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# METALLURGICAL STUDIES OF EXTRA DEEP DRAWN STEEL IN STRETCH FORMING AT ELEVATED TEMPERATURES

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## ABSTRACT

This paper investigates the detailed study of microstructure, micro-hardness, grain size and grain density of low carbon extra deep drawn steel. The stretching operation was carried out on square and rectangular extra deep drawing steel specimens by keeping the length constant and varying the breadth and at different temperatures. The stretching has performed in three different regions namely safe, necking and fracture. The formability limit diagrams were constructed. The factrography studies for fractured surfaces of stretched samples were carried out.

***Keywords:*** *EDD steels, Microstructure, Microhardness, grain density.*

## 1. Introduction

Fractures were occurring upon industrial stretching operations which are specially applying in automobile and aerospace at strains below what is predicted by traditional. This observation is attributed to the complex interaction(s) between the constituents present in alloy material. Many micro structural properties, including constituent grain size, grain morphology, martensite volume fraction (MVF), and the hardness of the individual constituents are known to have an effect on the formability of individual material.

It is very important for a production engineer who is dealing with material forming processes to select the right material for a certain forming operation. An important concern in forming is whether the desired deformation can be accomplished without failure of the material or not. The ability of the material to be plastically formed under specified conditions into a required final shape is usually called formability. For a given process and deformation geometry, the forming limits vary from material to material. Three aspects should be taken into account for a forming operation:1)The properties of the object like sheet metal, bar, rod, wire, billet etc.; usually show complex internal structures determined by a non-uniform distribution of some material properties i.e. chemical composition, grain shape and size, texture. Thus, different sheets with identical chemical composition can show different behavior during forming processes.2).Forming parameters which are determined by the kind of operation, geometry of the punch and die, forming temperature, lubrication, press type, press ram velocity etc.3).Formability criteria which are different criteria applied depending on the forming conditions, for example ductile fracture, wrinkling, etc

The maximum deformation that the material can suffer in any metal forming operation is usually limited by various unfavorable phenomena. When the maximum load necessary for forming exceeds the ultimate and/or fatigue strength of the tool causes a rapid wear or damage of the forming tools. If the forming load exceeds its strength outside the forming region of the workpiece, causes the failure of the forming material. If the failure occurs in the forming region of the material then it is called ductile failure. It is usually preceded by strain localization in the form of shear bands. This failure limits for stretch forming operations in sheets.

According to literature various factors like, tool geometry, friction [3], anisotropy, strain hardening exponent [9], strain rate sensitivity, grain size [6] and strain path changes [2] influences the formability of the material and hence on the formability limit diagrams.

In the present work EDD steel material sheets were into square and rectangular blanks of size 110X110 mm to 110X20 mm and stretched on specially designed die punch assembly by using hydraulic press. The experimentation was carried out in three different regions namely safe, necking and fractured. The FLDs were plotted by taking major strain as ordinate and minor strain as abscissa. Later on fractured surfaces are mounted and under gone the factrography.

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## 2. Experimental Procedure

### 2.1. Chemical analysis and tensile test

**Table 1: Composition of EDD steel**

| Element | % of weight |
|---|---|
| C | 0.048 |
| Si | 0.83 |
| Mn | 0.39 |
| S | 0.024 |
| P | 0.019 |
| Cr | 0.027 |
| Sn | 0.004 |
| Cu | 0.019 |
| Ni | 0.054 |
| Mb | 0.028 |
| Fe | Rest |

The most commonly used specimen is the flat bar with reduced-section, where the gauge length is usually 105 mm long and 21 mm wide, and with holes at ends for holding purpose. It is loaded at a constant speed rate in a tensile machine until fracture occurs. The test procedure is described in DMRL standards. The applied load and extension is measured by means of a load cell and strain gauge extensometer. The load extension data can be plotted directly from the measured values but usually the data is converted to engineering stress and strain or true stress and strain. These are calculated as:

Engineering stress ($\sigma e$)= $F/A_0$
Engineering strain (e)= $\Delta l/ l_0$
True stress ($\sigma t$)=F/ A
True strain ($\varepsilon$)=ln $l/ l_0$

Where:

F = force (N).
$A_0$= original cross-sectional area.
A = instantaneous cross-sectional area.
$l_0$= original length.
l = instantaneous length.
$\Delta l = l- l_0$

The true stress-strain curve is extensively used in the literature especially for large deformations. For uniaxial tension the true stress-strain curve has an advantage because it has been shown to be equivalent to the stress-strain curve for effective stress and effective strain. To evaluate plastic anisotropy behavior the Lankford coefficient, frequently called the plastic anisotropy parameter [8] (r-value), is evaluated through uniaxial tensile tests with two extensometers, one in the longitudinal direction and one in the transverse direction. The ratio between the major strains is calculated through the conservation of volume and the measured data from the extensometers

$r = \varepsilon w/ \varepsilon t= \varepsilon w/-(\varepsilon w- \varepsilon l)$

Where is the strain in width, $\varepsilon l$ is the longitudinal strain and is the thickness strain at a uniaxial tension test. This is normally carried out with samples produced at 0,45 and 90 degrees from the rolling direction. Since the r-values vary for the different directions an average value can be used, which is called normal anisotropy, and is defined as:

$r = (r_0 + 2r_{45} + r_{90})/4$

Where, the index indicates the angle from rolling direction.

It has been known for a long time that deep drawing is governed by plastic anisotropy. For deep drawing operations a high r -value indicates that the material can be relatively easily compressed in the flange while the wall of the drawn part can sustain high load without excessive thinning and fracturing and this indicates that the material is good for deep-drawing operations. Another description of anisotropy is the variation of the r-value in the plane of the sheet, which is called planar anisotropy and is defined as:

$\Delta r = (r_0 - 2r_{45} + r_{90})/2$

For deep drawing operations this value correlates well with the ‘earing’ of a deep-drawn cylindrical cup. When $\Delta r>0$ then ears is formed at $0^0$and $90^0$to the rolling direction, while if $\Delta r<0$, ear formation occurs near $45^0$to the rolling direction. Thus from a uniaxial test, several mechanical properties of material useful for forming operations are evaluated. These are tabulated in Table 2.

### 2.2. Stretching test

Many forming operations involve stretching a material to different shapes, for example aerofoils and hubs. The FLD was evaluated following Hecker's simplified technique [6]. In this method, mainly the experimental procedure involves three stages

1) Grid marking on the specimen sheets.
2) Stretching the grid-marked samples to failure or onset of localized necking or safe
3) Measurement of strains.

Grid marking on the EDD steel sheet samples was done using a non-contacting grid of 5 mm diameter circles. The grid pattern was etched on the samples using an electro-chemical etching machine. Punch-stretching experiments were carried out on a 20 tonne capacity hydraulic press. The punch-die assembly was designed and fabricated depending on the thickness of the sheets. A typical punch-die assembly [5] used in the experiments is shown in Fig. [3]. The sheet samples were subjected to different states of stain, i.e. the tension-tension zone, plane strain and the tensioncompression zone by varying the width of the sample. In this method samples were cut using sharing machine. The length of the blank was 110 mm and width was varied between 110 to 20 mm insteps of 10 mm. For each blank width, at least five specimens were tested for each temperature to get maximum number of data points. To obtain the maximum values in the magnitude of the negative minor strain, uniaxial tension tests were also done using grid-marked of localized specimens. The blanks were stretched to before necking i.e. safe, the experiments were stopped at the time of onset of localized necking in some cases and continued till fracture in other cases. The circles on the sheet samples became ellipses after stretching, falling into safe, necked and failed zones. The major and minor diameters of the ellipses were measured using a travelling microscope with an accuracy of 0.01mm.Major strains and minor strains were calculated in three regions.FLD was drawn by plotting the minor strain in abscissa and corresponding major strain in ordinate and by drawing a curve which separates the safe region from the unsafe region. The fracture limit and forming limit curves were drawn by connecting the fracture strains for various blanks of EDD steel sheets. The accuracy of the FLD lies well within a band of ±2% in the engineering strain values.

### 2.3. Formability limit diagrams

The ratio of the major strain against the minor strain is plotted and resulted diagram is called a forming limit diagram (FLD). This diagram is shows the strain combinations that produce instability or/and fracture and those which are permissible in forming operations. For failure by localized necking it is useful to think of the strain in the sheet at the time when necking occurs, this strain is usually referred to as the limit strain that is determined from the principal surface strains e1 and e2.The ratio of these strains should be below the forming limit curve (FLC) in the forming limit diagram (FLD) to prevent necking in the material. The FLDprovides information that is very useful in press-shop operations and is very important in the theoretical analysis (with computer modelling) of press operations. This diagram is also called The Keeler-Goodwin diagram.

The FLD is frequently plotted in terms of engineering strains but it can also be given in true (logarithmic) strains. For determining experimental FLD's the biaxial state of stress varied by stretching rectangular strips of different widths and with different interface lubrication over a rigid hemispherical punch with the ends of the strip being held down by flat hold-down pads. After each blanks loaded to failure, the major and minor strains are obtained from measurements made of the distortion of small circles of a circular grid previously etched on the surface of the sheet, see Figure 11. The ratio of the major and minor strain is then plotted into a FLD diagram[10,11].The objective of FLD testing is to simulate the various states of the strain ratios that could be encountered in forming operations. These strains could vary fromequibiaxial strain (e1=e2) through plane strain (e2=0) to pure shear (e1=-e2).When both strain components are positive the test is measuring thestretchability of the material. When the minor strain component is negative and the major strain component is positive the test is measuring the drawability of the material. In most forming operations the localized necking and failure occurs near the plain-strain state i.e. -10 %< e2 < +20%. Because of the influence of factors like strain path, strain rate, strain gradient, punch curvature, friction, grid size, yield strength and the thickness of the tested material, diagrams obtained by different methods and under different conditions should not be compared.

### 2.4. Microstructure & grain density

Microstructural analysis was done mainly on fractured EDD steel specimen during the stretching operation. The microstructural analysis was confined to the selected specimens being sectioned at the fractured end. Several samples from 110X110mm to 110X20mm were cut and mounted ready for microstructural study. The samples were polished in five gradual stages from 120 to 2400.While grinding care should be taken the grinding lines were unidirectional. Then all the specimens were cleaned by the water and dried by air dryer. After that the specimens were etched with Nital (2%) in order to examine the microstructure of fractured area.

### 2.5. Microhardness

Microhardness test is an indentation hardness test which measures the resistance on the indentation of a material under static or dynamic loading. Vickers hardness test is suitable for testing the very hard steels and hardened steel surfaces. The Vickers hardness machine gives a quick method of hardness measurement. The Vickers diamond indenter is a highly polished, pointed square based pyramidal diamond with $136^0$ angle. The Vickers indenter produces the depth of indentation about one seventh of the diagonal length .The hardness value of Vickers is a stress value and is expressed as Kg/mm$^2$.In this study Vickers hardness test was carried out on base metal and fractured ends of the various stretched specimen ranging from 110X110 mm to 110X20 mm.

## 3. Results & Discussions

### 3.1. Tensile test

**Table 2: Mechanical properties of EDD steel**

| Temperature (°C) | UTS (M Pa) | YS (M Pa) | Strain at YS | Elongation (%) | Strength Coeffecient (M Pa) | Work Hardening Exponent (n) |
|---|---|---|---|---|---|---|
| 25(RT) | 337 | 202 | 0.0222 | 44 | 677 | 0.304 |
| 150 | 304 | 188 | 0.0291 | 35 | 577 | 0.274 |
| 300 | 294 | 184 | 0.0314 | 29 | 548 | 0.261 |
| 450 | 329 | 216 | 0.0582 | 39 | 684 | 0.289 |

The tensile parameters namely strain hardening exponent (n) and strength coefficient (K) of various steel sheets taken for study obtained from the tensile tests are tabulated in Table 2

Singh [7,8] investigated the properties of EDD steel at various temperatures using 5tonne electronically controlling UTM. For this material it was observed that serrations in the work hardening regime it start appearing between 350°C to 400°C.It was also observed that there was slight increase in the properties like strength coefficient work hardening coefficient and strength of material in this temperature range. It is because of presence of silicon etc which increases the dislocation density within the material due to phenomena of dynamic strain regime. In the present investigation the formability limit diagrams were constructed in this range to see the impact of serrations on the formability.

### 3.2 Formability limit diagram

FLDs were determined experimentally for the EDD steel sheets by following Hecker's simplified technique are shown in Fig:1.The above FLDs shown that stretchability of sheet metal is strongly influenced by the value of strain hardening exponent (n).The n values of EDD steel sheets are shown in table 2.From the table it can be seen that the values obtained from true uniform strain in tensile test agreed well with the FLDs obtained at room temperature,150$^0$C ,300$^0$C and 450$^0$C mainly in plain strainregion. The formability of EDD steel at room temperature ,150$^0$C ,300$^0$C and 450$^0$C temperatures are consistent with expectations based on the uniaxial tensile properties. The effect of temperature on EDD steel sheets is observed the level of the FLD is clearly seen, particularly at the plain strain condition. The level of the FLD decreased with increase in sheet temperature, which is approximately coincident with strain hardening exponent (n) at each considered temperature. But the level of FLD was increased at temperature of 450$^0$C irrespective of increase in temperature. It is because by increasing the temperature further there was effect of sensitivity index and also dynamic strain regime starts appearing in the material near this temperature [8].It can be seen the table 2 that at 450$^0$C there is increase in strength, strength coefficient and relative increase in the work hardening exponent.

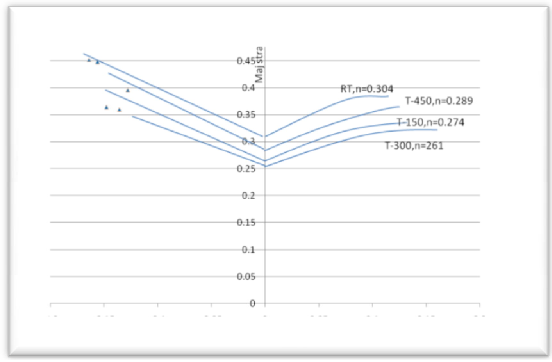


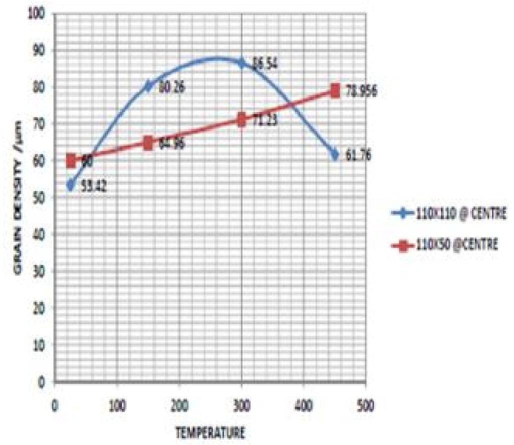

**Fig. 1 Combined Formability limit diagrams**

### 3.3 Microstructure grain density

**Fig. 2 Microstructure images selected EDD steel**

Extra deep drawing quality steel (EDD steel) is stretch formed at various temperatures for the purpose of studying formability .In the present experimental set up a draw bead is present at approximately 45 mm from the centre to restrict the metal flow. Stretching experiments were conducted the deformed materials were cut to sizes and moulds were prepared .specimens were cut from the point where fracture appear in the material from a specimen of 110X110 mm and also 110X50 mm while deforming 110X110 mm specimen .



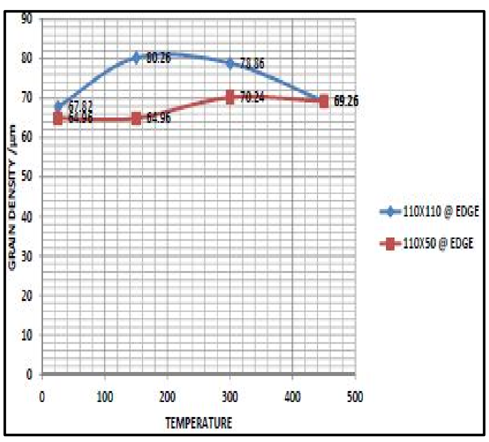




**Fig. 3 Grain density graphs**

Since there will be biaxial stretching work hardening is expected to be more while deforming 110X50 mm specimen the sample is subjected to partly uniaxial stretching and partly drawing.

**Table 3(a): Grain density results at room temperature**

| Sl. No. | Position | Dimension | No. of intercepts | Depth of intercept (µm) | Grain Density |
|---|---|---|---|---|---|
| 1 | Centre | 110X110 | 748 | 14 | 53.42 |
| 2 | Edge | | 841 | 12.4 | 67.82 |
| 3 | Centre | 110X50 | 792 | 13.2 | 60 |
| 4 | Edge | | 825 | 12.7 | 64.96 |

**Table 3(b): Grain density results at 150°C**

| Sl. No. | Position | Dimension | No. of intercepts | Depth of intercept (µm) | Grain Density |
|---|---|---|---|---|---|
| 1 | Centre | 110X110 | 915 | 11.4 | 80.26 |
| 2 | Edge | | 915 | 11.4 | 80.26 |
| 3 | Centre | 110X50 | 825 | 12.7 | 64.96 |
| 4 | Edge | | 825 | 12.7 | 64.96 |

**Table 3(c): Grain density results at 300°C**

| Sl. No. | Position | Dimension | No. of intercepts | Depth of intercept (µm) | Grain Density |
|---|---|---|---|---|---|
| 1 | Centre | 110X110 | 952 | 11 | 86.54 |
| 2 | Edge | | 907 | 11.5 | 78.86 |
| 3 | Centre | 110X50 | 862 | 12.1 | 71.23 |
| 4 | Edge | | 857 | 12.2 | 70.24 |

**Table 3(d): Grain density results at 450°C**

| Sl. No. | Position | Dimension | No. of intercepts | Depth of intercept (µm) | Grain Density |
|---|---|---|---|---|---|
| 1 | Centre | 110X110 | 803 | 13 | 61.76 |
| 2 | Edge | | 852 | 12.3 | 69.26 |
| 3 | Centre | 110X50 | 908 | 11.5 | 78.96 |
| 4 | Edge | | 852 | 12.3 | 69.26 |

Fig. 3 and table 3 represents the grain density of the stretched components at various temperatures and also for different sample sizes .it can be observed from table 1 that for 110X50 mm specimen grain density is always lower as compared to 110X110 specimen (up to 300c).it is because when the width of specimen decreases due to drawing component compressive hoop stresses will appear in the region and as a result of that grain will be more elongated but the density will be slightly lower the elongated grains can be observed From following images it is also observed that there is not much change in the grain density of the component up to 300$^0$C.

## 3.4. Microhardness

**Table 4: Microhardness results**

| SNO | LOAD | TEMPERATURE | DIMENSIONS | AVERAGE HARDNESS NUMBER |
|---|---|---|---|---|
| 1 | 50 | ROOM TEMPERATURE | 110X110 | 184 |
| 2 | | | 110X50 | 194 |

| SNO | LOAD | TEMPERATURE | DIMENSIONS | AVERAGE HARDNESS NUMBER |
|---|---|---|---|---|
| 1 | 50 | 150C | 110X110 | 202 |
| 2 | | | 110X50 | 206 |

| SNO | LOAD | TEMPERATURE | DIMENSIONS | AVERAGE HARDNESS NUMBER |
|---|---|---|---|---|
| 1 | 50 | 300C | 110X110 | 220 |
| 2 | | | 110X50 | 266 |

| SNO | LOAD | TEMPERATURE | DIMENSIONS | AVERAGE HARDNESS NUMBER |
|---|---|---|---|---|
| 1 | 50 | 450C | 110X110 | 430 |
| 2 | | | 110X50 | 310 |

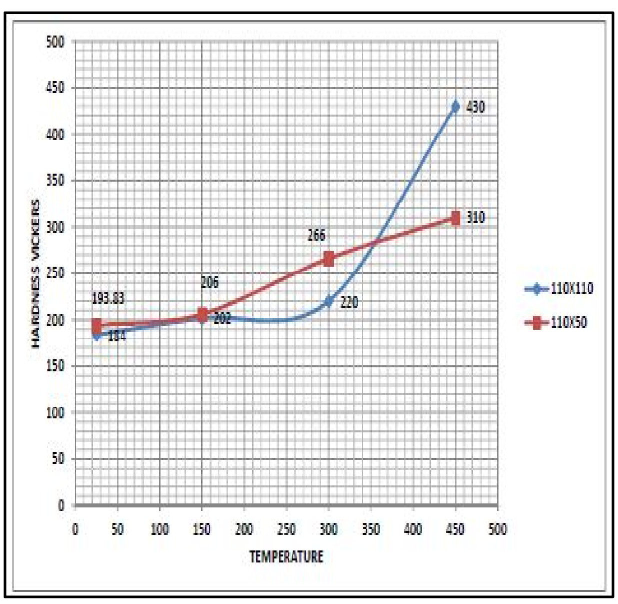



**Fig. 4 Microhardness graphs**

Fig 4 and table 4 represents micro hardness in the fractured region of specimen at various temperatures .in this data we can see that there is not much change in the microhardness value upto 300$^0$C it is because 300$^0$C is much below recrystallization temperature and microstructural changes are not accepted below this temperature .

As investigated by Singh et.al [7,8] near 400$^0$C a phenomenon called Dynamic strain aging appears in the material primarily due to the presence of small amount of chromium when the load is applied there will be mobility of dislocations due to presence of Cr in a certain temperature band mobility of cr becomes more than mobility of dislocations. So Cr breaks this dislocations into many parts due to this sudden increase in dislocation density material not only becomes slightly hard and brittle but also work hardening exponent of the material suddenly increases this phenomenon can be seen in micro hardness test that at 450$^0$C there is almost 70% increase in the microhardness in the fracture region.

Scanning electron micrographs are presented between fig 5-7 and it can be seen that approximately at 400$^0$C material is subjected to cleavage fracture which is an indication of brittle fracture and the microhardness value observed in the present investigation validates this fact. At 400c since the material is becoming slightly brittle due to this phenomenon grains will be lesser and lesser elongated because excessive elongation leads to fracture. This can be seen in the grain density observation that at 450c grain densities are slightly lesser.

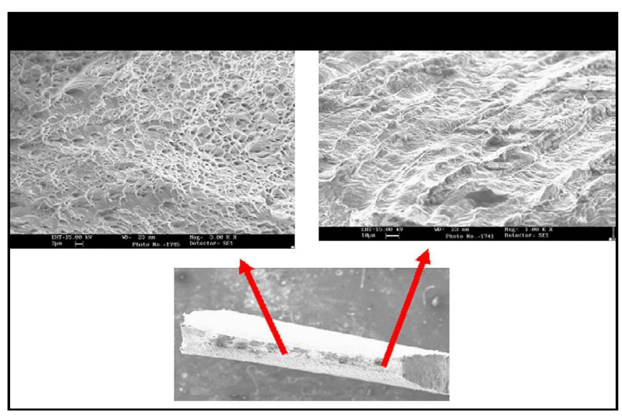


**Fig. 5 SEM images taken for fractures surface of UTM specimen at room temperature (25 $^0$C).**

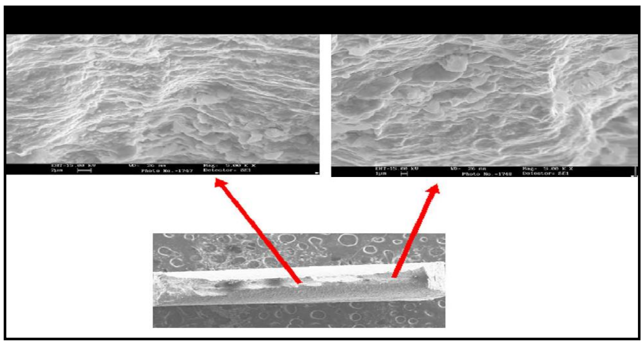


**Fig. 6 SEM images taken for fractures surface of UTM specimen in dynamic strain regime (400 $^0$C).**

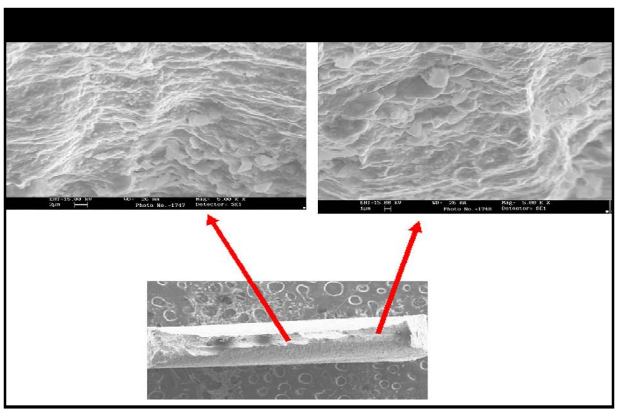


**Fig. 7 SEM images taken for fractures surface of UTM specimen in plastic region (700 $^0$C).**

So the conclusion is material can be safely formed before 400c but the formability of material is further expected to increase when the temperature of sample is beyond 550c because in SEM it can be seen that mode of fracture is ductile.

## 4. Conclusion

Stretch formability of extra deep drawing steel sheets was investigated by Hecker's simplified technique at room temperature, 150$^0$C, 300$^0$C and 450$^0$C. The affect of microstructure, microhardness, grain size and grain density, and dependences on stretch formability of EDD steel were discussed. The results are concluded as follows:

1. By analysing micro hardness in the fractured region of specimen at various temperatures according to data obtained we can see that there is not much change in the micro hardness value upto 300$^0$C it is because 300$^0$C is much below recrystallization temperature and micro structural changes are not accepted below this temperature

2. Due to the presence of materials like Chromium (Table.1) in EDD Steel, it is observed during experimentation that around 400$^0$C, dynamic strain regime (Blue Brittle phenomena) appears in the material. It is found that the fracture mechanism in this temperature range is primarily brittle but also work hardening exponent of the material suddenly increases this phenomenon can be seen in micro hardness test that at 450$^0$C there is almost 70% increase in the micro hardness in the fracture region.

3. Hence beyond 450$^0$C only larger reductions are possible to this material.

4. It is observed that approximately at 400$^0$C material is subjected to cleavage fracture which is an indication of brittle fracture and the micro hardness value observed in the present investigation validates this fact

5. At 400$^0$C since the material is becoming slightly brittle due to this phenomenon grains will be lesser and lesser elongated because excessive elongation leads o fracture .This can be seen in the grain density observation that at 450$^0$C grain densities are slightly lesser so the conclusion is material can be safely formed before 400$^0$C but the formability of material is further expected to increase when the temperature of sample is beyond 550$^0$C

6. It is observed that for 110X50 mm specimen grain density is always lower as compared to 110X110 specimen (up to 300$^0$C).It is because when the width of specimen decreases due to drawing component compressive hoop stresses will appear in the region and as a result of that grain will be more elongated but the density will be slightly lower the elongated grains can be observed. From fig.3 and table.3 it is also observed that there is not much change in the grain density of the component up to 300$^0$C

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