# EVALUATION OF FRACTURE TOUGHNESS OF MEDIUM CARBON LOW ALLOY FORGED STEELS

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## Abstract

*The purpose of the work is to determine the critical stress intensity factor K1C, according to ASTM E399 named as plane strain fracture toughness. The specimen used is chevron notchedCompact Tension specimen (CT-specimen) to create a fatigue crack by cycling the sample to minimum and maximum loads. Polyethylene glycol (PEG) H−(O−CH2−CH2)n−OH as quenchant was studied to investigate the fracture toughness (K1C) on the medium carbon low alloy forged steels in heat treated condition by hardening and step tempering process. The step tempering process of the 30% polymer quenched specimen results high fracture toughness compare to 10% polymer quenched and as forged samples. By heat treatment the microstructure of the steels is also varied and its effect on the fracture toughness is also observed. It has been found that fine grained structure results high fracture toughness. The microstructural examination of the samples were found to have justified reason for the increment recorded in some of the mechanical properties, as it displayed a high proportion of the martensitic phase.*

***Keywords:****Fracture toughness (K1C), Polyethylene glycol (PEG), Microstructure.*

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## I. INTRODUCTION

Medium carbon low alloy steel is being used in the forged condition in the automobiles, aerospace and transportation industries. Reliability of critical components made of EN Series is directly based on the toughness of the steel, which in turn is dependent on forging conditions. A review of literature shows that substantial information is available relating to fracture toughness of medium carbon low alloys forged steels **[1]**. EN Series 18 (AISI 5140), 19 (AISI 4140), 24 (AISI 4340) and 25 (3430) are medium carbon low alloy steels under HSLA categories.Hardening heat treatment develops extreme hardness but reduces toughness, hence they become brittle and are unsuitable to be used in most service conditions, and hence step tempering is carried out to increase the toughness. The synthetic quenching medium as PEG**[2]**, are used for the quenching of the heat treated parts. The uses of synthetic quenchant have advantages compare to convention type of quenchants, due to less risk of cracking and less distortion. Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture.The (CT-specimen)**[3]**,samples were characterized using servo-hydraulic test machines, which cover a range of load capacities up to 100KN.In practice, heat treatment is the process by which change in fracture toughness can be achieved. It is mainly depends on the microstructural transformation,

he microstructural changes occur at different heat treatment condition with varying the holding time and with varying the tempering

temperature. The heat treatment of steels gives improved in fracture toughness. The synthetic quenching medium as PEG are used for the

quenching of the heat treated parts. The effect of polyethylene glycol as quenchant studied with a view to investigate the fracture toughnessand microstructural evaluation of steels. The microstructure ofquenching and tempering parts produces the fine tempered martensitic structure which yields the high strength.

## 2. MATERIALS AND METHOD

The chemical composition of medium carbon low alloy steels used for the examination is given in Table 1.

### 2.1. Heat Treatment/ Quenching and Step Tempering

The prepared forged samples were taken for the heat treatment process. The furnace used is electrical furnace, where the maximum heating temperature is $1200^{o}C$.The samples were heated at a certain predefined temperature and held at that temperature for a period of 60 min. where the homogeneous phase transformation takes place. Then the heated samples were directly quenched in the quenching medium which is already prepared for the hardening process. The samples were directly quenched in the polymer solution which constitutes the water and polymer at different proportion. Quenchant used in the hardening process is polymer solution. The preparation of the solution is done before carrying the hardening process. The proportion of the mixture used is 10% and 30% polymer the ratio is 1:9 and 3:7.Then directly

the heated samples were quenched in the quenching medium which is already prepared for the hardening process the heated samples

were quenched in the quenching medium which is already prepared for the hardening process.

After hardening process the step tempering is carried out further.Table 2.Shows the temperature and soaking time of the steels.

**Table 2.**Temperature and soaking time [5]

| **Process** | **Temp °C** | **Soaking time** |
|---|---|---|
| Hardening | 855 | 60 Min |
| Tempering I | 575 | 60 Min |
| Tempering II | 220 | 60 Min |

The material is heated in the heat treatment furnace for the maximum hardeningtemperature at 855°C and soaking period for about 60 min. The samples were quenched in the prepared solution. Step tempering is done on the hardened samples at 575 °C for about 60 min and then the samples werecooled in the air, again tempered at 220 °C for 60 min.

## 2.2. Test Specimen Preparation [3]

A set of samples was prepared for the fracture toughness test and for microstructural analyses. The standards used for the samples to carry out the test are ASTM E399, Standard compact specimentoughness is a chevron notched and fatigue cracked plate loaded in tension. The general proportions of this specimen configuration are shown in fig 1.

## 2.3 Method for determining fracture toughness

ASTM E399 standard test method is used to findthe plain strain fracture toughness of metallic materials.The Loading method preferred for the examination is tensile load.

**Table 1. Chemical composition [4]**

| **Steel** | **Element** | **Wt %** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **C** | **Mn** | **P** | **S** | **Si** | **Ni** | **Cr** | **Mo** |
| EN18 (AISI 5140) | Min | 0.35 | 0.65 | 0 | 0 | 0.10 | -- | 0.85 | -- |
| | Max | 0.45 | 0.95 | 0.040 | 0.040 | 0.35 | -- | 1.15 | -- |
| EN19 (AISI4140) | Min | 0.38 | 0.75 | 0 | 0 | 0.15 | -- | 0.80 | 0.15 |
| | Max | 0.43 | 1.10 | 0.035 | 0.040 | 0.30 | -- | 1.10 | 0.25 |
| EN24 (AISI4340) | Min | 0.37 | 0.60 | 0 | 0 | 0.15 | 1.65 | 0.70 | 0.20 |
| | Max | 0.43 | 8.80 | 0.035 | 0.040 | 0.30 | 2.00 | 0.90 | 0.30 |
| EN25 (AISI3430+Mo) | Min | 0.27 | 0.45 | 0 | 0 | 0.10 | 2.30 | 0.50 | 0.45 |
| | Max | 0.35 | 0.70 | 0.04 | 0.04 | 0.40 | 2.80 | 0.80 | 0.65 |

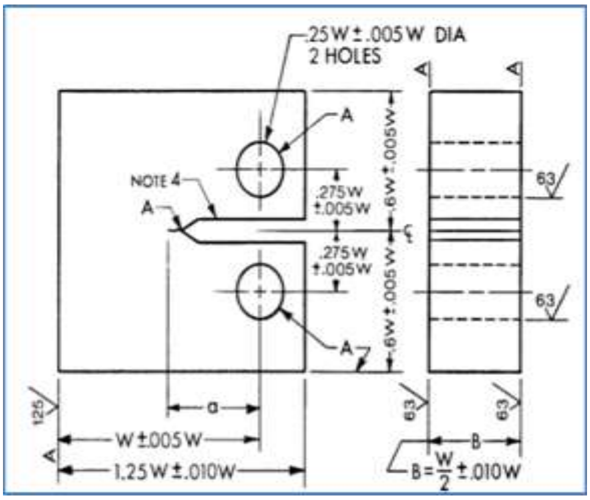



**Fig 1.** CT-specimen Standard proportions and tolerances

$K_{IC}$=Plane strain fracture toughness
B=specimen thickness
a=nominal crack growth
w= width of the specimen
K =stress intensity factor
a/w= should be around 0.5

**Fig 2.**Samplesfor Fracture Toughness ($K_{1C}$) test

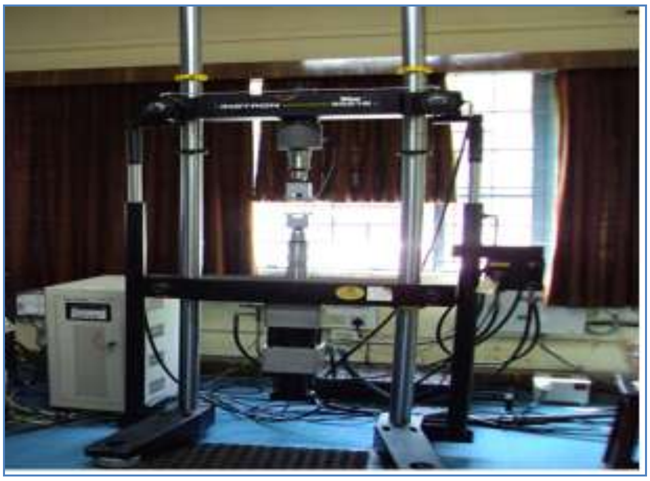


**Fig 3.**Servo-Hydraulic Test Machine

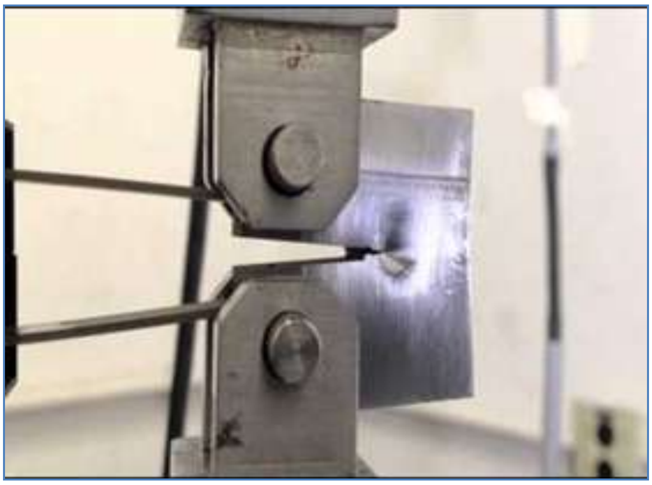


**Fig 4.**Tensile loading for $K_{IC}$ test

**2.4 Determination of $K_{IC}$:** Critical stress intensity factor is also named as plain strain fracture toughness **[6]**, due to toughness of the material, chevronnotched (CT-specimen) must be used in order to get the valid test according to ASTM E399.

$K=K_{IC}$ (Crack is critical) $=Y\sigma\sqrt{\pi a}$ ----- (1)

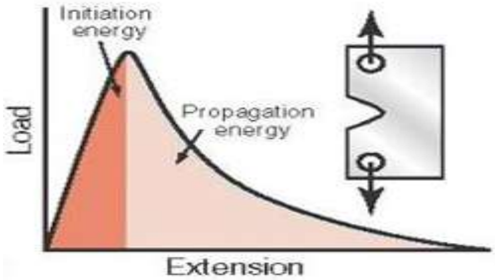
σ = Nominal stress

Y= Geometry correction factor depends on crack shape and size, specimen shape and size,

$Y=\{Cos(\pi a/w)\}^{1/2}$

$P_{Max}$= Maximum Applied force

A=Area




**2.5 Determination of $J_{IC}$:** $J_{IC}$ can be used for quality control and allows the determination of a theoretical $J_{IC}$**[7]**, value through the equation (2), applying equation (1) values.

$J_{IC}= (1-\nu^2/E) *K^2$----------- (2)

Where $\nu$(0.30) is Poisson's ratio

E= Young's modulus

$K=K_{IC}$ ,Plain strain fracture toughness

## 3.RESULTS AND DISCUSSIONS

**Table 3.** Shows the Mechanical properties of forged and polymer quenched steel samples

| EN Series | Sample quenching medium | Tempering Temperature (°C) | Force (N) | Nominal stress $N/mm^2$ | Tensile strength $N/mm^2$ | $K_{IC}$ $Mpa\sqrt{m}$ | $J_{IC}$ $KJ/M^2$ |
|---|---|---|---|---|---|---|---|
| EN 18 | As Forged | --------- | 5795.9 | 6.182 | 819.7 | 34.8 | 35.6 |
| | 10% Polymer | 575,220 | 6737.4 | 7.18 | 952.8 | 42.6 | 69.09 |
| | 30% Polymer | 575,220 | 7267.0 | 7.75 | 1027.7 | 46.1 | 75.02 |
| EN 19 | Forged | ---------- | 5913.6 | 6.30 | 836.3 | 37.4 | 40.4 |
| | 10% Polymer | 575,220 | 6923.4 | 7.384 | 1135.9 | 43.8 | 71.15 |
| | 30% Polymer | 575,220 | 7393.4 | 7.886 | 1098.9 | 46.8 | 75.98 |
| EN 24 | Forged | ----------- | 6423.5 | 6.851 | 894.3 | 40.6 | 43.78 |
| | 10% Polymer | 575,220 | 7649.5 | 8.159 | 1081.8 | 48.4 | 78.59 |
| | 30% Polymer | 575,220 | 7816.2 | 8.337 | 1105.4 | 49.5 | 80.29 |
| EN 25 | Forged | ------------ | 6777.3 | 7.229 | 923.3 | 42.9 | 46.42 |
| | 10% Polymer | 575,220 | 8123.5 | 8.665 | 1212.2 | 51.4 | 83.46 |
| | 30% Polymer | 575,220 | 8354.7 | 8.911 | 1239.9 | 52.9 | 85.74 |

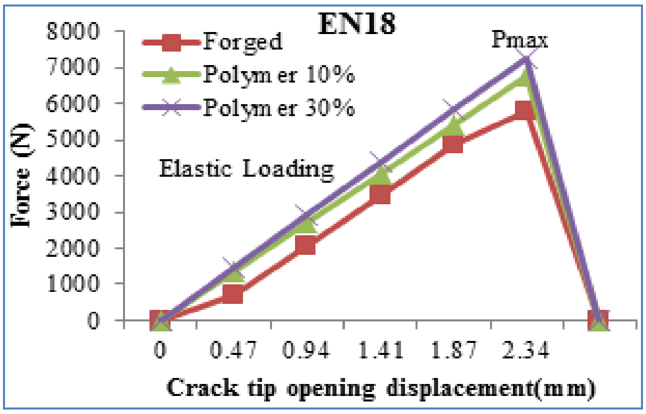



**Fig 5.** Principal Types of EN18 Force-Displacement Records

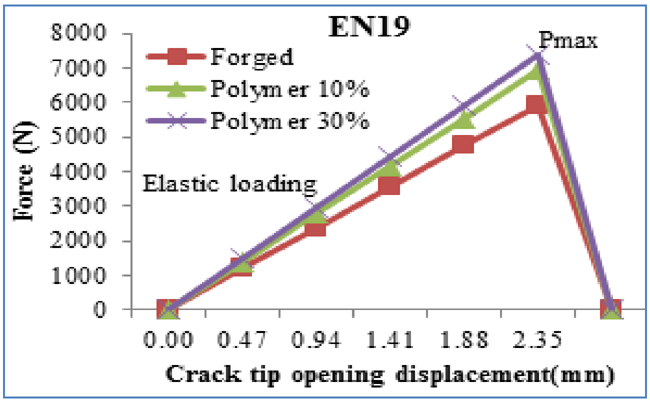



**Fig 6.** Principal Types of EN19 Force-Displacement Records

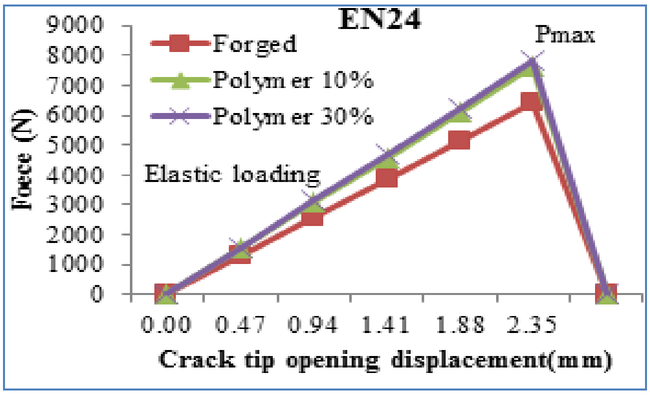



**Fig 7**. Principal Types of EN24 Force-Displacement Records

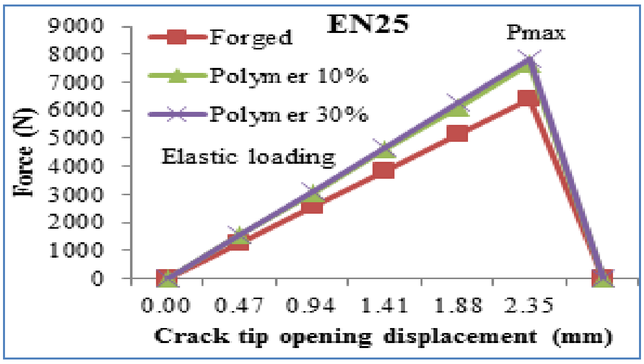



**Fig 8.** Principal Types of EN25 Force-Displacement Records

**Observation:** The maximum load value recorded by the machine, $P_{max}$is for 30 % polymer quenched EN 18, 19,24&25 steels compare to 10% polymer quenched and as forged samples.

## 4. METALOGRAPHY

The microstructural investigation**[8],** was performed using a Carl Zeiss optical microscope. In sequence, the steps include sectioning, mounting, course grinding, fine grinding, polishing, etching and microscopic examination. Thesamples were polished using a series of emery papers of grit size varying from 1000µm- 1500 µm.High napped polishing pads with a colloidal alumina polishing abrasive is used.The polishing times should nominally be less than 30 seconds. The samples were etched with Nital solution, 100 ml Ethanol and 1-10 ml Nitric acid for about 10 – 20 seconds before observation in the optical microscope.

**Observation:**Medium carbon low alloy forged steel vs. polymer quenched and tempered steels have strong influence on fracture toughness($K_{IC}$).The polymer quenched and tempered steels results high fracture toughness value for as forged samples. The microstructure of forged sample consists of proeutectoid ferrite and pearlite. The white region results the proeutectoid ferrite and black region results pearlite in the microstructure. The resultant pearlite is resolved into alternative phases of ferrite and cementite. The microstructure of polymer quenched and tempered steel consists of fine tempered martensite with the small amount of ferrite.By step tempering retained austenite converts into non equilibrium but more stable phases like troosite, sorbite or bainite,which improve ductility, toughness and impact strength.

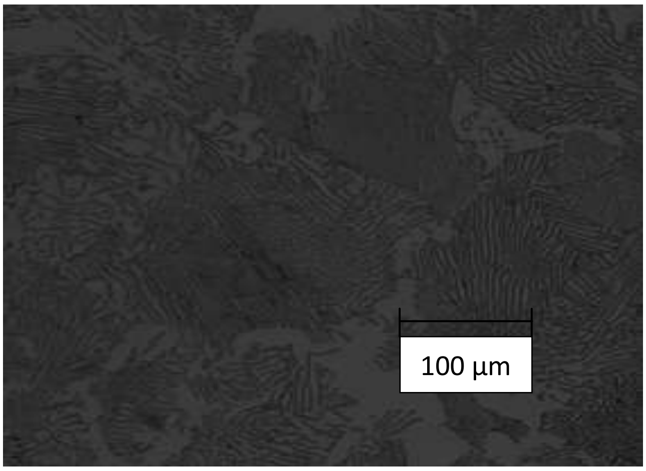



**Fig 9:** Microstructure of EN18 steel in Forged condition

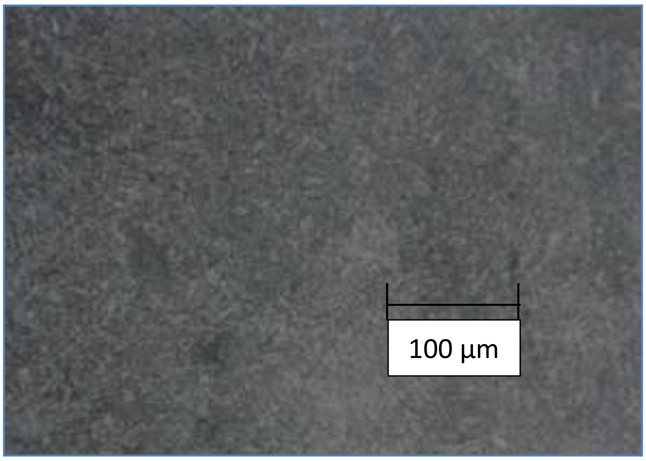


**Fig 10:** Microstructure of EN18 steel quenched in 10% Polymer solution.

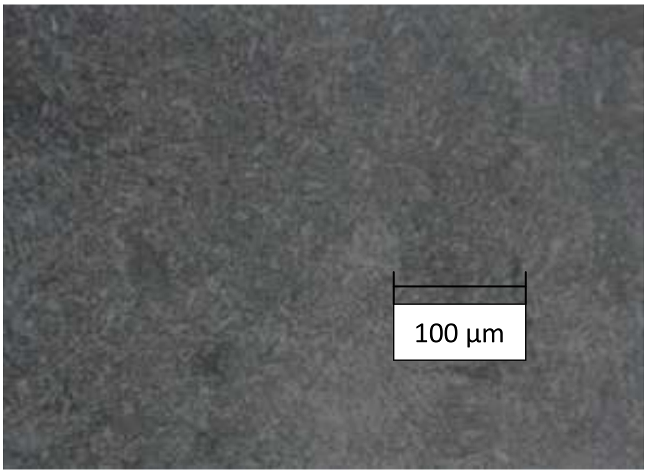


**Fig 11:** Microstructure of EN18 steel quenched in 30% Polymer solution.

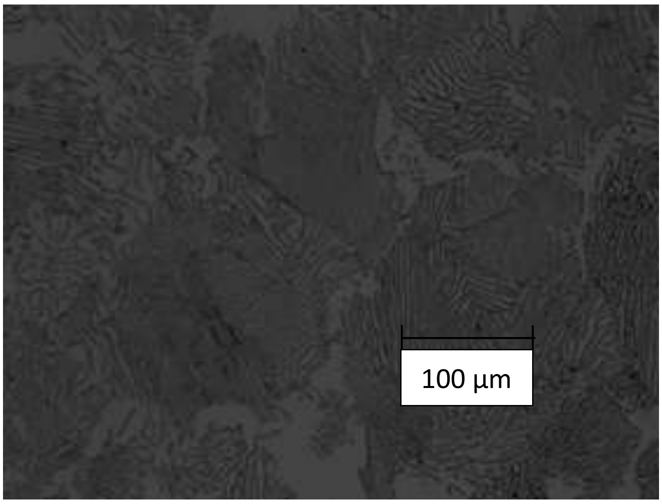


**Fig 12**: Microstructure of EN19 steel in Forged condition

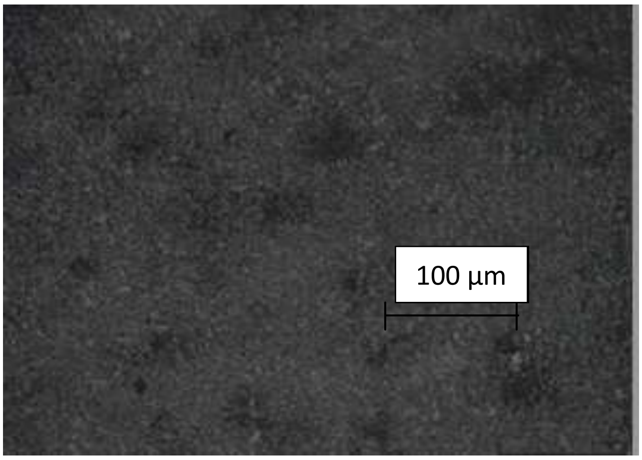


**Fig 13**: Microstructure of EN19 steel quenched in 10% Polymer solution.

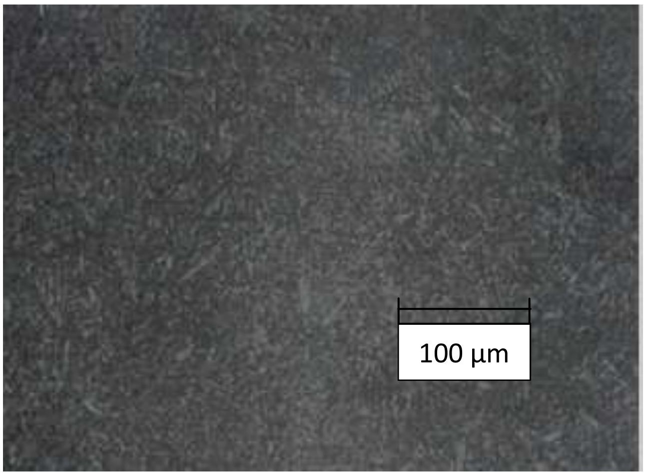


**Fig 14:** Microstructure of EN19 steel quenched in 30% Polymer solution.

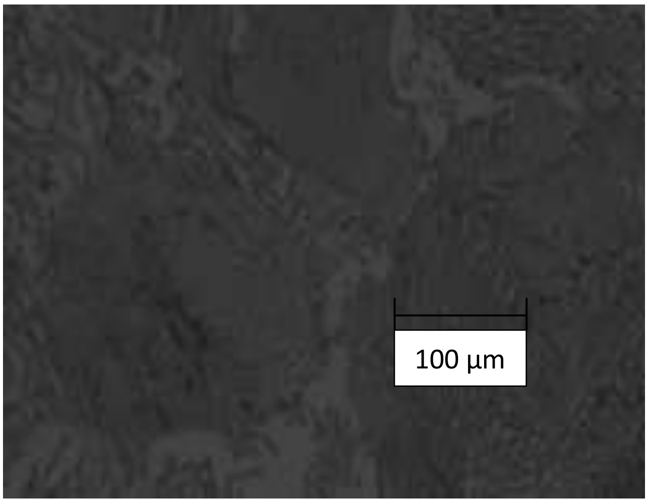


**Fig 15:** Microstructure of EN24 steel in Forged condition

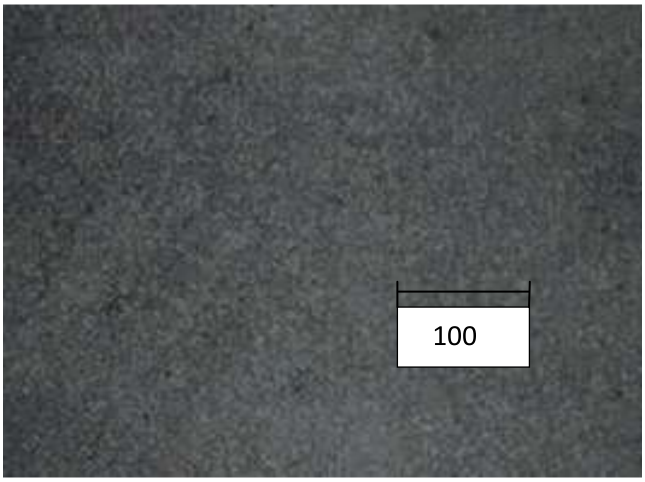



**Fig 16:** Microstructure of EN24 steel quenched in 10% Polymer solution

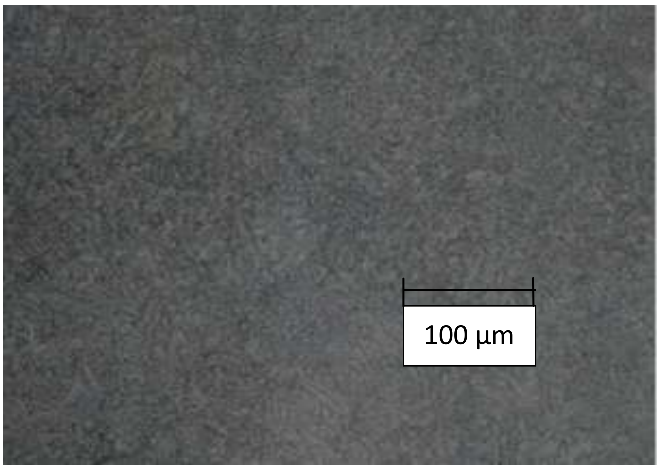



**Fig 17**: Microstructure of EN24 steel quenched in 30% Polymer solution.

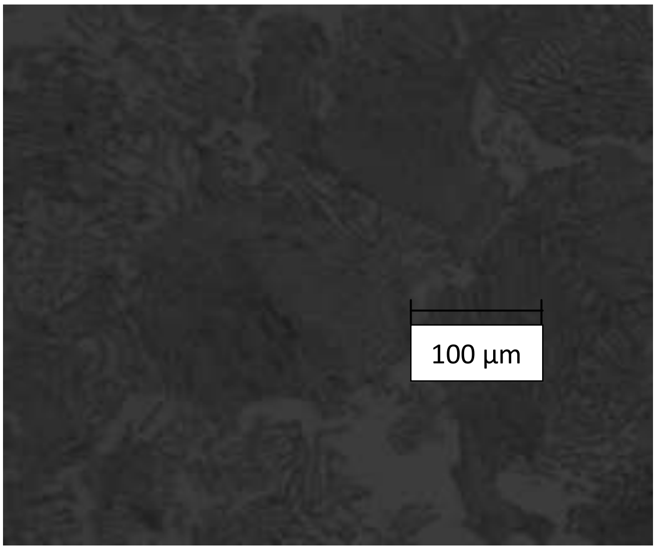



**Fig 18:** Microstructure of EN25 steel in Forged condition

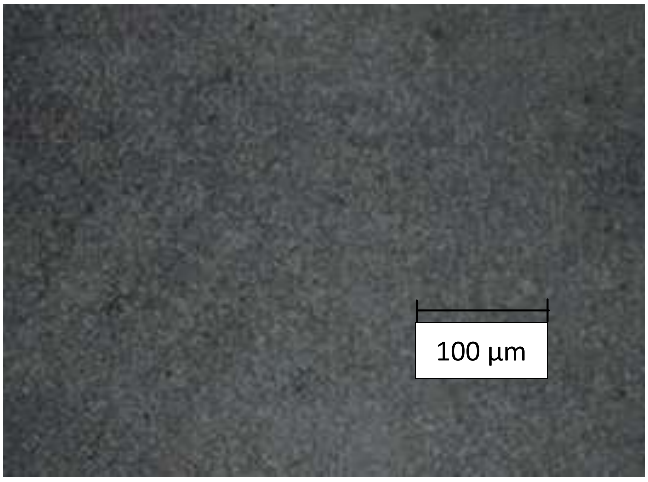



**Fig 19:** Microstructure of EN25 steelquenched in 10% Polymer solution

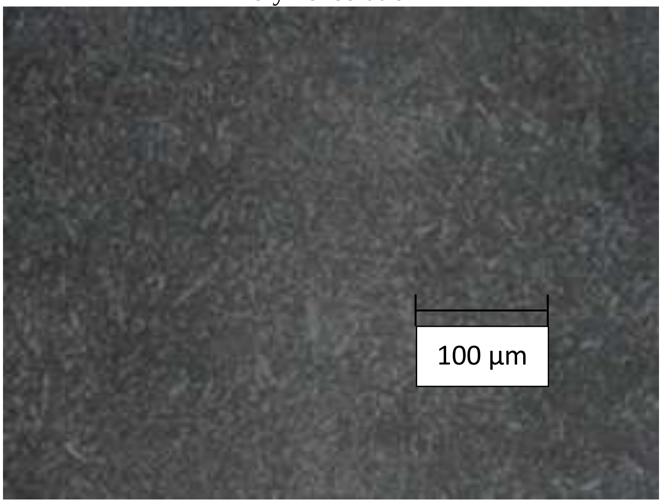



**Fig 20:** Microstructure of EN25steel quenched in 30% Polymer solution.

## 5. FRACTOGRAPHY [9]

The fatigue fractured specimen surfaces was examined using a Scanning Electron Microscope (LEICA 4401) with the Secondary electron imaging performed using an applied voltage of 20KV.

Observation:A fine grained structure results better resistance to crack propagation results in higher fracture toughness due to higher grain boundary.

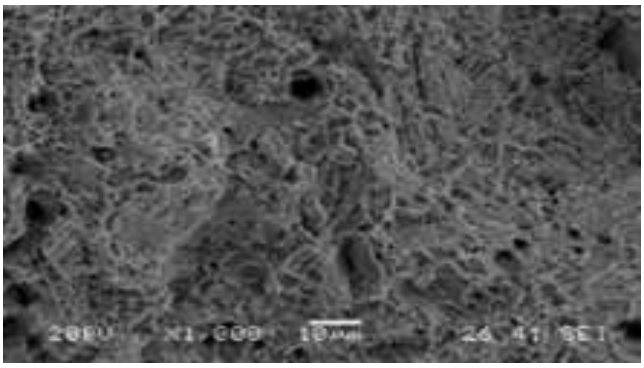


**Fig 21:** Fractured surfaces of EN18 steel quenched in 30% Polymer solution

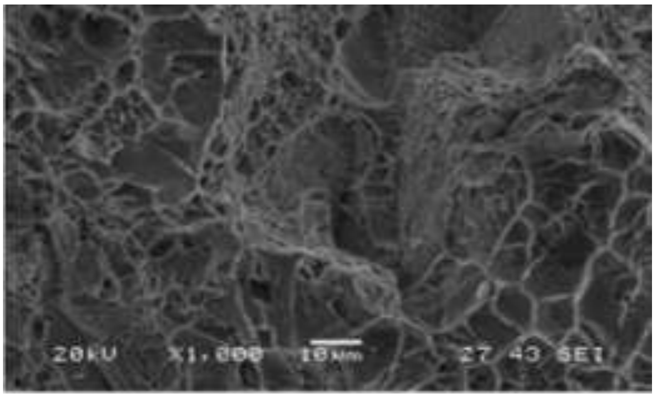



**Fig 22:** Fractured surfaces of EN19 steel quenched in 30% Polymer solution

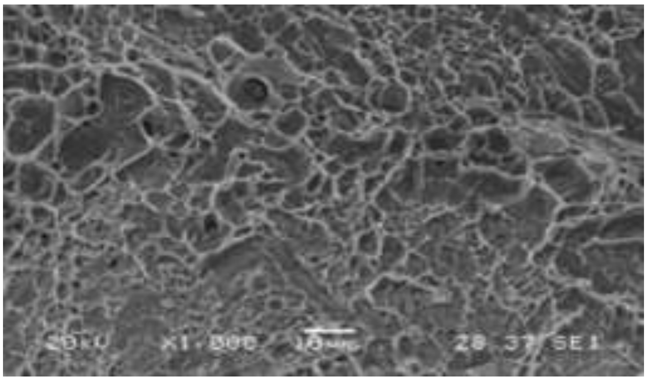



**Fig 23:** Fractured surfaces of EN24 steel quenched in 30% Polymer solution

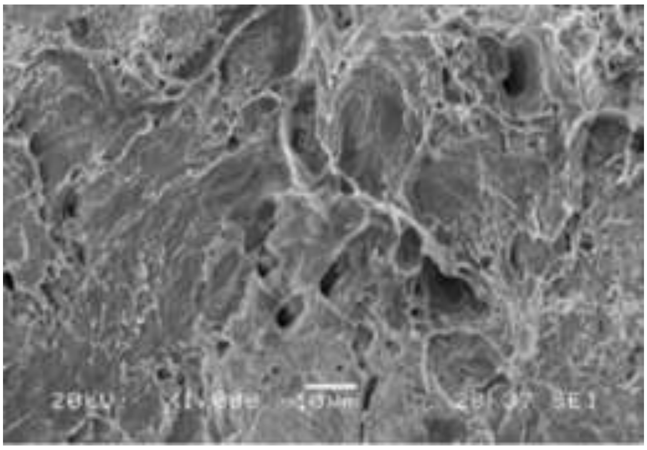


**Fig 24**: Fractured surfaces of EN25 steel quenched in 30% Polymer solution

## CONCLUSION

This study tends to investigate the Fracture Toughness of Medium Carbon Low Alloy Forged steels vs. Polymer Quenched steels

[1]. The following conclusions were made from the results obtained:
[2]. The step tempering process of the samplesresults high fracture toughness.
[3]. PEG is preferred as a quenching medium to minimize the stresses and cracking due to uniform cooling rate then the water, ice and brine solution.
[4]. The ultimate tensile strength increases with increase in polymer concentration.
[5]. The fracture toughness of 30% polymer quenched samples results high compare to 10% polymer quenched and forged samples for the same notch depth and thickness.
[6]. The microstructure of polymer quenched and tempered steel consists of fine tempered martensite with the small amount of ferrite.
[7]. A fine grained structure has been found to have higher value of $K_{1C}$ than a coarse grained structure.

The fracture surface of the polymer quenched samples follows the grains of the material, where cracks that takes place along the grain boundary.

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