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Chapter 1: Introduction

The use of numerical simulations for understanding mechanical behaviour of materials is becoming more common day by day. It is a cost effective alternative to the old trial and error experimentation method in the design and manufacture of components. The simulations involving deformation response of a material to static loading generally involve small strains and are easily simulated using merely the elastic constants of a given material. The simulations of dynamic deformation response of a material to loading under various conditions involving large deformations are more complicated than the static loading case. These simulations, which are performed using a commercial code such as ABAQUS heavily, rely on the accuracy of the material model peculiar to the application to correctly describe the material behaviour. Material models define the relationship between variables such as stress, strain and strain rate.

Polyamides or nylons are the first engineering plastics and still represent the biggest and most important class of these types of material. Polyamides comprise a wide range of materials, depending on the monomers employed. Commonly used products are designated as nylon 6; 6,6; 6,12; 11 and 12 with the nomenclature designating the number of carbon atoms that separates the repeating amide group. Nylon 6,6 continues to be the most popular types among polyamides commercial products, still accounting for more than 90% of Nylon used in the global market.

This paper examines the constitutive equations from an engineering design point of view and focuses on how the ability to accurately predict the behavior of Nylon 6,6 plastic component under tensile loading condition. Finally, effects of stress and strain under different strain rate condition are analyzed.

1.1 Application of Nylon-66

Nylon 66 is a semi-crystalline engineering thermoplastic with universal applications.

The main characteristics of Nylon 66 are:

- It has good sliding properties and electrically insulating and very abrasion resistant
- Resistant to many oils, greases, diesel, petrol, cleaning fluids
- Strong, tough and rigid
- Easily machined, welded and bonded

Popular applications for the use of Nylon 66 are:

- Gear wheels, Friction strips, Bushes, Spindle nuts
- Piston guides, Castors, Impact plates, Rope pulleys ,Plug parts
- Nylon is a high strength fibre. It is used for making fishing nets, ropes,

parachutes and type cords

- It is used for making fabrics in textile industry
- Crinkled nylon fibers are used for making elastic hosiery
- Nylon is widely used as plastic for making machine parts. It is blended with wool to

increase the strength.

1.2 Mechanical behaviour of nylon-66

The preferred fields for the use of Nylon 66 are: mechanical engineering, automotive engineering, transport and conveyor technology, textile, packaging and paper processing machinery, printing and drinks dispensing machinery, household articles, electrical engineering, building machinery, and agricultural machinery.

Mechanical Properties	Unit	Test Method DIN ASTM	Result dry	Result wet
Density	g/cm3	53479	1.1.4	-
Tensile strength at yield	MPa	53455	90	70
Tensile strength at break	MPa	53455	-	-
Elongation at break	%	53455	40	150
Modulus of elasticity in tension	MPa	53457	3300	2000
Modulus of elasticity in fracture	MPa	53457	2830	-
Ball indentation hardness	MPa	53456	170	100
Impact strength(charpy)	kg/m²	53453	No break	-
Creep rapture strength after 1000 hours with static load	MPa	-	55	-
Time yield limit for 1% elongation after 1000 hours	MPa	-	8	-

Coefficient of friction against harden and ground steel P+0,05 N/mm2, V=0,6 m/s	-	-	.35-.42	-

Table: 1.1 Mechanical Properties of Nylon 6,6

1.3 Motivation for experimental testing of Nylon 6,6

The behaviour of plastics has long been a topic of keen interest for scientists across many disciplines. Their behaviour has led to many industrial and commercial applications of plastic as engineering materials. The aim of our thesis is to measure tensile strength of nylon plastic, so that we can acquire knowledge on the strength ability and the limitations of nylon plastic under different conditions. The particular study represents the behaviour and mechanical failure of Nylon 6,6 at different strain rates. The world around us is evolving every day. And to cope up with this evolving world a vast range of different materials are used. Plastic is one of those materials. Plastics have displaced paper, glass and metal from many traditional applications. Such diverse applications result from plastic material properties such as resistance to chemical and environmental degradation, tuneable optical properties, ease of shaping and moulding, dependence of mechanical and thermal properties on degree of cross-linking, and temperature dependence of plasticity and flow properties. In fact, it is impossible to think of any industry or business that could exist without plastic products. The types and diversity of plastic products are seemingly without boundaries.

Thus we want to study the material strength of nylon plastic to enhance our knowledge about this material which is of immense importance.

The Johnson Cook model (1) is a very popular material model that captures the strain hardening and strain rate sensitivity of a material by establishing stress as a function of strain and strain rate. For uni-axial deformation it is given by

$$\sigma = (A + B(\varepsilon^p)^n)(1 + C\ln\left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_o}\right))$$

Where, σ = equivalent yield stress

ε^p= equivalent plastic strain

$\dot{\varepsilon}^p$= plastic strain rate

$\dot{\varepsilon}_o$= reference strain rate= 0.1mm/s

and A, B, C, n are constants which are unique to each material. Similar to the Johnson-Cook model, all material models include constants which are combined with the physical variables to relate them to each other. These constants are determined from experimental data and accuracy of these constants decides the accuracy of the material model in simulating the material behaviour. Thus, the accuracy of experimental data, in turn is a very important aspect of successful numerical simulations. For the present project, experimental data for plastic deformation of Nylon-66 is generated and studied over a vast range of strain rates.

A key issue in understanding the Johnson Cook model is strain rate. The effective strain rate in an element is dependent not only on the rate of loading but also such factors as the shape and dimensions of your specimen. If we assume that the specimen stretches uniformly (no necking/localization) in a uni-axial test such that the strain rate is spatially uniform over the whole specimen, then the following is true:

- Change in length = ΔL
- Engineering strain = ΔL/L
- Engineering strain rate = strain per time

- True strain = ln(1+ engineering strain)

Where, L = length of specimen in loaded direction;

The quantities of true stress and true strain provide an accurate measure of instantaneous stresses and strain in a deformed material. While engineering stress is defined as the instantaneous force divided by the initial area, true stress is defined as the instantaneous force divided by the instantaneous area; likewise, true strain is the integral of the instantaneous change in material length divided by the instantaneous material length. True stress (σ_{true}) and true strain (ε_{true}) can be derived from engineering stress (σ_{eng}) and engineering strain (ε_{eng}).

Thus the greater the strain level, the larger the deviation between engineering measures of stress and strain and true measures of stress and strain.

1.4 Literature Review

Engineering plastics are widely used in vehicle applications. The strain rate dependent stress-strain data are important inputs in crash and safety analysis. Nevertheless, no standard exists for material tests at these strain rates. To develop an industrial standard for strain rate dependent tensile test of plastics, Society of Automotive Engineers (SAE) sponsored a co-operative research project "Standardization of High Strain Rate Tensile Test Techniques for Automotive Plastics. The paper presents the results of round robin generated at GM lab and discusses the interpretation and reduction for high rate tensile testing data on plastic.

General Motors Corporation (GM) along with other 13 companies including OEMs, tier-1 suppliers and resin suppliers participated in the SAE Standardization of High Strain Rate Tensile Test Techniques project. S. Hill of University of Dayton Research Institute (UDRI) was the principle investigator. A practice guide for high strain rate tensile testing of automotive polymeric materials was developed in phase-I of the project (April 2001-March2004). In phase-II (April 2004-March 2005), the guide was subjected to a round robin test.

GM R&D lab was one of the nine labs participating in both the load and strain measurement portions of the round robin. After the round robin, the guide will be developed into an SAE J standard. An SAE High Strain Rate Plastics Sub-committee (HSRPS) has been formed to carry out the task.

Another thesis had been done on “Temperature, Moisture, and Strain Rate Effect on the Compressive Mechanical Behavior of Nylon 6,6” by W.A. Kawahara, S.L. Brandon and J.S. Korellis of Sendle National Lab. in New Mexico, But no thesis has been done solely on strain rate effect on tensile properties of Nylon 6,6 yet.

Therefore in this study, we analyzed on the strain rate effect on tensile properties of Nylon 6,6.

Chapter 2: Experimental Procedure

2.1 Choice of Specimen

Polyamides or Nylon are a versatile family of thermoplastics that have a broad range of properties ranging from relative flexibility to significant stiffness, strength and toughness. Major properties such as resistance to chemicals, toughness, thermal stability, good appearance and good process ability are key considerations that make Nylon suitable for engineering applications.

The availability of material is a big issue and upon market survey, it was confirmed that Nylon 6/6 with 16 mm diameter is available in the local market. Initial tensile test was conducted by using 16 mm gauge diameter and 11 inch length cylindrical specimen (as shown in Figure 2.1.1). In the test approximately 4 inch from the top and bottom part was used for gripping the specimen, as indicated schematically in Figure 2.1.2. Therefore the remaining 3 inch is considered to be the gauge length in this case and it is assumed that the specimen should fail approximately at the middle of the gauge length. However, after the completion of the test it was observed that the specimen failed at the grip part (shown in Figure 2.1.3). In order to elucidate this, FEM simulation has been conducted by using commercial software ABAQUS. The results are shown in Figure 2.1.5. We can see from the figure that the stress is mainly concentrated at the grip part of the specimen. The gripping load acts as a stress concentrator which eventually fails the specimen near the grip part. Therefore, the specimen geometry has been modified by reducing the gauge diameter and hence the gauge length. Initially specimen having 10 mm gauge diameter and 2 inch gauge length was chosen. FEM analysis clearly indicated that the stress is in the gauge part of the specimen, as shown in Figure 2.1.6. Tensile experimental result of such modified specimen clearly showed that the specimen fails at the gauge part (shown in Figure 2.1.7). Therefore this specimen geometry in the following figure was adopted for the entire tensile test in the present study, as shown in Figure 2.1.8.

Fig: 2.1.1 Available form of Nylon 6,6

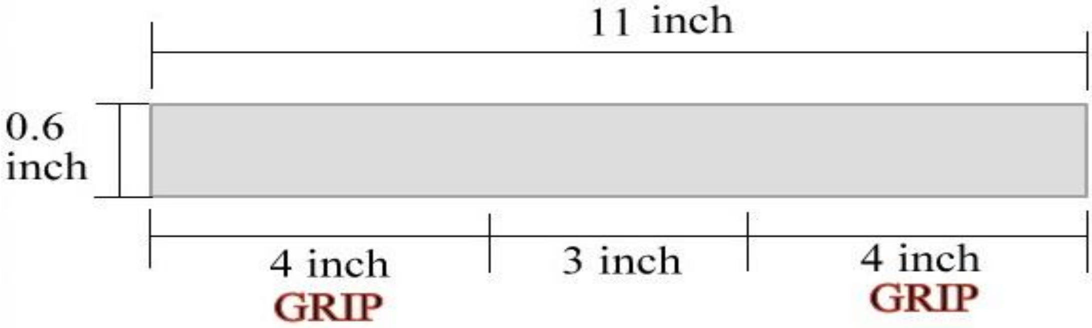


Fig: 2.1.2 Schematic view of specimen with length and gauge diameter

Fig: 2.1.3 Initial failure in the circular rod specimen

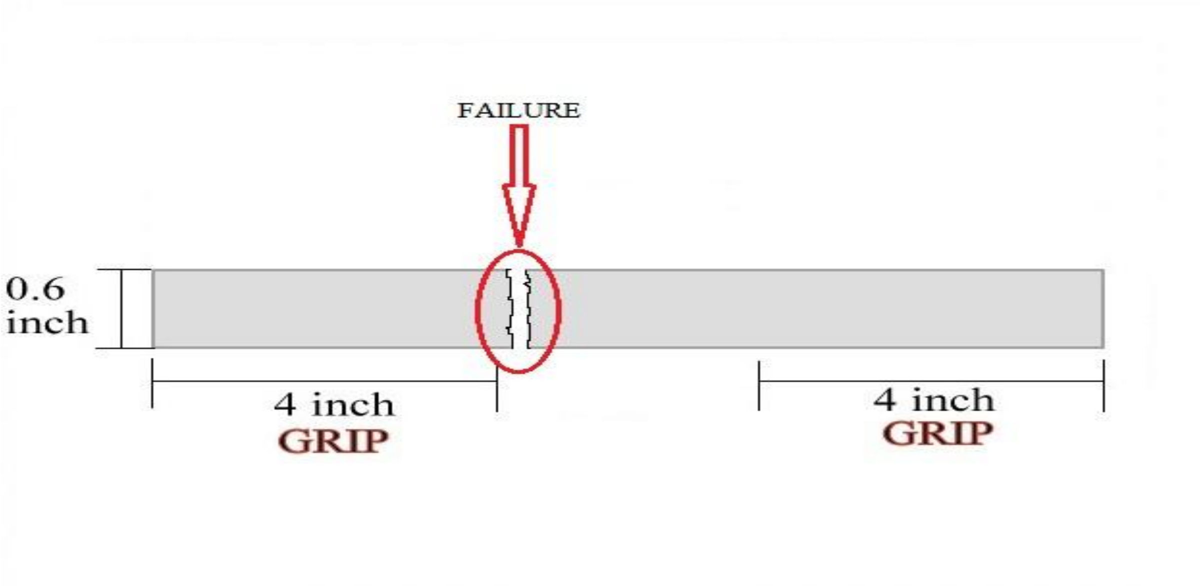


Fig: 2.1.4 Schematic view of specimen with failure in the grip part

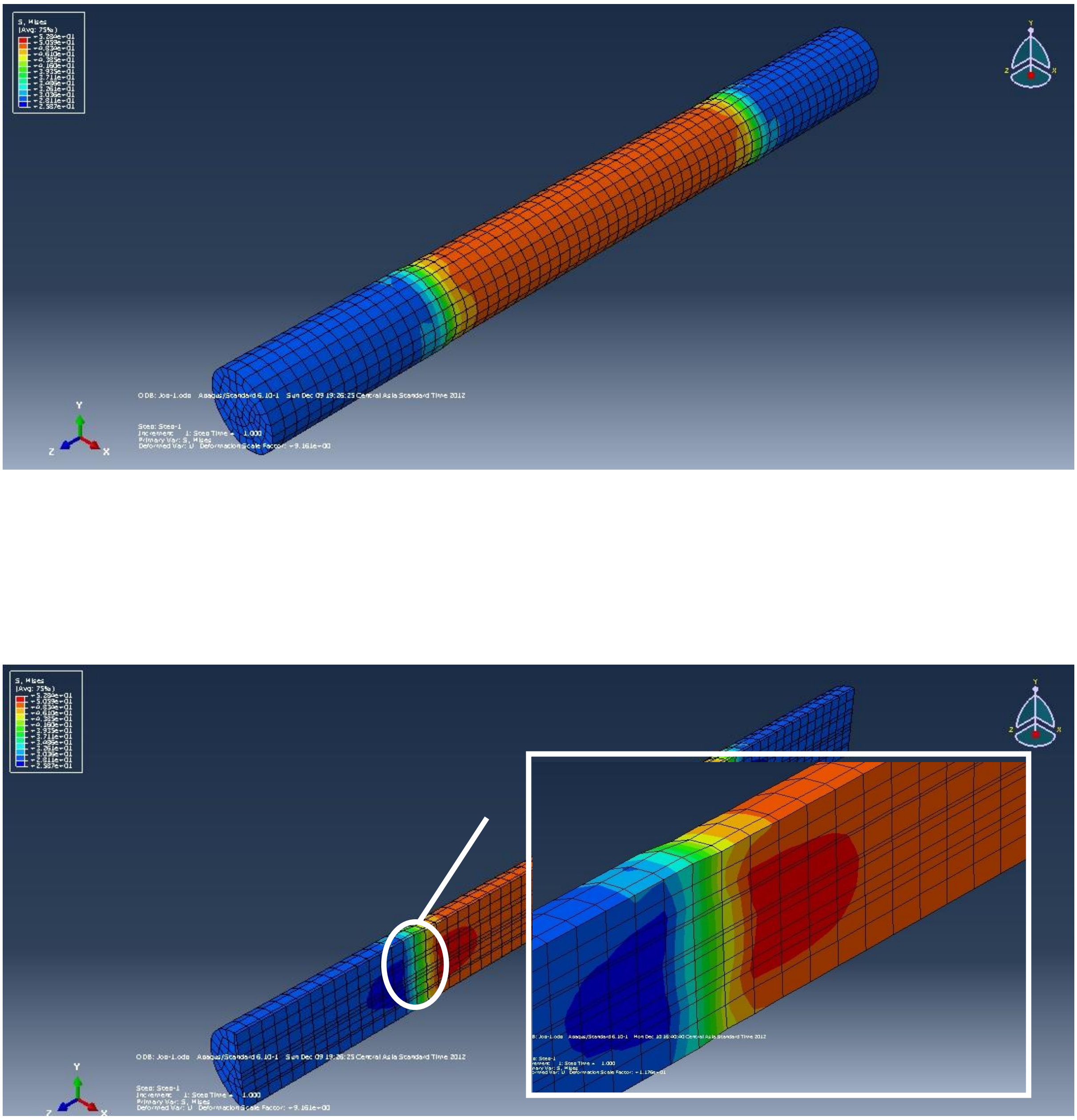


Fig: 2.1.5 FEM simulation in ABAQUS

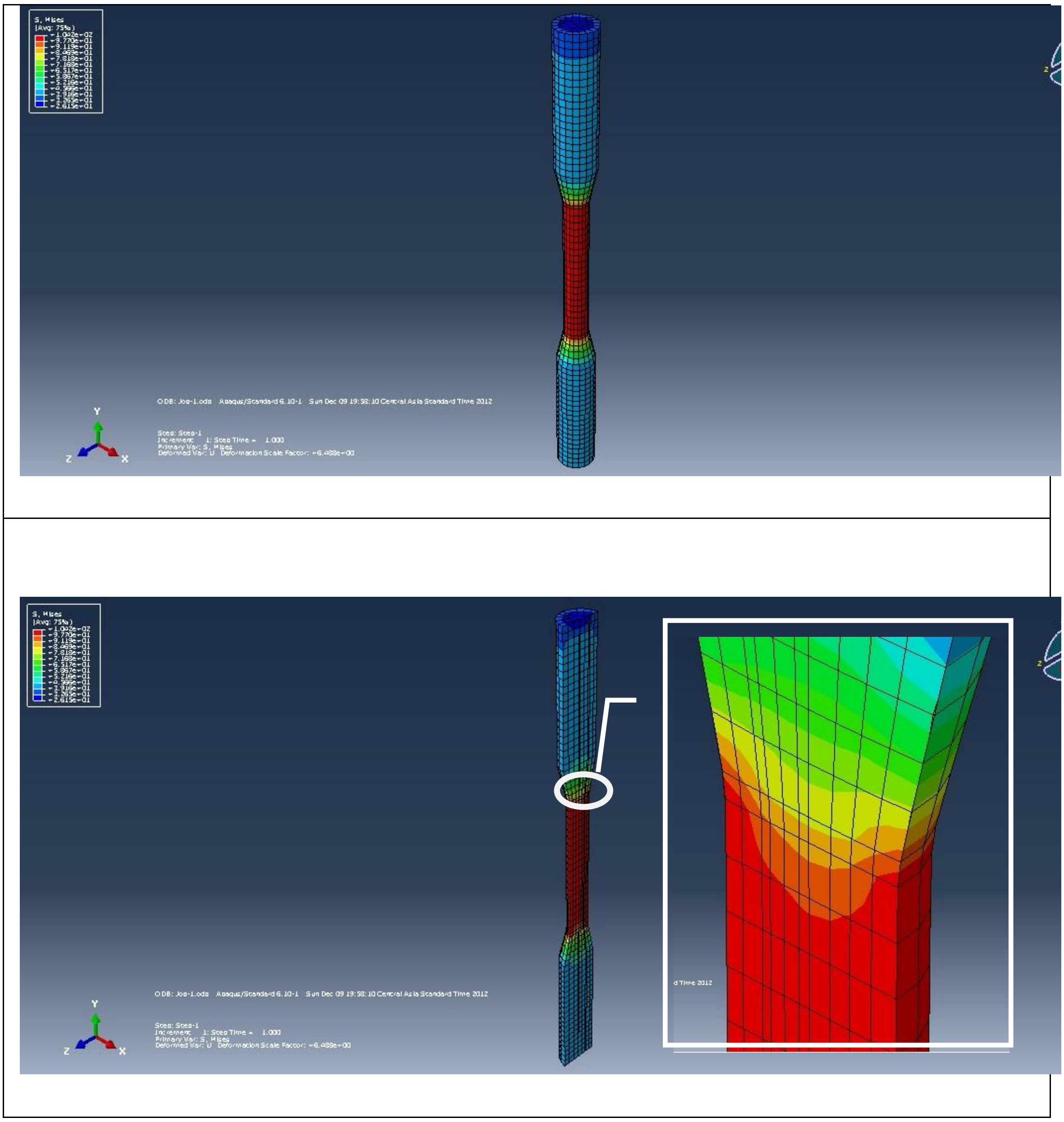
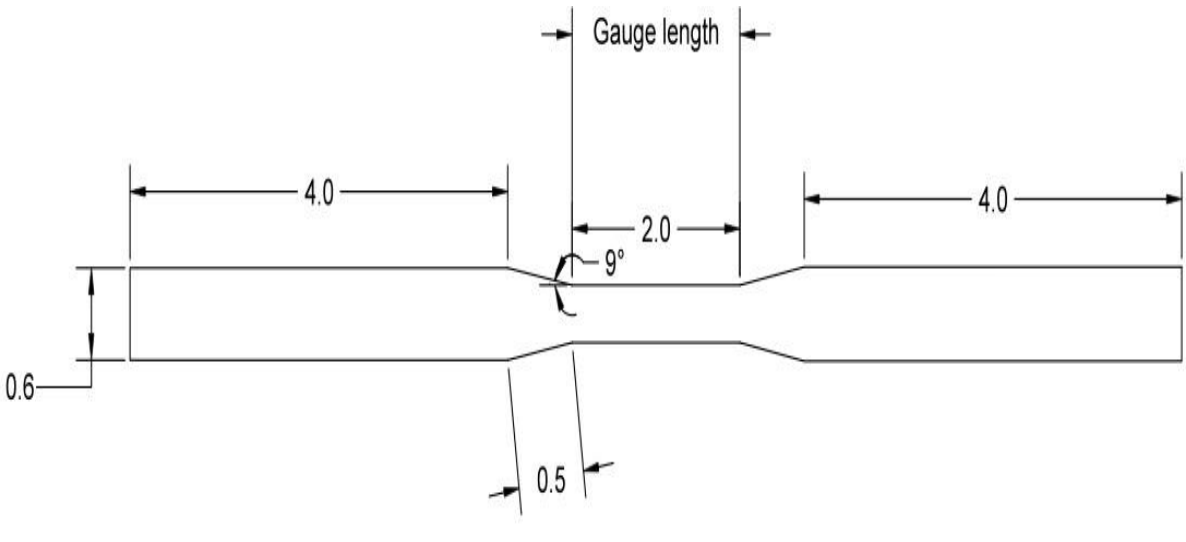


Fig: 2.1.6 FEM simulation of modified specimen in ABAQUS

Fig: 2.1.7 Modified machined specimen with failure part



Unit: inch

Fig: 2.1.8 Modified Specimen with gauge length and diameter

2.2 Experimental Technique

Tension experiments were performed across a range of strain rates from 0.1 to 50 mm/min, at laboratory temperature. An INSTRON model 5592-E1-F4-G1 with a load cell capacity of 100 kN was used for loading, in which the cylindrical samples were nominally 16 mm diameter. The strain in the sample was determined from crosshead displacement, and the stress was determined from the load cell output. All data was acquired using INSTRON's Merlin software.

The UTM machine consists of two vertical load bearing columns on which are mounted a fixed horizontal plate at the top and a moveable horizontal plate below it. The specimen was fitted between the two plates in the machine carefully ensuring that the alignment of the specimen was accurate. Vertical alignment of the specimen is an important factor to avoid side loading or bending moments created in the specimen. The specimen was mounted on the upper grip assembly first allowing it to hang freely to help maintain the alignment for the test.

Then through a computer the loads are balanced, the machine is calibrated, details of the specimen are entered and the speed at which the bottom fixture will move is stated. Then the machine is started. We could not carry out experiments using strain rates lower than 0.1mm/min due to limitations of access to the lab. We could not carry out experiments using strain rates higher than 50mm/min because this was the maximum strain rate that could be used in the machine. Each experiment was carried out twice to ensure accuracy. All the data were recorded and stress vs. strain curves for each strain rate was plotted

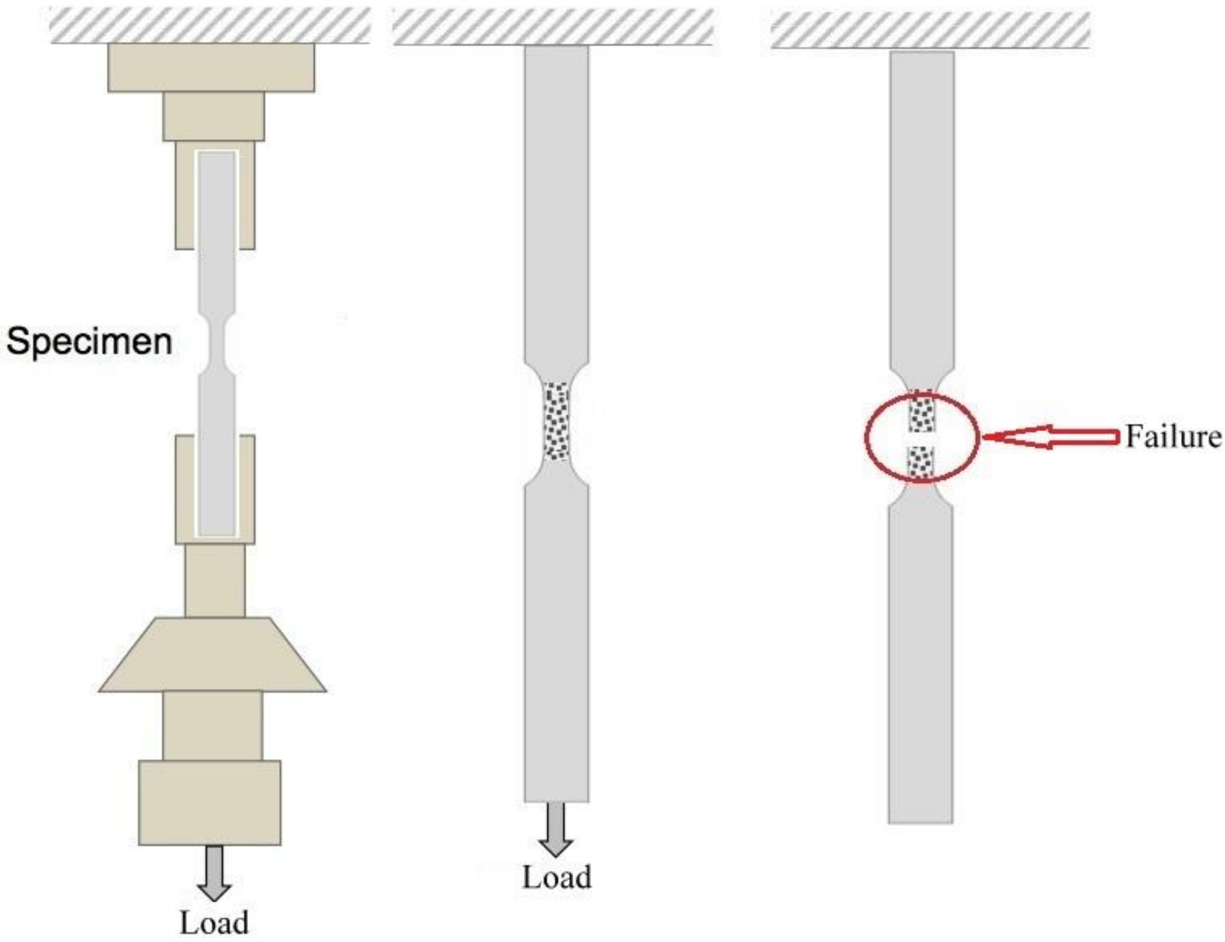


Fig: 2.2.1 Failure of the specimen with machine setup

Chapter 3: Results and Discussion

This chapter presents the data generated from the tests carried out as per the experimental method discussed in the previous chapter. The data presented is the result of the tensile tests conducted at seven different strain rates.

With the data obtained from our experiments we plotted the stress-strain curves for each strain rate and found out their corresponding yield strength, modulus of elasticity and ultimate strength. The calculations and analysis of the data and graphs is shown later in the chapter. We can see from the table below that as strain rate increases, yield stress, modulus of elasticity and ultimate strength also increases. A similar behaviour is also observed in another investigation (2).

STRAIN RATE (mm /min)	YIELD STRESS (MPa)	MODULUS OF ELASTICITY (GPa)	ULTIMATE STRENGTH (MPa)
0.1	15.3	299.84	25.59
1	24.2	361.84	29.58
10	26.2	337.84	29.95
20	28.4	359.22	30.74
30	28.0	395.52	33.11
40	30.9	366.90	37.21
50	25.0	469.90	36.38

Table: 3.1 Corresponding values of E, σ_y and σ_u for different strain rates

3.1 Johnson-Cook Model

The Johnson-Cook model expresses the equivalent Von Mises flow stress as a function of strain, strain rate and temperature as follows:

$$\sigma = (A + B(\varepsilon^p)^n)(1 + C\ln\left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_o}\right)) \quad \text{....................................(i)}$$

Where, σ = equivalent yield stress

ε^p= equivalent plastic strain

$\dot{\varepsilon}^p$= plastic strain rate

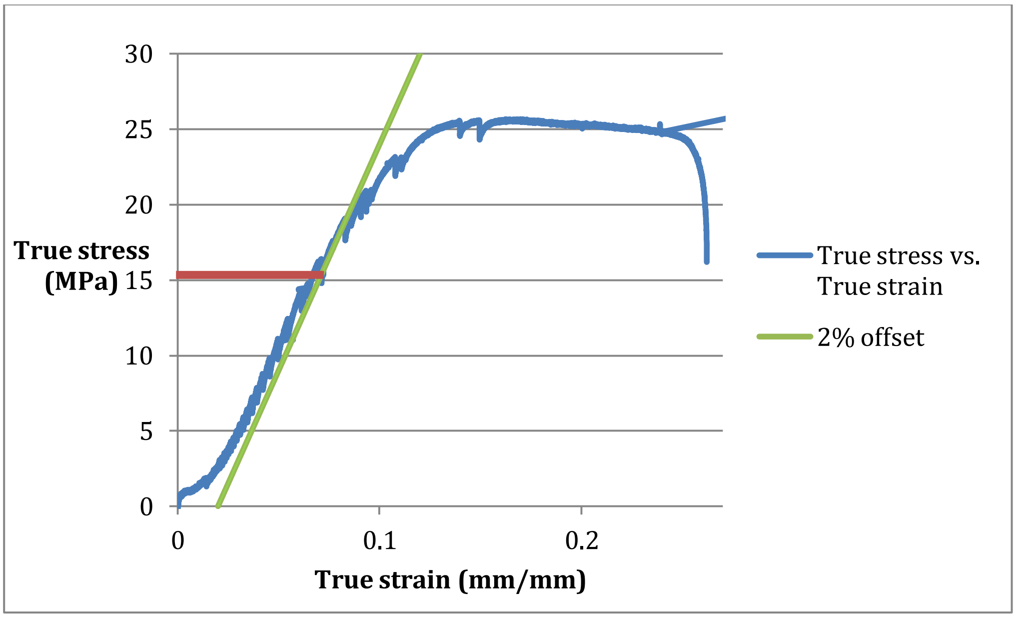
$\dot{\varepsilon}_o$= reference strain rate= 0.1mm/min

and A, B, C and n are material constants

The expression in the first set of brackets gives stress as a function of strain when strain rate is 0.1mm/min and at room temperature. The second set of brackets expresses the strain rate effect. The experimental data obtained from the above experimental technique has been used to find out the above constants as explained below.

3.1.1 Determination of *A*:

A is the yield stress corresponding to 2% offset strain on a true stress vs. true strain curve at the strain rate of 0.1mm/min as shown in Graph: 3.8. The value of constant *A* is 15.3 MPa.



Graph: 3.1 True Stress Vs True Strain Curve With 2% Offset

3.1.2. Determination of *B* and *n*:

Constants *B* and *n* are determined from rearranging equation (i). At the reference strain rate of 0.1mm/min, the second set of brackets equals to unity and therefore the equation is written as:

$$\sigma = A + B(\varepsilon^p)^n$$

Adding log to both sides we get,

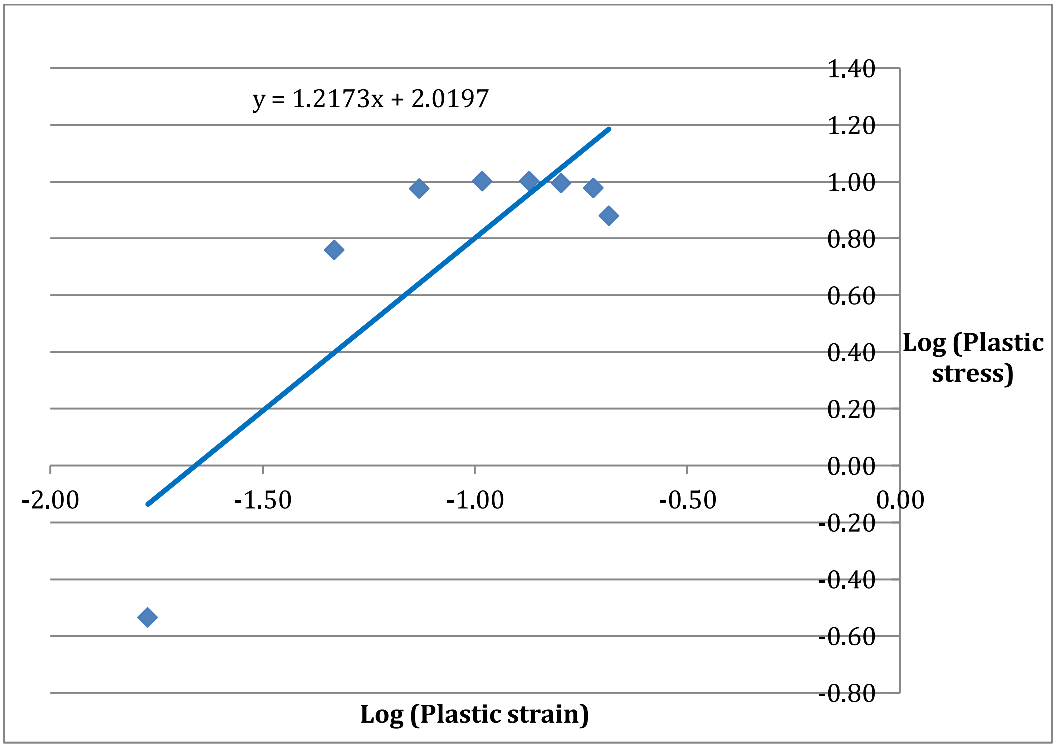
$$\log(\sigma - A) = logB(\varepsilon^p)^n$$

Simplifying it we get,

$$\log(\sigma - A) = nlog\varepsilon^p + logB$$

.....................................(ii)

This equation is in the form $y = mx + c$. From the above equation, a Log (Plastic stress) vs. Log (Plastic strain) graph is plot. Constant *n* represents the slope of the linear fit graph plotted and constant *B* is equal to $10^{y-intercept}$. The blue dots are actual plastic stress plastic strain readings from the experiment while the line is the best possible linear fit. Plastic strain was found by subtracting elastic strain from the total strain corresponding to different values of true stress and strains. The value of constant *B* is 104.64 MPa and the value of *n* is 1.2173.



Graph: 3.2 Log (Plastic Strain) Vs Log (Plastic Stress)

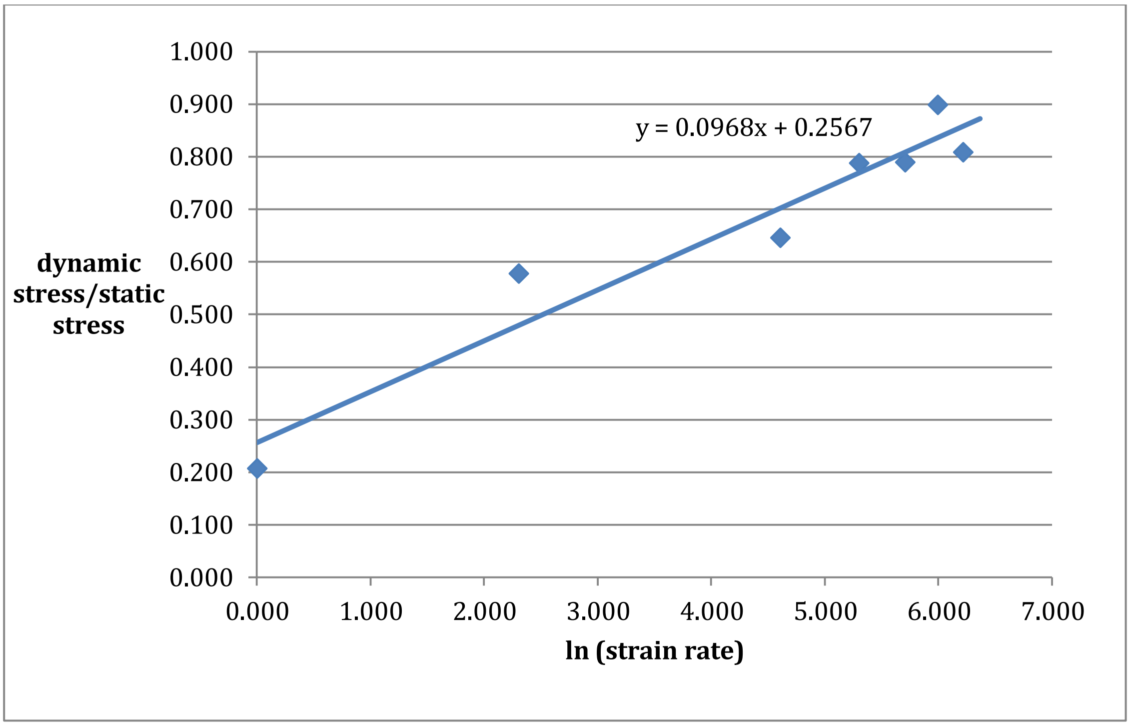
3.1.3. Determination of *C*:

The constant *C* from equation (i) dictates the strain rate sensitivity of a material. It is found out using the following equation:

$$\left(\frac{\sigma}{(A + B(\varepsilon^p)^n)}\right) - 1 = C ln\left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}^o}\right)$$

...........................(iii)

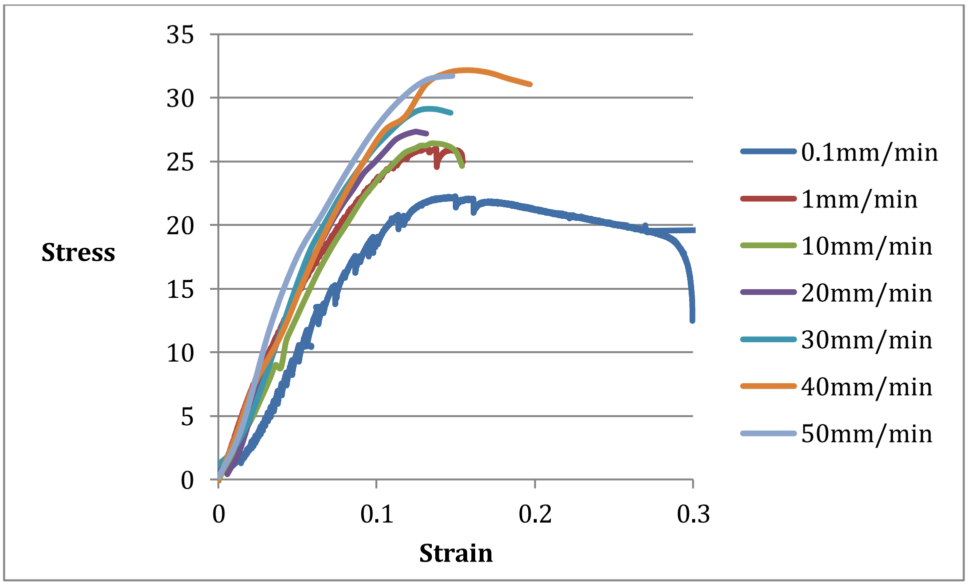
This equation is in the from $y = mx$. The constant *C* is found by plotting a dynamic stress to static stress ratios at 10% plastic strain from tests carried out at varying strain rates and against the natural log of the strain rate of that test. The slope of the linear curve fit of all these points gives the constant *C*. The constant *C* is determined as the slope of the linear fit of Log (Strain rate) vs. (dynamic stress/static stress) using the high strain rate data corresponding to a strain of 10%. The following table data is used to plot the graph. The value of *C* from is 0.0968.



Graph: 3.3 Dynamic Stress/Static Stress Vs ln(Strain rate)

3.2 Strain Rate Sensitivity

The Graph: 3.11 shows the stress vs. strain curves of all the strain rates. All these experiments were carried out at room temperature. The maximum strain rate achieved is 50mm/min. The limiting maximum strain rate depends on the apparatus as well as the properties of the material being tested. In our experiments the maximum strain rate was limited only by the apparatus used.



Graph: 3.4 Stress Vs Strain Curve at Different Strain Rate

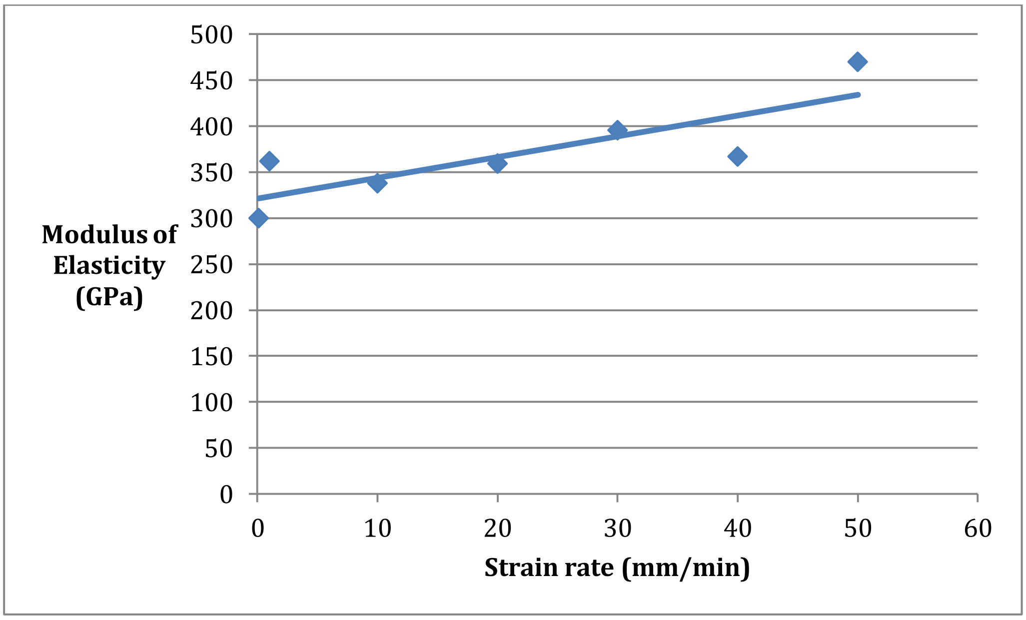
The strain rate sensitivity of the material is illustrated in the above plots as the yield stress increases with increase in strain rate from 0.1mm/min to 50mm/min. It can also be seen that the rate of strain hardening of the material changes with strain rate i.e. at higher strain rates a steeper stress strain curve is observed as compared to the flatter stress strain curves observed at lower strain rates. Lee Lin (2) studied the strain rate effect of Ti-6Al-4V only on a narrow strain rate region (0.01 s-1 to 1 s-1) and reported that at lower strain rate a steeper post yield stress strain curve is observed as compared to a flatter post yield curve observed at higher strain rates. Jennifer L. Jordan (3) also studied the strain rate effect of Epon 826/DEA epoxy across a range of strain rates from 10-3 to 104 and observed that the ultimate compression stress at which the specimen fails increases with increasing the strain rate. The present work on Nylon 6/6 also shows a similar trend of increase in ultimate tensile strength under different strain rates.

From the Johnson-Cook Model we get the following values for the constants.

A	*B*	*n*	*C*
15.3	104.64	1.2173	.0968

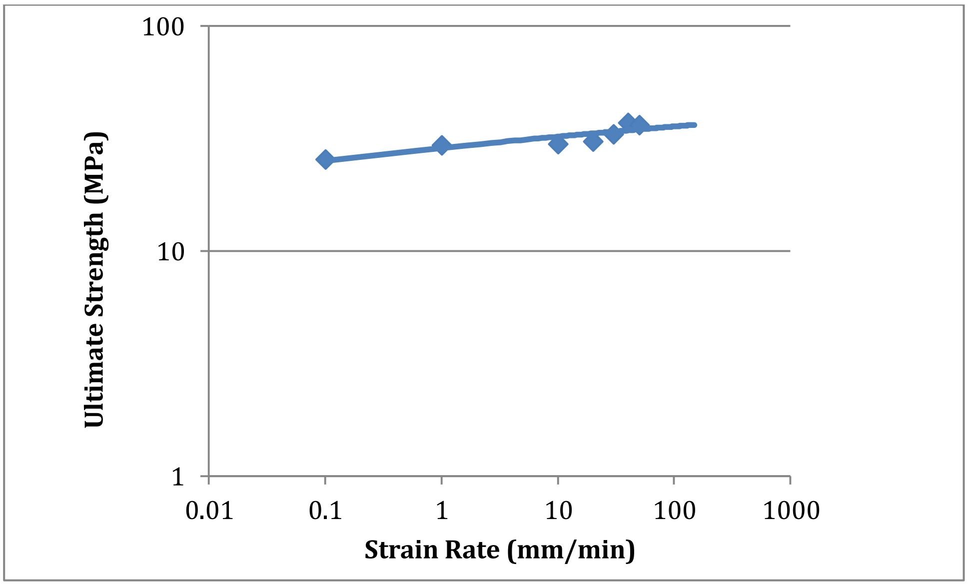
The above data shows that the material is more strain rate sensitive since the value of *C* is almost four times higher than the value obtained in other investigations (1). The value of constant *A* determines the strength of the material. Nylon 6,6 has a very low value of *A*. This shows that the material strength is very low. The constants *B* and *n* influences the strain hardening of the material. Smaller values of *n* and higher values of *B* enhance the strain hardening effect of the material. But we have higher values of *n* and lower values of *B*. This shows that at higher strain rates, strain hardening is less and at lower strain rates strain hardening is more. The constant *n* is also a measure of the resistance to necking. Therefore as the value is high we can say that nylon is more resistant to necking.

We have observed from our data that as the strain rate increases from lower to higher values, the modulus of elasticity also increases. The modulus of elasticity of Nylon 6,6 with 0.1mm/min was recorded lower than the other strain rate values. In materials like thermoplastic, when it is loaded at a low strain rate, the molecular chain have sufficient time to adjust to the imposed stress and the modulus value is lower than would be the case for the same material loaded at a higher strain rate (5). The modulus of velocity vs. strain rate curve shows a linear fit.



Graph: 3.5 Modulus of Elasticity (GPa) Vs Strain Rate (mm/min)

From our experimental data we also observe that the ultimate strength of the material increases as the strain rate increases from 0.1 to 50mm/min. The relationship between the ultimate strength and the strain rate is illustrated in the graph below.



Graph: 3.6 Ultimate Strength (MPa) Vs Strain Rate (mm/min)

Ultimate strength increases with strain rate because at low strain rate the molecules have sufficient time to adjust to the imposed stress. Therefore the molecules can change their shape and elongate and allow the stress to distribute evenly throughout the material and thus requiring less strength to cause failure. On the contrary, at higher strain rate, the molecules do not get time to distribute load on it which results in a sudden application of load and thus requiring higher strength to cause failure.

3.3 Conclusions

The findings of the tensile tests on Nylon 6,6 are summarized here:

- The varied strain rate tests show that Nylon 6,6 is a strain rate sensitive material.
- The strain hardening behaviour of Nylon 6,6 changes with change in strain rate. There is more strain hardening at lower strain rates than at higher strain rates.
- The strain rate affects the ultimate strength of the material, which increases with strain rate.
- Modulus of Elasticity increases with strain rate.
- The toughness of the material decreases at higher strain rates.

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