.

10.3. Finite Element Modelling:

The following steps have to be followed to completely define the geometric model and create its finite element model.

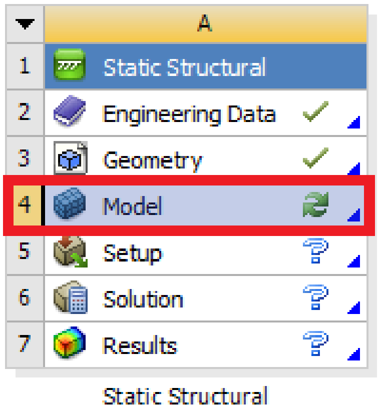


Figure 27: Starting window in ANSYS Workbench for Model definition.

(i) Assignment of material to each geometric part:
Each geometric part is assigned it's material as shown:

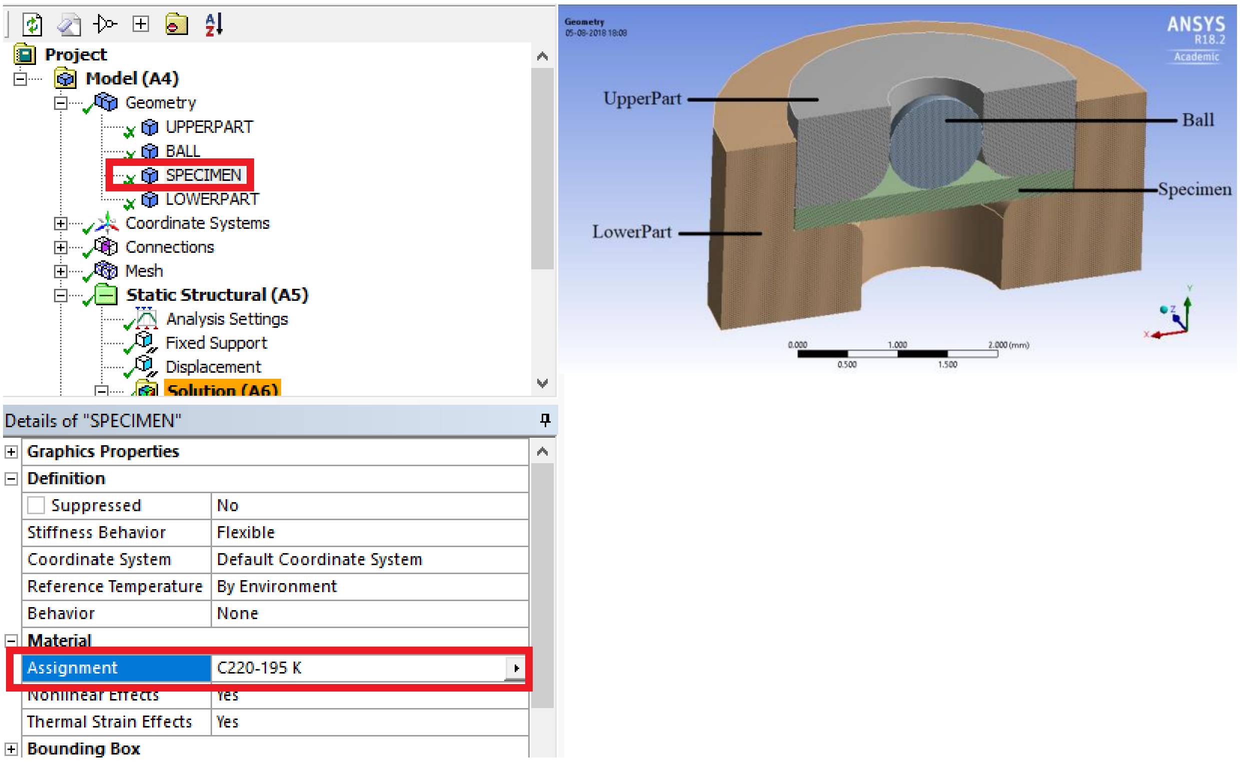


Figure 28: Illustrative image from ANSYS Workbench window showing assignment of material to the geometry.

(ii) Defining the type of contact between each geometric part:
Since the geometric parts come in contact with each other it is necessary to define the type of contact.

Three types of contacts are defined for this model:
(a) Bonded-
When there is no relative motion between the two parts in contact.

(b) Frictional-
When there is relative motion between two parts and the friction cannot be neglected.

(c) Frictionless-

When there is relative motion between two parts and the friction can be neglected.

Five contacts are defined for this model:

1) Frictionless - *between Upperpart and Ball*

2) Bonded - *between Upperpart and Lower part*

3) Frictional

-between Upper part to Specimen

-between Lower part to Specimen

-between Specimen and Lower part

The contact pairs are shown as follows:

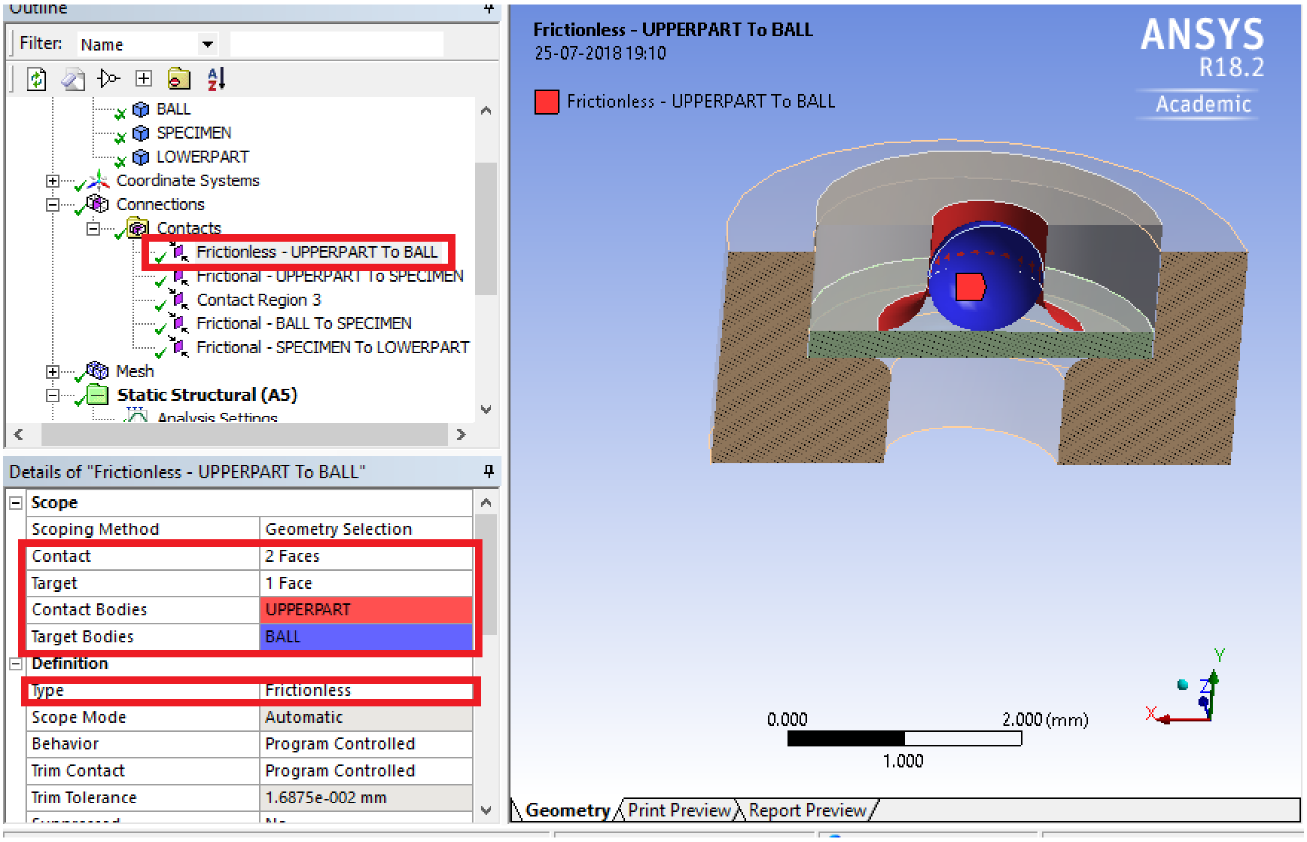


Figure 29: Illustrative image from ANSYS Workbench window showing frictionless contact between Upper part and Ball.

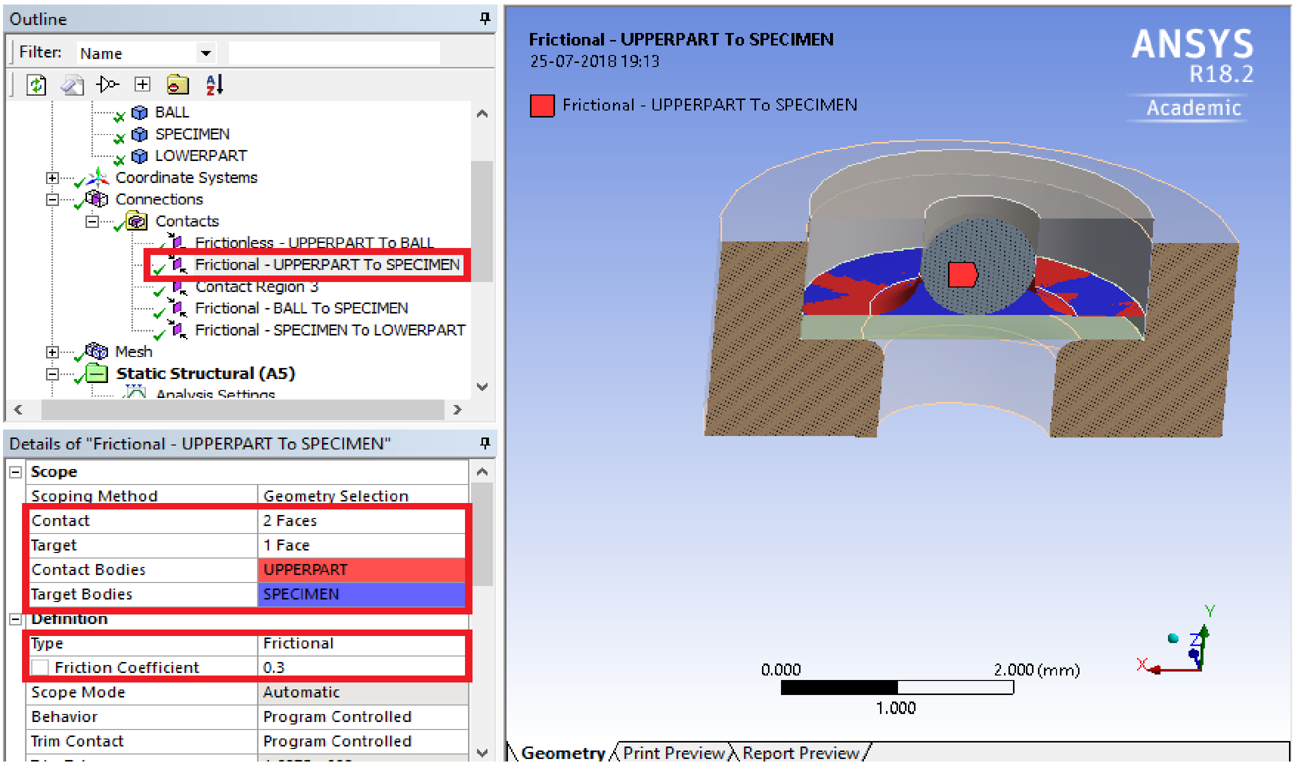


Figure 30: Illustrative image from ANSYS Workbench window showing Frictional contact between Upper part and Specimen.

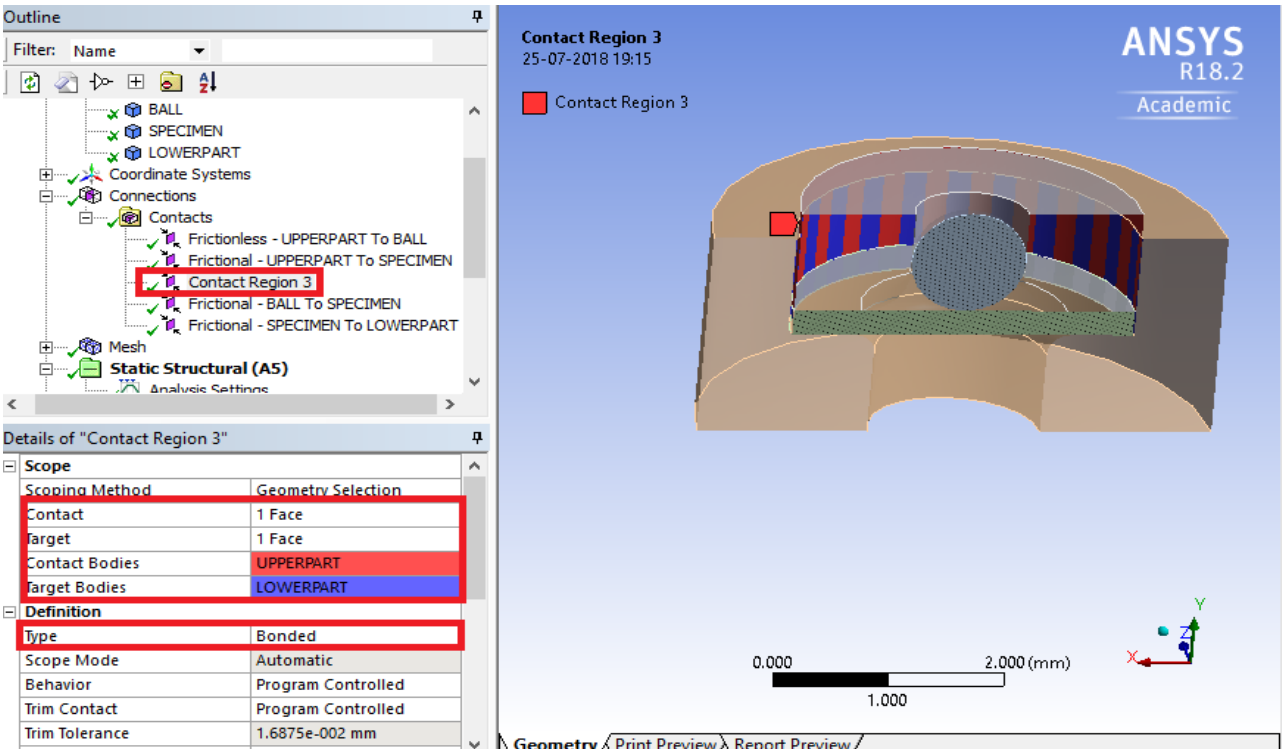


Figure 31: Illustrative image from ANSYS Workbench window showing Bonded contact between Upper part and Lower part.

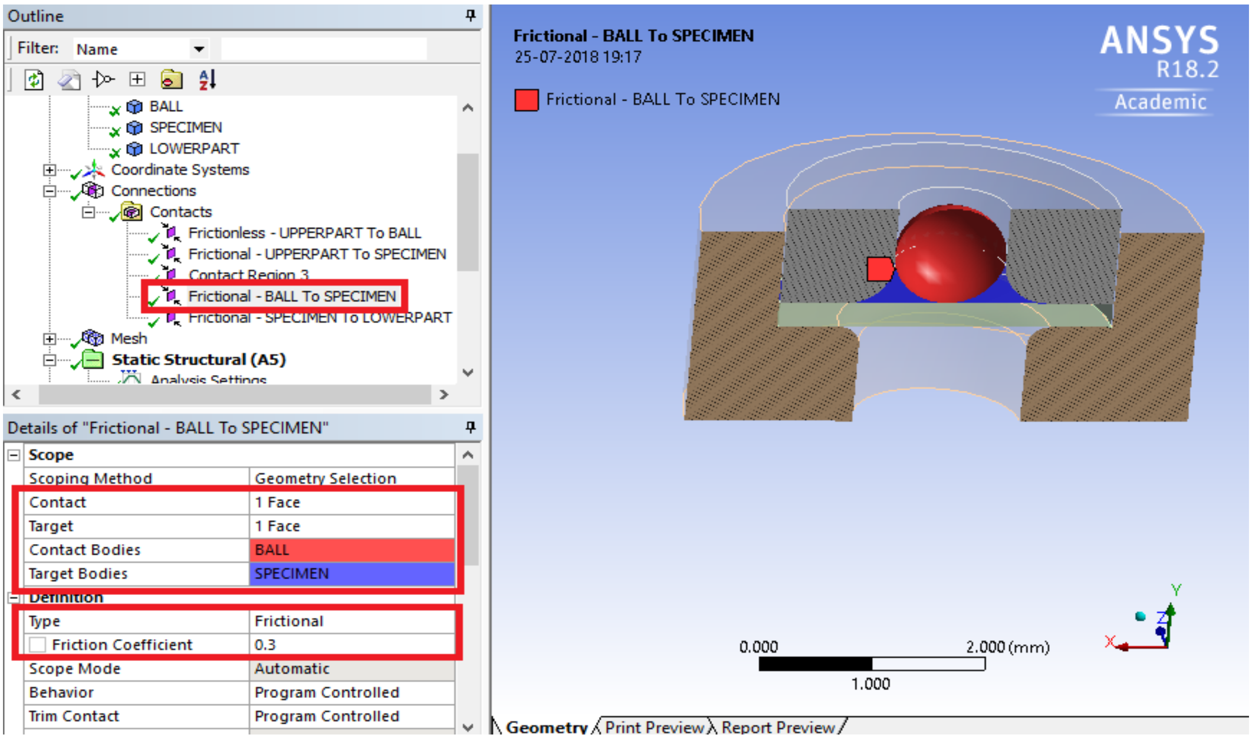


Figure 32: Illustrative image from ANSYS Workbench window showing frictional contact between Ball and Specimen.

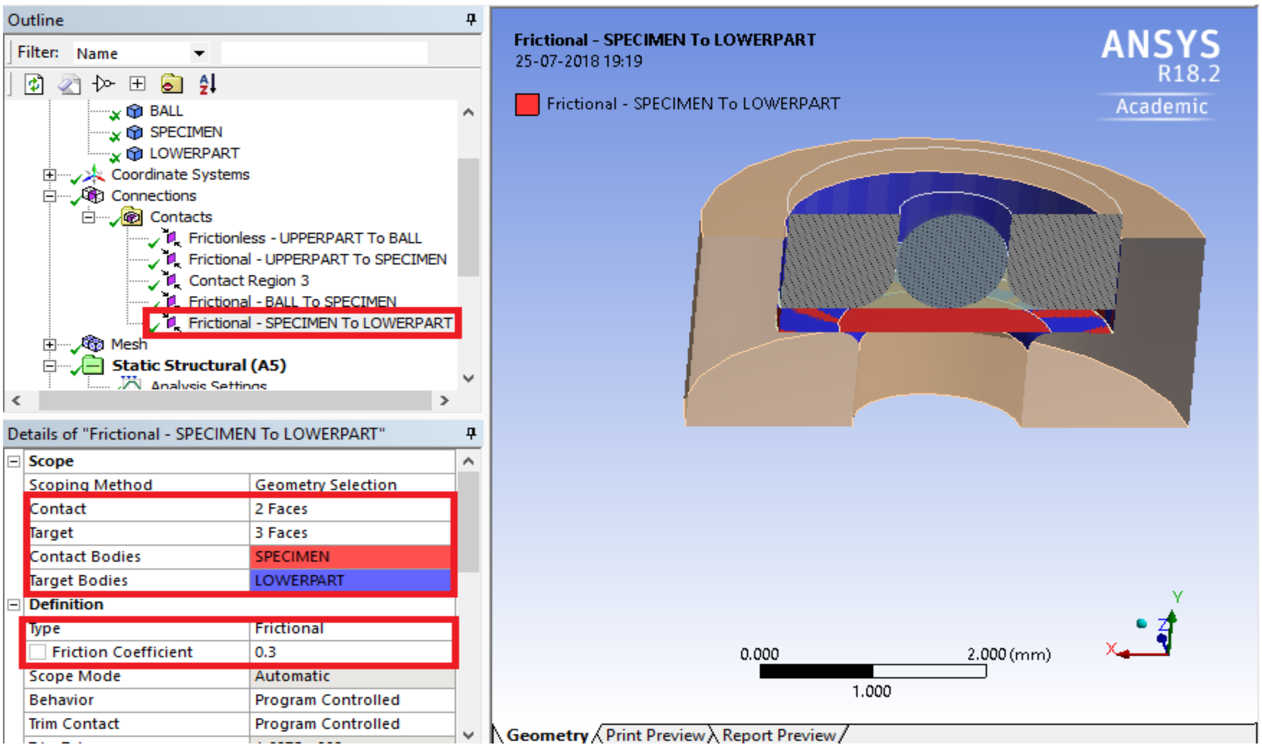


Figure 33: Illustrative image from ANSYS Workbench window showing frictional contact between Specimen and Lower part.

(iii) Meshing:

A coarse type of mesh is done with an element size of 0.4 mm.

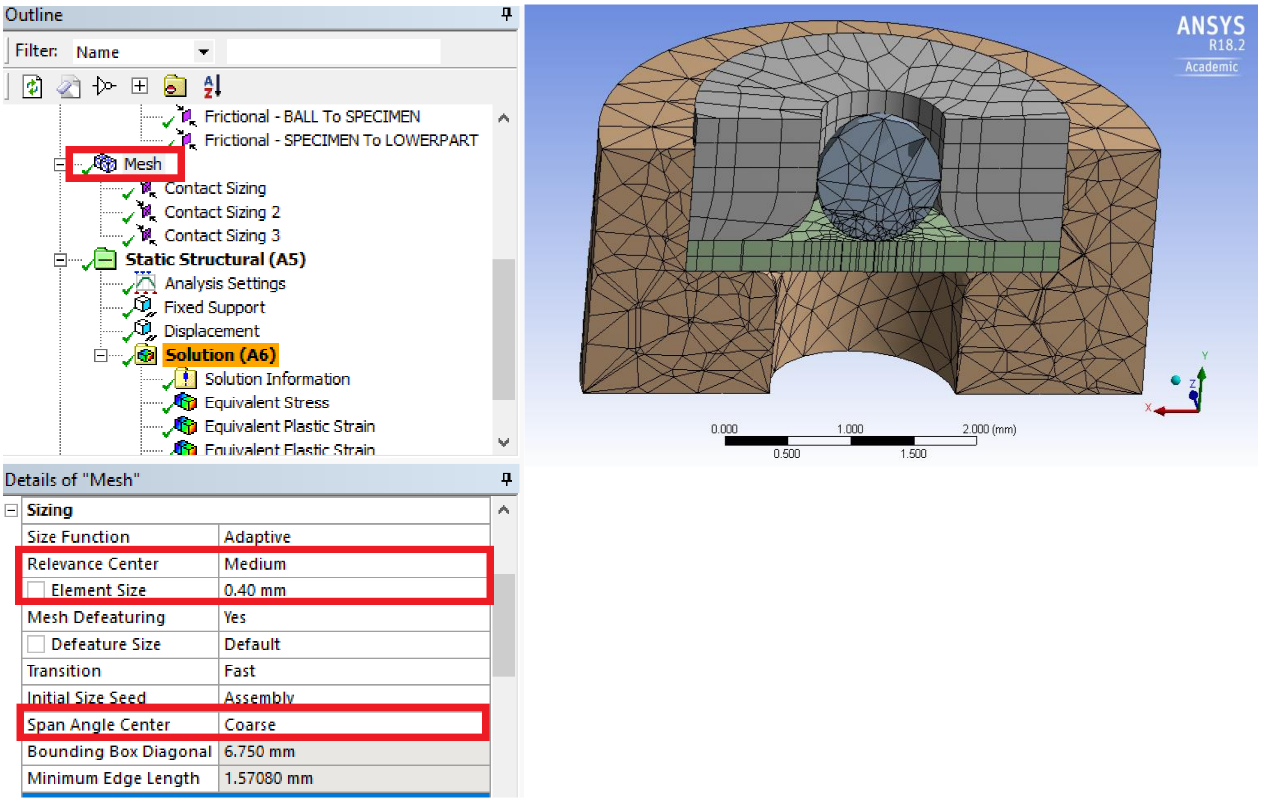


Figure 34: Illustrative image from ANSYS Workbench window showing Mesh properties.

A refinement of mesh is done at contacts with the help of contact sizing. 3 contact sizing is done (between Specimen and Ball, between Specimen and Upperpart and between Specimen and Lower part).

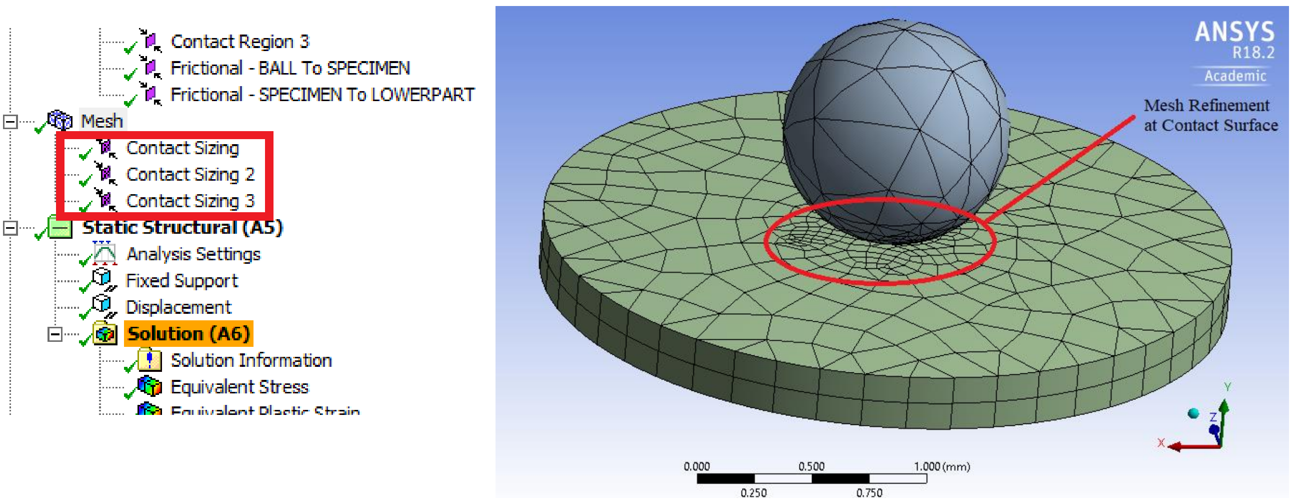


Figure 35: Illustrative image from ANSYS Workbench window showing refinement of mesh at contact surface.

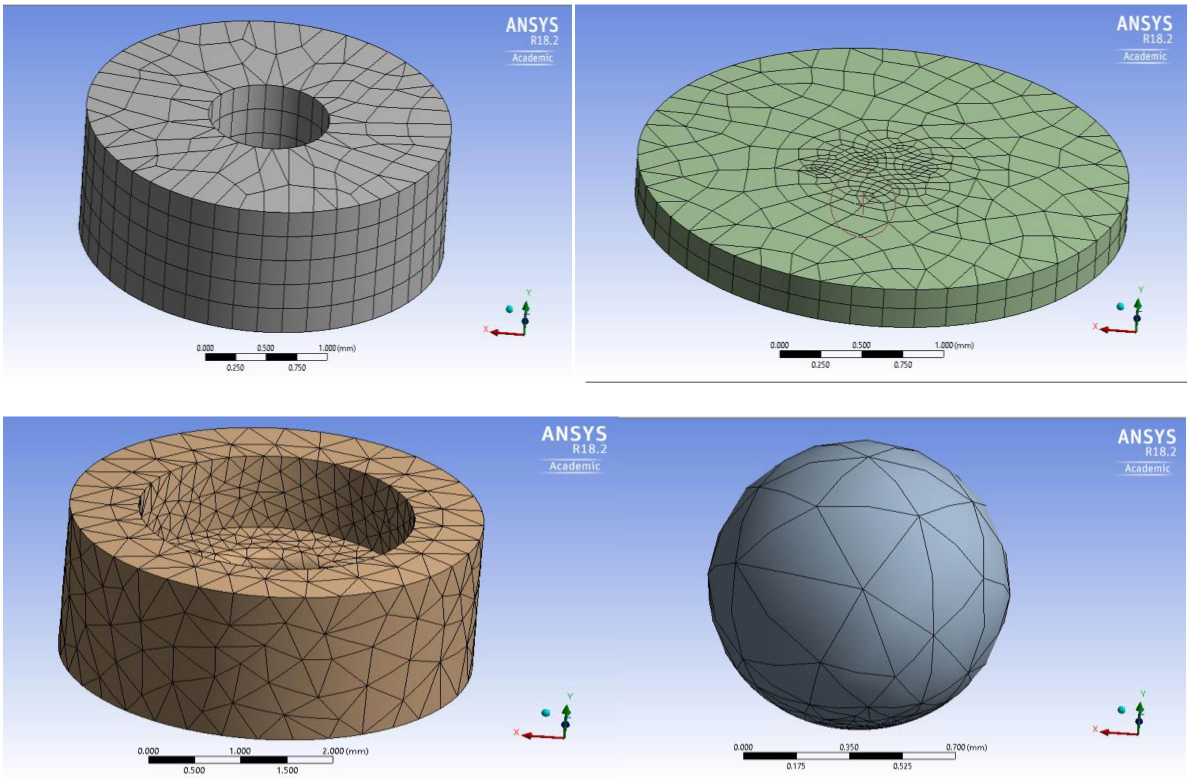


Figure 36: Meshed bodies of Upper part, Specimen, Lower part and Ball.

10.4. Boundary Conditions:

For the analysis, two boundary conditions are defined.

(i) Fixed Support:

The fixed support is considered as the surface of the Lower part where the specimen is placed.

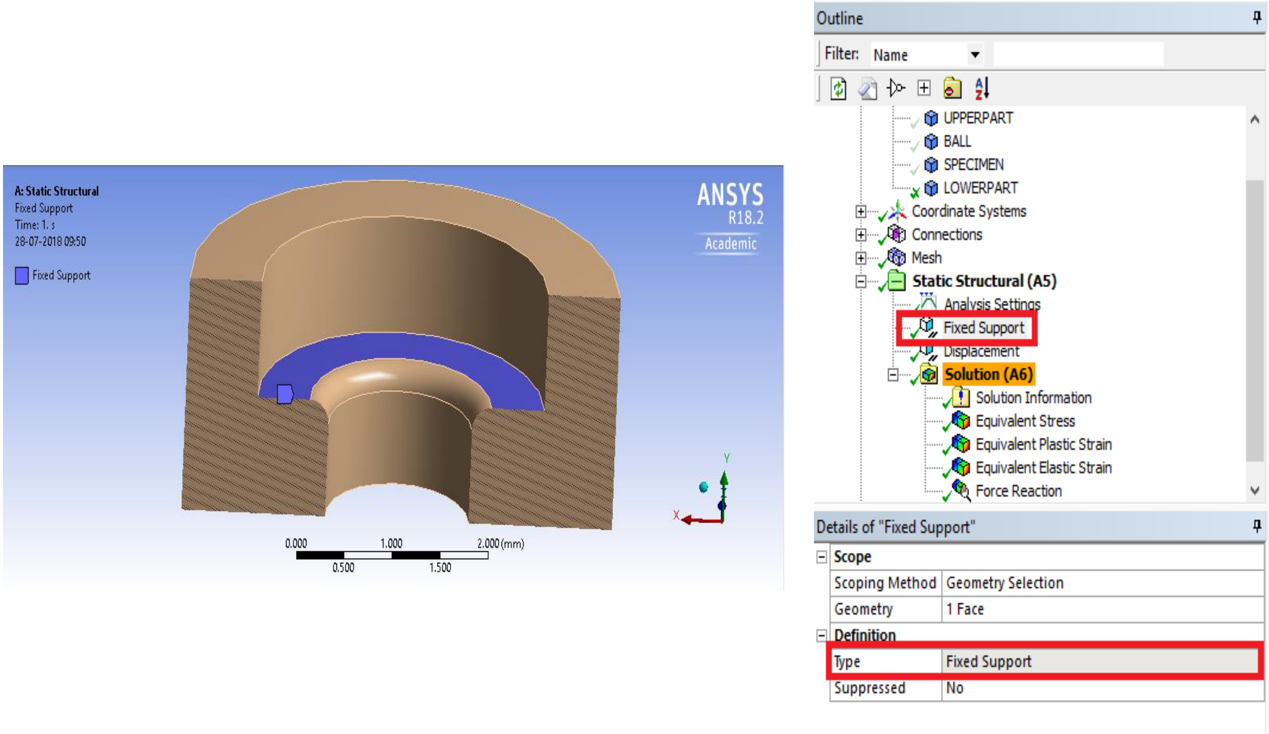


Figure 37: Illustrative image from ANSYS Workbench window showing Fixed Support.

(ii) Displacement:

A **1.5 mm** downward displacement is given to the Ball.

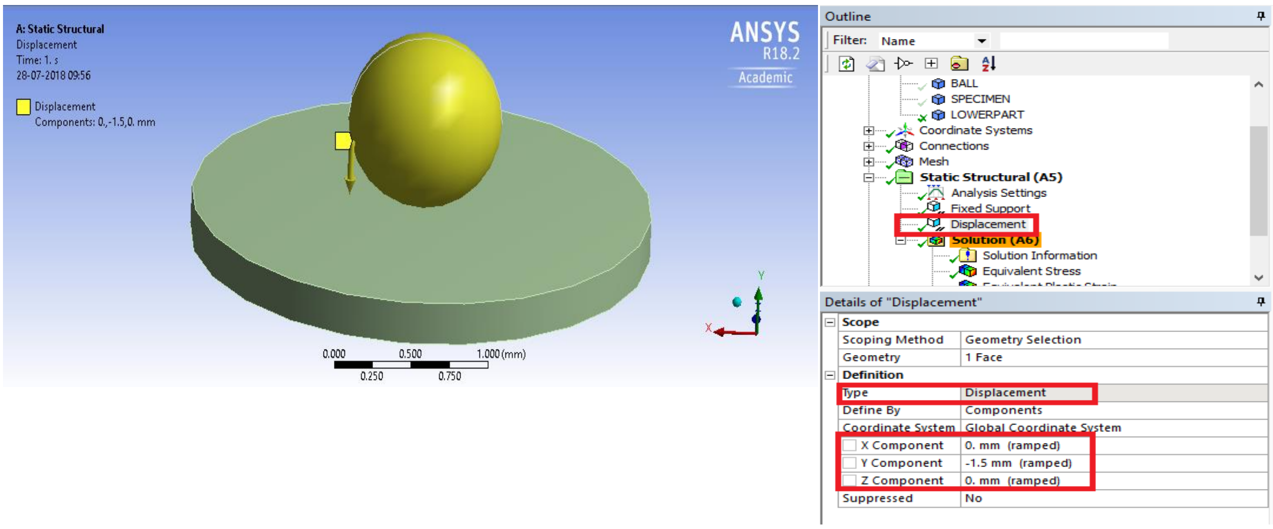


Figure 38: Illustrative image from ANSYS Workbench window showing displacement given to the ball.

10.5. Solution:

Now the Finite Element Model is created and the boundary conditions are applied. The goal of this analysis is to find the Load-Displacement curve. The Load is measured by finding the Force Reaction at the Fixed support and the displacement is measured by the actual displacement of the Ball. Thus, a chart of Load vs. Displacement is obtained.

Equivalent Stress, Strain and Plastic Strain of the specimen is also obtained.

Before the solution is run in ANSYS, it is made sure that it supports the large deflection of the specimen since the analysis is of Static type.

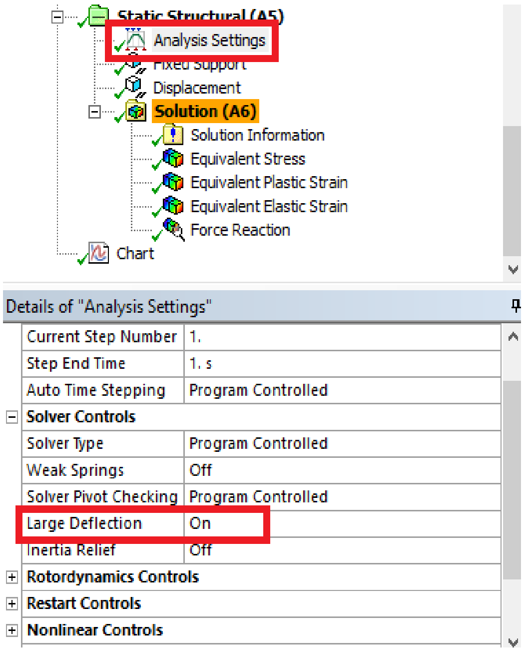


Figure 39: Illustrative image from ANSYS Workbench window showing the changes in 'Analysis Settings' that has to be done for the analysis.

The results were obtained from ANSYS after the solution was complete. Following figures shows an example of results obtained after analysis of material C220 at 195K.

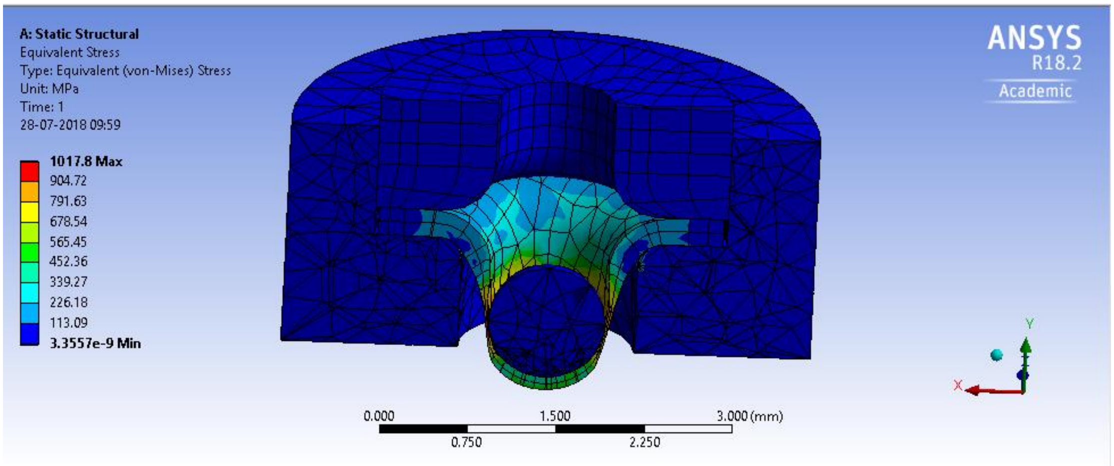


Figure 40: Equivalent (Von-Mises) Stress for C220 at 195K.

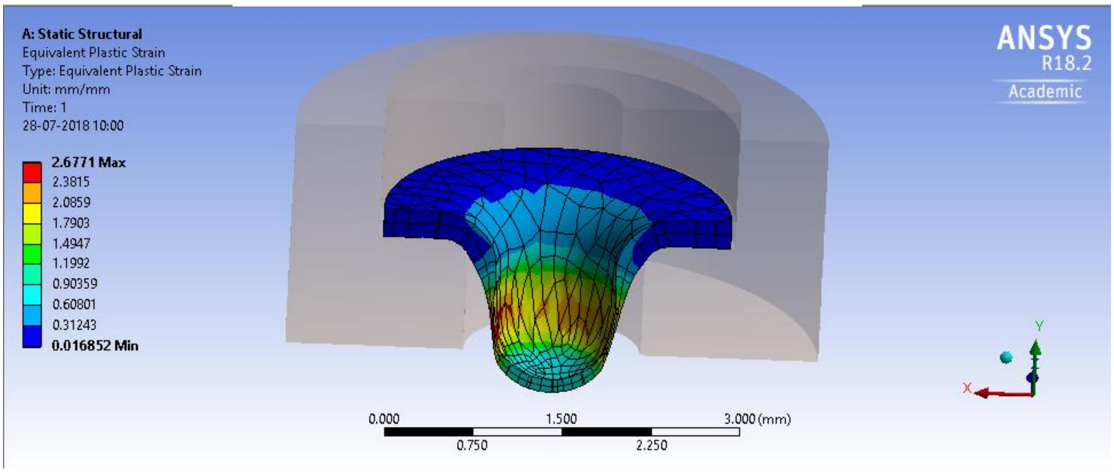


Figure 41: Equivalent Plastic Strain for C220 at 195K.

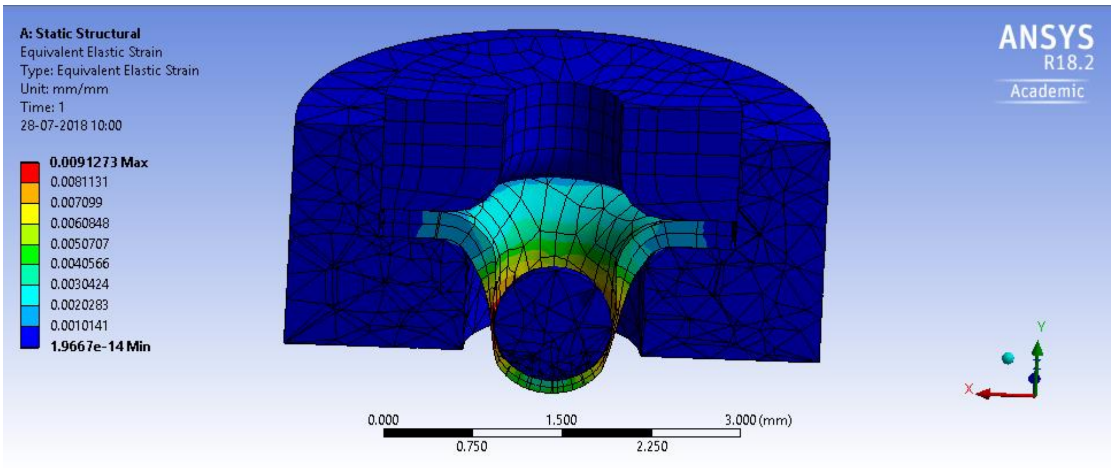


Figure 42: Equivalent Elastic Strain for C220 at 195K.

[B] Displacement (Y) [mm]	[E] Force Reaction (Y) [N]
0.	
= -6.4305e-003	4.6629
= -1.2862e-002	8.65
= -2.2515e-002	12.607
= -3.6975e-002	15.782
= -5.868e-002	19.214
= -9.1245e-002	24.638
= -0.14008	32.989
= -0.18885	42.322
= -0.23775	52.697
= -0.2634	59.319
= -0.28905	66.113
= -0.32745	77.035
= -0.366	90.037
= -0.3861	97.649
= -0.40635	105.1
= -0.43665	116.1
= -0.46695	127.63
= -0.48285	134.21
= -0.49875	140.28
= -0.5226	149.96
= -0.54645	159.63
= -0.58215	173.58
= -0.618	187.65
= -0.6717	207.92
= -0.72525	225.35
= -0.7656	235.84
= -0.79575	243.23
= -0.8259	249.
= -0.84855	251.84
= -0.8712	254.92
= -0.89385	255.52
= -0.92775	256.62
= -0.95325	256.23
= -0.97845	254.12
= -0.98715	252.97
= -0.996	251.72
= -1.0092	250.13
= -1.0253	248.62
= -1.0389	246.54
= -1.0525	244.57
= -1.0651	242.16
= -1.0741	240.5
= -1.083	238.53
= -1.0961	235.68
= -1.113	231.45
= -1.13	226.64
= -1.1477	221.13
= -1.1609	216.41
= -1.174	212.06
= -1.1864	207.99
= -1.1987	203.96
= -1.2156	199.25
= -1.2327	194.59
= -1.2452	192.1
= -1.2576	188.49
= -1.2764	184.34
= -1.2903	181.48
= -1.3044	178.46
= -1.3254	174.26
= -1.3464	170.2
= -1.3779	164.76
= -1.4096	159.52
= -1.441	154.63
= -1.4648	151.
= -1.4883	147.46
-1.5	145.71

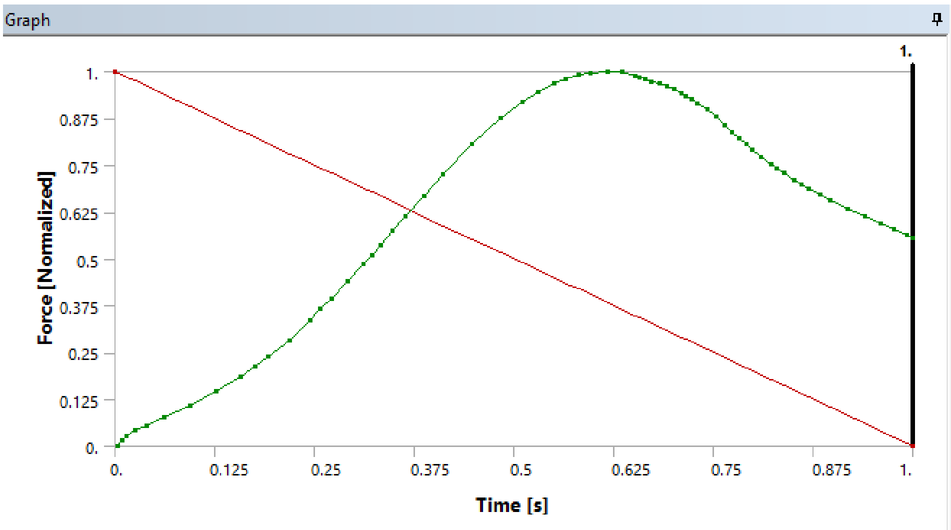


Figure 43: Force Reaction vs. Displacement plot obtained from ANSYS for C220 at 195K.

11. Results

The Load-Displacement curves obtained for the various copper alloys at different temperatures are replotted in Microsoft Excel and shown as follows:

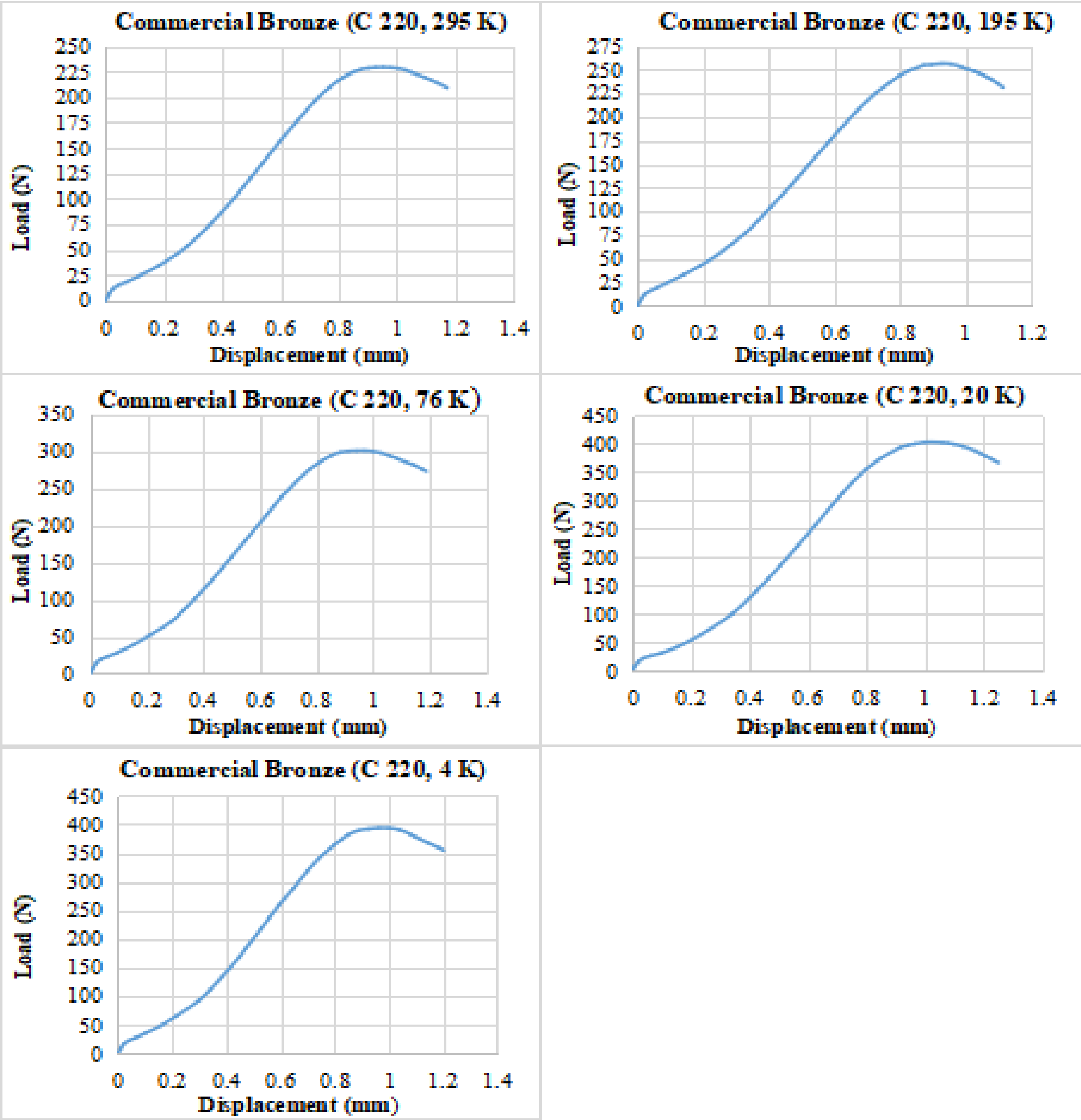


Figure 44: Load-Displacement plots for Commercial Bronze (C220) at 295K, 195K, 76K, 20K and 4K.

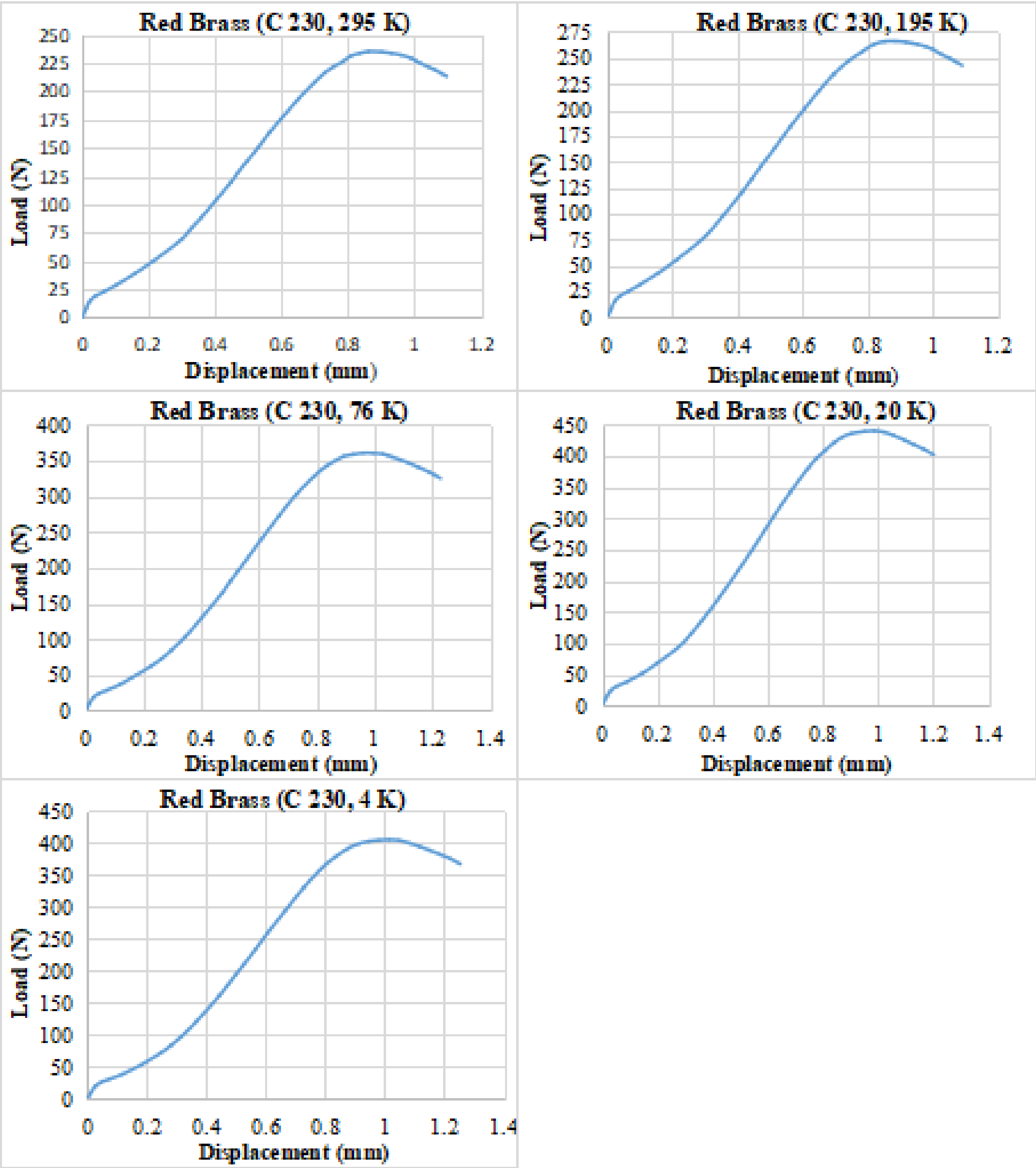


Figure 45: Load-Displacement plots for Red Brass (C230) at 295K, 195K, 76K, 20K and 4K.

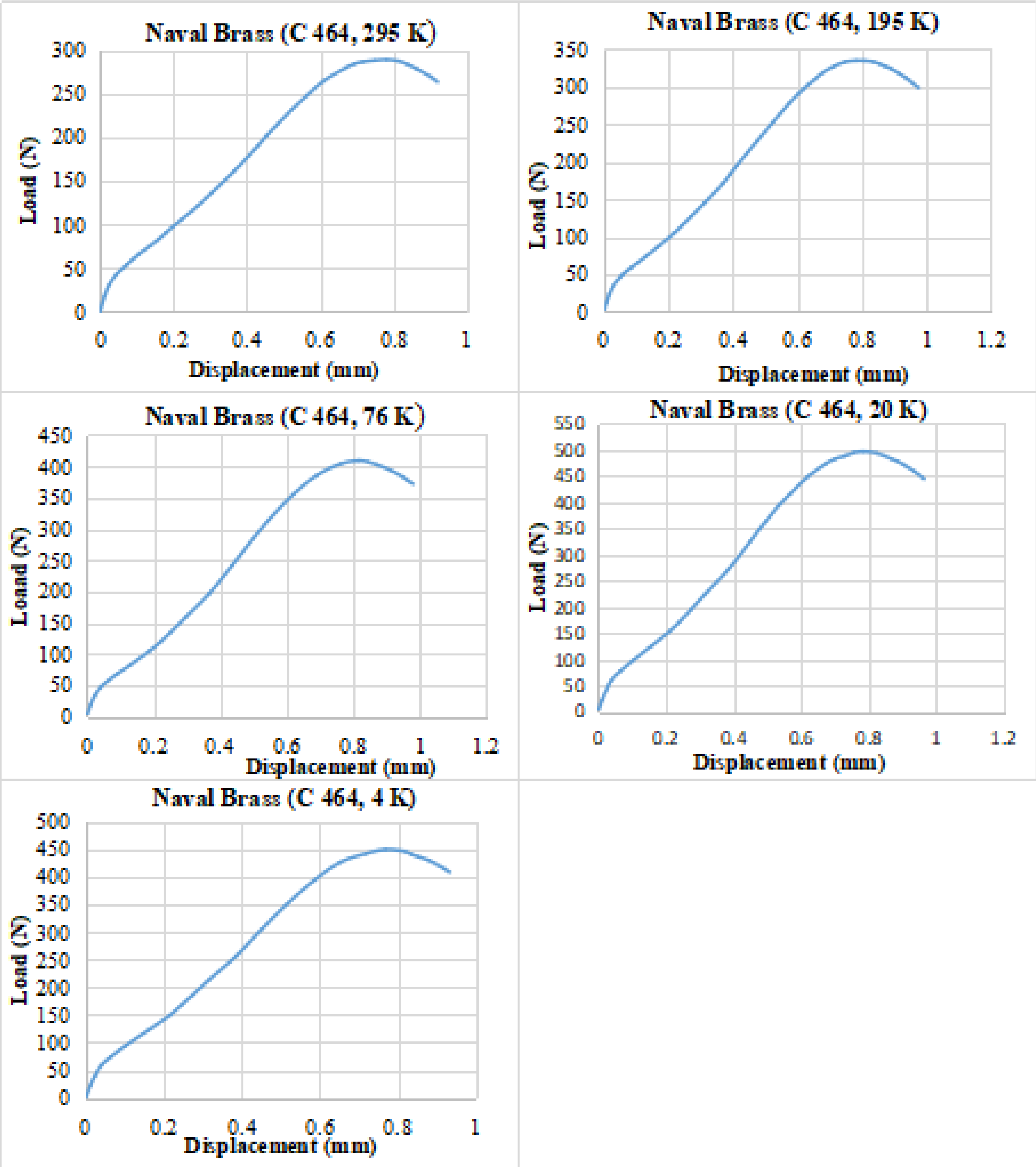


Figure 46: Load-Displacement plots for Naval Brass (C464) at 295K, 195K, 76K, 20K and 4K.

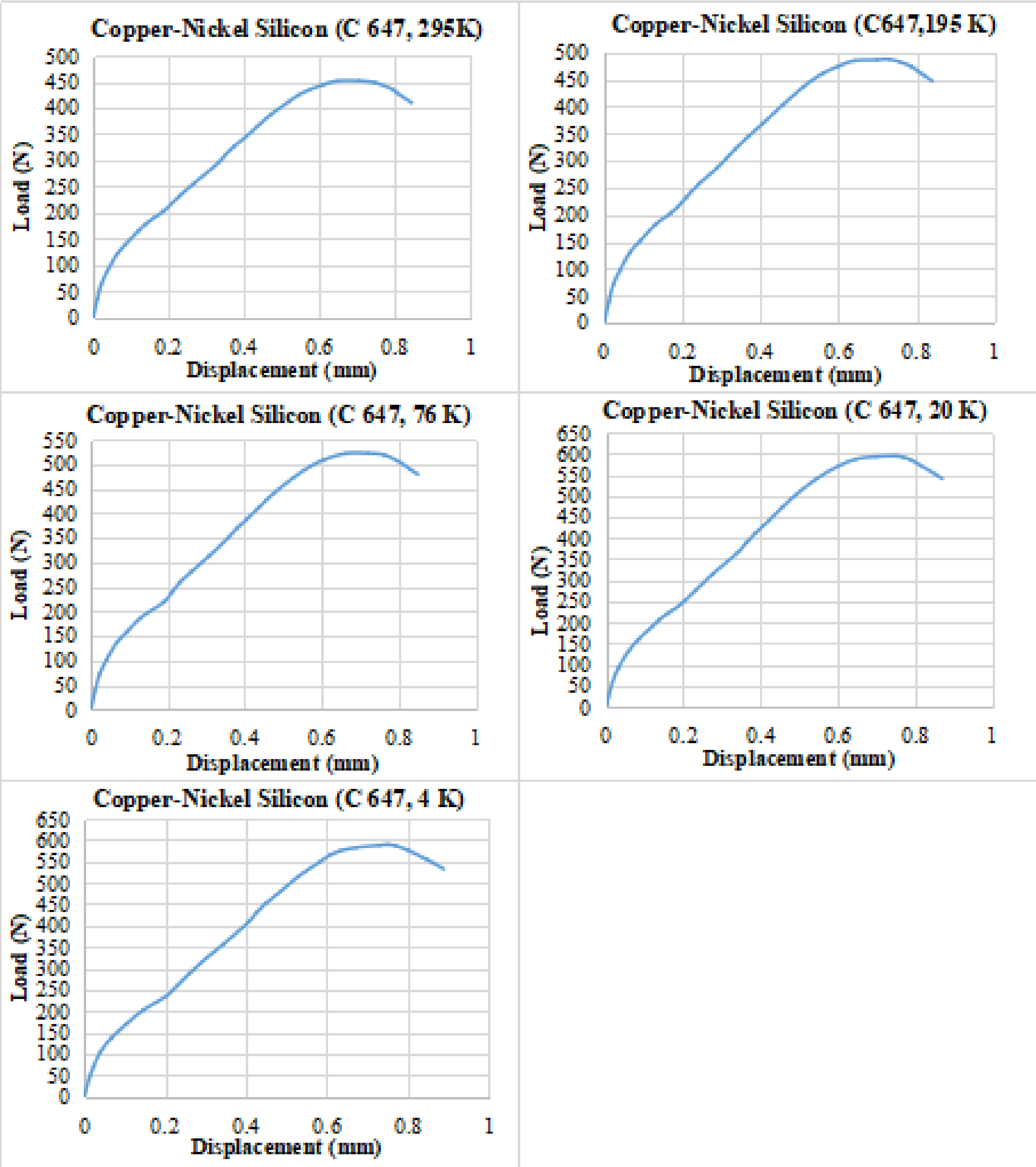


Figure 47: Load-Displacement plots for Copper-Nickel Silicon (C647) at 295K, 195K, 76K, 20K and 4K.

Table 5: Comparison of Results of Ultimate Tensile Stress and Toughness from S. P. T. and Ultimate Tensile Test.

Sr. No.	Mate-rial Name	Temperature	Ultimate Tensile Stress - from Ultimate Tensile Test (MPa)	Maximum Load - F_u - from S. P. T. (N)	F_u/t^2 - from S. P. T. (t = 0.25mm) (MPa)		Toughness - from tensile test (Area under Stress-Strain curve) (N/mm^2)	Toughness - from S. P. T. - (Area under Load-displacement plot) (N-mm)
1		295	269.076	229.51	3672.16		120.33	161.77
2		195	294.597	256.62	4105.92		138.68	168.77
3	C220	76	384.73	300.89	4814.24		264.40	215.66
4		20	509.748	402.84	6445.44		373.24	296.3
5		4	469.125	393.67	6298.72		345.67	282.93
6		295	277.771	234.94	3759.04		111.10	157.02
7		195	321.068	266.1	4257.6		175.12	176.17
8	C230	76	423.439	360.19	5763.04		286.32	267.24
9		20	543.933	440.07	7041.12		340.88	315.87
10		4	489.751	404.64	6474.24		312.17	304.68
11		295	435.005	288.9	4622.4		140.05	172.73
12		195	461.446	334.92	5358.72		150.21	208.66
13	C464	76	555.512	409.31	6548.96		211.99	250.96
14		20	725.661	496.24	7939.84		259.44	306.87
15		4	685.928	449.55	7192.8		232.30	269.93
16		295	776.962	451.57	7225.12		108.30	280.39
17		195	826.159	487.72	7803.52		138.94	298.52
18	C647	76	849.909	521.74	8347.84		191..68	324.89
19		20	927.945	594.51	9512.16		288.81	364.63
20		4	938.123	589.61	9433.76		267.97	357.91

The Load-Displacement curves obtained, were used to find the maximum Load (F_u) and toughness (Area under Load-Displacement curve considering the points up till 90% percent Load after F_u (Table 5). Similarly, the Ultimate Tensile Stress and Toughness (Area under Engineering Stress-Strain curve) were also found.

For each Material and corresponding temperatures, the Ultimate Tensile Stress and Maximum Load (F_u) are plotted as 20 points (4 materials*5 temperatures) and a linear relation between them is found by curve fitting using the software OriginPro 8 (figure 48).

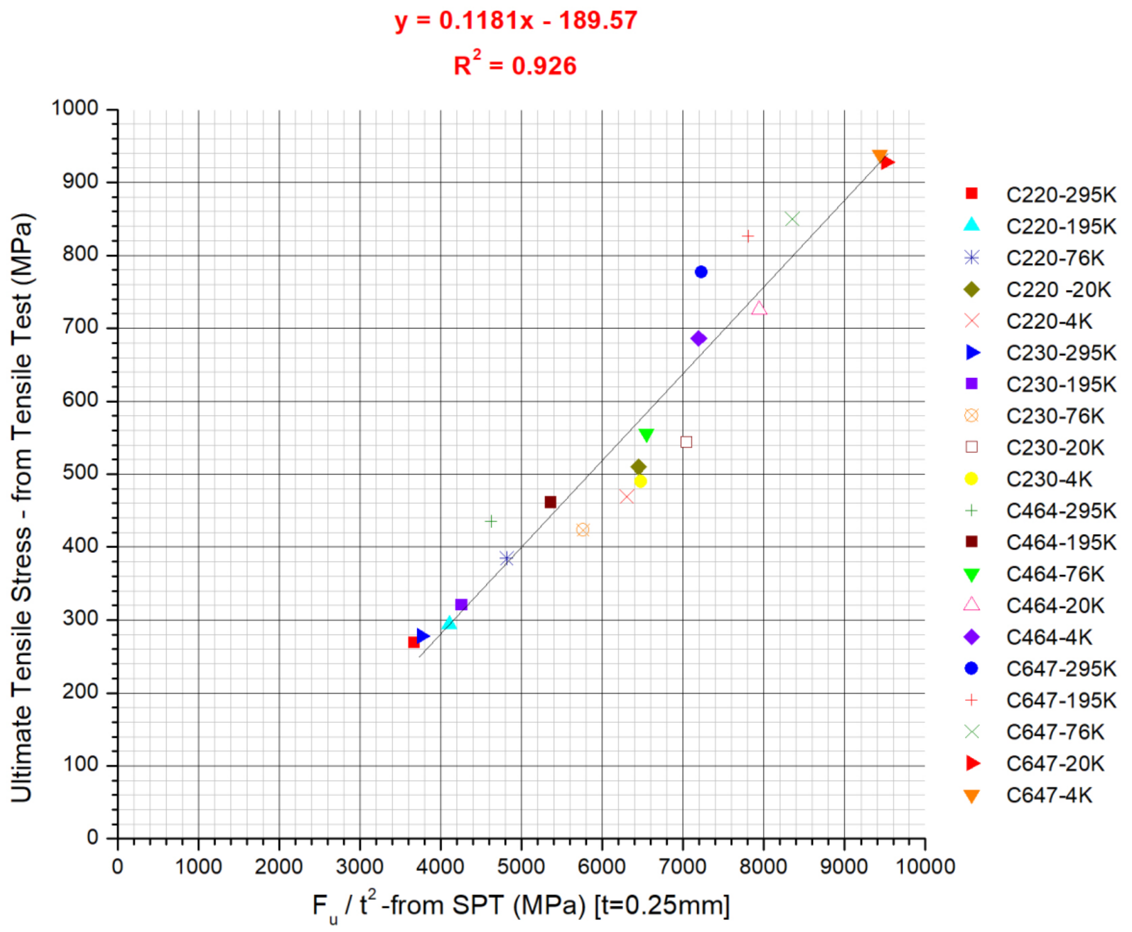


Figure 48: Linear Regression curve fitting of Ultimate Tensile Stress from Tensile Test and F_u / t^2 from S. P. T. of copper alloys (considering all the 20 points obtained) plotted using the software OrginPro 8.

The relation obtained between Ultimate Tensile Stress (in MPa) from Universal Tensile Test and Maximum Load divided by thickness squared - ${F_u}/{t^2}$ (in MPa) from S. P. T. is as follows

$$\boldsymbol{UTS = 0.1181 * \left({F_u}/{t^2}\right) - 189.57}, \text{ with } \mathbf{R^2 = 0.926}$$

where, UTS = Ultimate Tensile Stress.

Since R^2 = 0.926, it indicates a good fit.

Similarly, for each Material and corresponding temperatures the Toughness - from Tensile test and Toughness – from S.P.T. are plotted as 20 points (4 materials*5 temperatures) and a linear relation between them is found by curve fitting using the software OriginPro 8 (figure 49).

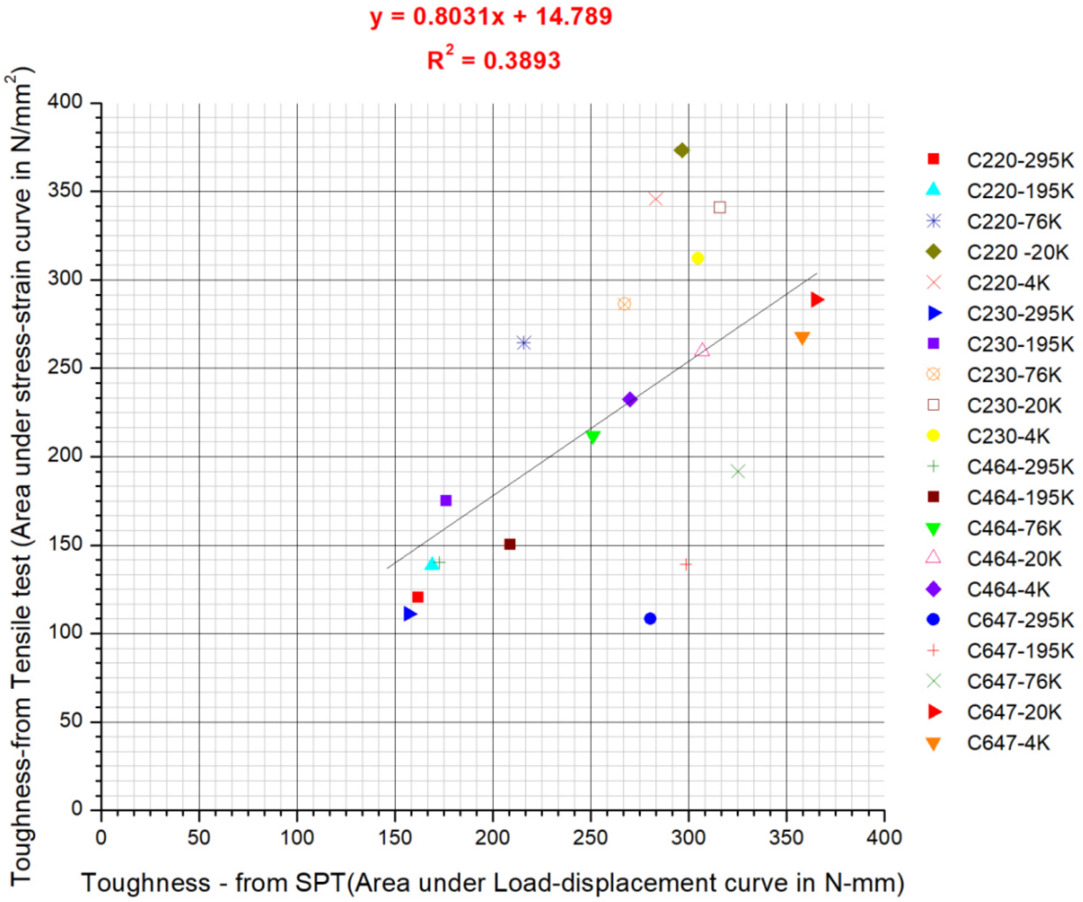


Figure 49: Linear Regression curve fitting of Toughness from Tensile Test and Toughness from S. P. T. of copper alloys (considering all the 20 points obtained) plotted using the software OrginPro 8.

Since the R^2 value obtained is very low (0.3893), 8 deviated points were omitted and the curve fitting is done again.

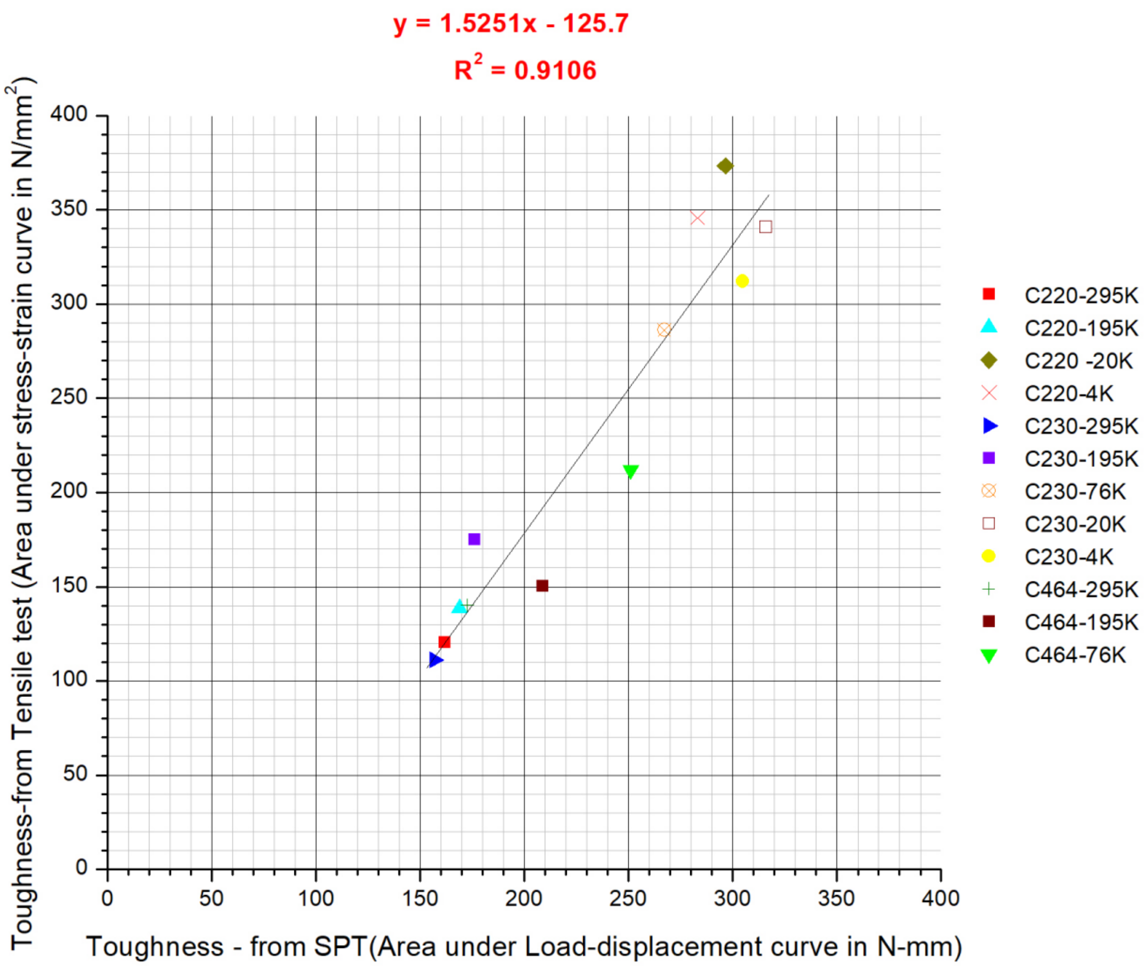


Figure 50: Linear Regression curve fitting of Ultimate Tensile Stress from Tensile Test and F_u / t^2 from S. P. T. of copper alloys (considering 12 points only) plotted using the software OrginPro 8.

The relation obtained between Toughness (in N/mm^2) from Universal Tensile Test and Toughness (in N-mm) from S.P.T. is as follows:

$$\boldsymbol{T_{UTT} = 1.5251 * (T_{SPT}) - 125.7}\text{, with } \mathbf{R^2 = 0.9106}$$

Where T_{UTT} = Toughness from Tensile Test; T_{SPT} = Toughness from S. P. T.

Since R^2 = 0.9106, it indicates a good fit.

12. Conclusion

Several complications are faced while conducting testing of materials, especially during service period, as per the standard ASTM Universal Tensile Test method hence paving the path for the development of novel methods such as the Small Punch Test (S. P. T.). The small punch test method is used to predict the mechanical properties of materials using small volume to ascertain integrity of the components during entire service life.

During the course of this project, study was conducted on Fracture Mechanics of materials. The small punch test was studied successfully. Furthermore, simulations of the test were carried out for various copper alloys at room as well at cryogenic temperatures of 195 K, 76 K, 20 K & 4 K. The simulation results derived were compared with those obtained from the conventional testing methods. As the two test results closely collaborated with each other, it can be concluded that the simulations conducted were accurate to a good extent.

Further research work can be conducted by testing, verifying and generalising the method & results for a large sample of materials as well as obtaining more material properties by this procedure.

13. List of Figures and Tables

14. References

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