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Mechanical and Microstructural Behavior of *C*-Mnsteel Under Varying Strain Rates

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Abstract *The Prime Objective Of Vehicle Designers Is To Produce Vehicles With Fuel-Economy Along With The Safety Standards Imposed By The Government And Stringent Consumer Demands. It Is Known That Reducing The Weight Of A Vehicle Is A Straight Forward Strategy To Improve Fuel-Economy, But It Can Potentially Create Safety Problems Which In Turn Leads To Increased Use Of High Strength Steel Sheets For The Auto Body Components. C-Mn And DP Steels Consist Of Excellent Combination Of Both Strength And Ductility. High Strain Rate Experiments Are Generally Used To Study The Material Behaviour When These Are Subjected To High Speed Impacts, Like Crash. The Mechanical Behaviour Of These Materials At High Strain Rates Is Considerably Different From That Observed At Quasi-Static Loading Because Of The Strain Rate Sensitivity Of The Material. Hence, Automotive Industries Are Continuously Engaged With Designing Newer Materials For Car Body Applications. In This Investigation, Many Quasi Static Tensile Experiments Were Carried Out At Various Strain Rates On C-Mn 440 Steel At Ambient Temperature. It Has Been Observed That Yield And Tensile Strengths Of The Material Increase Drastically While %EL And %RA Significantly Decrease With The Strain Rate. The Fracture Surface Reveals Dimple Morphology With Variation Of Dimple Geometry With Strain Rate; Average Dimple Diameter Increases And Dimple Density Decreases With Strain Rate. The Void Accumulation (I.E., Void Density) Inside The Material Increases With The Increase In True Strain For All The Strain Rates. At The Initial Stage Of Strain, Void Density Increases Slowly And At The Later Stage, Void Density Increases Rapidly.*

Keywords*: C-Mn440 Steel, Strain Rate, Tensile Test, Void Density, Microstructure Changes*

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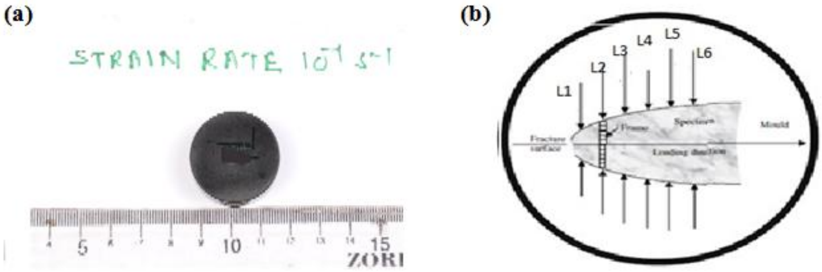
I. INTRODUCTION

Current Strong Demand For Vehicle Lightening From The Automobile Sector Requires Flat Carbon Steel Manufacturers To Develop New Advanced Grades Capable Of Fulfilling The Increasingly Stringent Technical Requirements Of Market. For This, The Steel Industries /Automobile Industries Are Regularly Trying To Produce Newer Kinds Of Steels With Superior Properties. C-Mn Steel Is One Of Such Kind Which Is Having High Strength, High Elongation, High Hardness And Toughness. Carbon Steel Stability Can Be Obtained At A Reduced Cost By Applying With Carbon And Manganese. Apart From The Positive Economic Impact, These Two Elements Also Provide Access To Superior Mechanical Properties. As Can Be Expected, In Such Applications The Car Body May Face Crash, High Impact And Various Kinds Of States Of Stresses. One Of These Could Be Manifested Experimentally As 'Loading At Different Rates Of Straining'. It Is Well Known That Materials' Behaviours Under Different Strain Rates Vary[1]. Although Scattered Results May Be Available For The Effect Of Strain Rate On Mechaniacal Behavior Of The Steel, Understanding About Their Response In Dynamic Loading Conditions Is Limited. Therefore The Aim Of This Investigation Is To Study The Deformation Behaviour Of C-Mn440 Steel At Different Strain Rates. The Test Matrix Has Been Chosen In Such A Manner That It Can Reflect The Actual Loading Conditions During Their Utilization. It Is Also Known That The Micromechanism Of Ductile Fracture Involves The Initiation, Growth And Coalescence Of Microvoids [2]. Voids Initiate From Inclusions, Precipitates, Secondphase Particles, Etc., In The Metallic Matrix And Grow Under The Influence Of Hydrostatic Stress And Plastic Strain [2,3]. The Void Formation Characteristics Has Been Studied Regorously At Various Levels Of True Strains Under The Investigated Strain Rates. In The Present Investigation, Attempts Have Been Made To Study The Effect Of Strain Rate On The Tensile Behaviour Of C-Mn440 Steel, Its Role In Void Formation On Tensile Straining At Strain Rates Ranging Between 0.0001 And 0.1 S^{-1}, And Quantitatively Correlate Fracture Features (Through Dimple Number Density) With Strain Rate Dependent Tensile Properties.

II. EXEPRIMENTAL

The Steel Was Available In The Form Of Thin Sheet Having Thickness Of 1.65 Mm. Chemical Composition Of The Investigated Steel Was Assessed By Using Optical Emission Spectrometer (Model: ARL 3460 Metals Analyzer, Thermo Electron Corporation Limited, Switzerland). Samples Of Approx. Size 15 Mm×15 Mm Were Mounted Using Copper Powder For Metallographic Study. These Were First Polishing By Silicon Carbide Paper At Different Grades (230-400-600-800-1200-1600-2000), Followed Cloth Polishing By Using Of Alumina And Silicon Colloidal Solution. The Polished Specimens Were Etched With 2% Nital For 10 S .The Microstructural Examinations Were Carried Out With The Help Of Optical Microscope (Model: Olympus BX61, Tokyo, Japan), Which Is Connected To An Image Analyzer. Microhardness Measurements Were Done Using Micro Vickers Hardness Tester (Model: Leco LV 700, USA) With An Indentation Load Of 50gf And Indentation Duration Of 10s.



Appropriate Care Was Taken Duringeach Measurement So That The Distance Between Two Indentations Was At Least Thrice The Diametric Length Of The Indentation.Tensile Tests Of The Investigated Cmn440 Steel Were Performed In A Servo-Hydraulic UTM (Model: INSTRON 8800R). The Samples (Width = 6 Mm) For Tensile Tests Were Prepared Following The ASTM Standard E8M [4]. These Tests Were Done At Various Strain Rates *Viz.* 0.0001, 0.001, 0.01, 0.1 And 1/S At Room Temperature (300K). A 25 Mm Gauge Length Extensometer Was Used To Measure The Strain Directly From The Sample. The Length Of The Specimens Has Been Kept Parallel To The Loading Direction Of The Sheets. All Tests Were Carried Out Under Computer Control Such That A Minimum Of 800 Data Points Are Collected For Constructing The Engineering Stress–Strain Curve Of The Material. Tensile Properties Data Are Tabulated In Table 1.

To Study The Fracture Surface, Specimen Were Cut From The Broken Tensile Specimens. To Investigate The Possible Structural Alternations Tensile Deformed Specimens Were Cut And These Were Subjected To Scanning Electron Microscope Analyses. In This Study, Extensive Investigation Was Carried Out On The Specimen Sub-Surfaces On Planes Along The Specimen Axis And Parallel To The Fracture Surface Using Optical Microscopy For Building A Relationship Between Strain Rate And Void Formation At Sub-Surfaces. In View Of This, Specimens Were Cut After Fracture Using A Slow Speed Cutter. Specimens Were Moulded For The Ease Of Polishing As Schematically Illustrated In Fig. 1. Starting From The Fracture End Of The Specimens, A Large Number Of Fields (I.E. Several Optical Images) Were Sequentially Viewed Under An Optical Light Microscope Along The Lines L_1, L_2, L_3, L_4, L_5 And L_6 As Shown In Fig. 1. The Microstructures Along All These Lines Were Digitally Recorded With A Magnification Of 100×. It Was Found That The Voids Appear Darker (I.E. Black Spot) In The Bright Background Of Ferrite Matrix Under The Optical Microscope. The True Strain Was Estimated By Measuring The Width Of The Specimen At The Specific Transverse Plane And Making Use Of The Relationship: True Strain (ϵ) = $Ln(W_o/W)$[1], Where W_o And W Are The Original/Initial Width And The Width At Selected Transverse Plane Respectively.

III. RESULT AND DISCUSSION

3.1 Chemical Compositions

The Chemical Composition Of The Investigated Carbon Manganese-440 Steel Shows That The Steel Is Having 0.065% Carbon And 1.46% Mn. Manganese Is Added To This Steel To Increase Its Hardenability And Strength. The Steel Also Contains Ni, Cr, Nb And Si Of The Order Of 0.016%, 0.017%, 0.016% And 0.017% Respectively. Nb And Si Also Contribute To Improve The Ultimate Tensile Strength And Yield Strength Values Of The Steel.

3.2 Microstructural Characteristics And Conventional Mechanical Properties

Optical Micrograph Of The As-Received Steel Is Shown In Fig. 2 Which Reveals That The Steel Contain Fully Ferritic Matrix With Polygonal Grains Have Been Taken In Three Orientations R-D And T-D.The Average Grain Size Of Investigated Steel Is Measured Using Linear Intercept Method And Estimated

As16.85±1.70µM And Its Vickers Micro Hardness ($Hv_{0.005}$) Is 254. Have Been Taken In Three Orientations R-D And T-D, Which Are Illustrated In Fig.2.

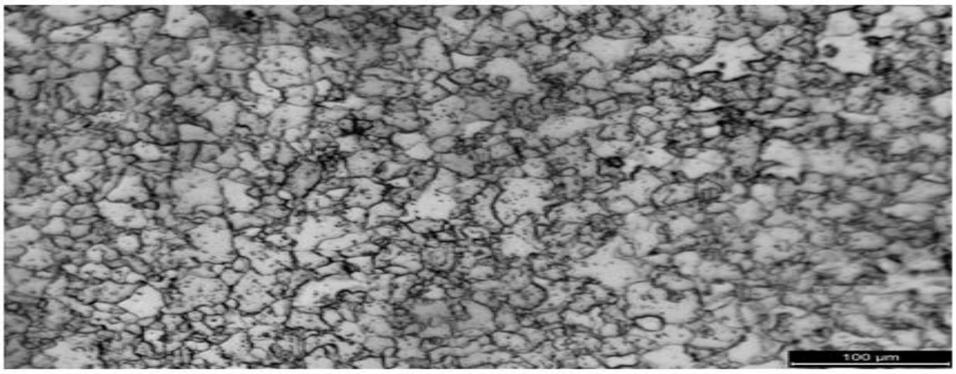


Fig. 2:(a) Microstructure of the as received material

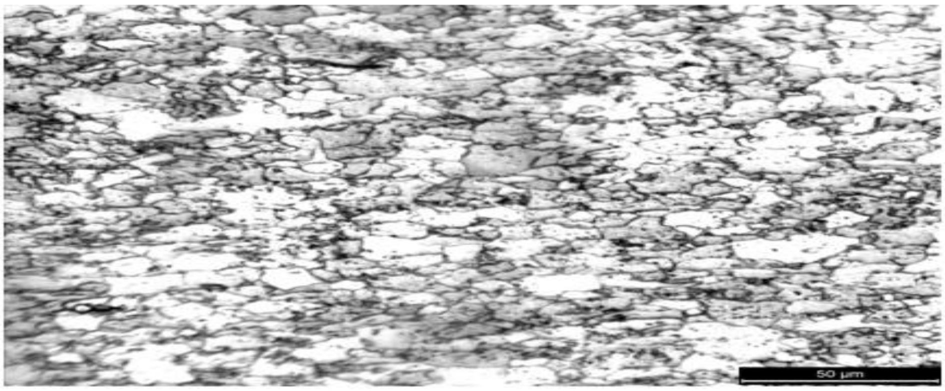
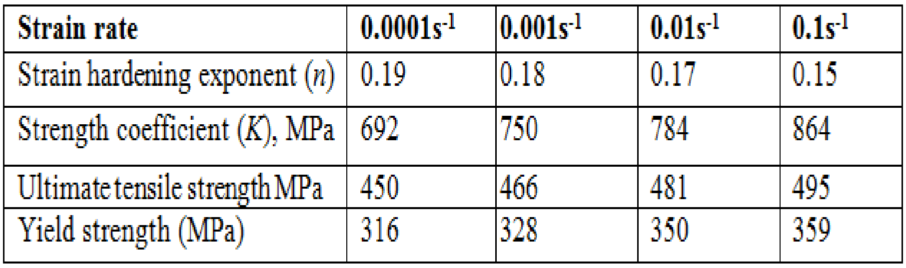


Fig .2(b). Microstructures of the investigated steel in transverse directions

3.3. Tensile Tests Under Varying Strain Rates:

The Tensile Tests Were Carried Out Under Five Different Strain Rates: 0.0001, 0.001, 0.01, 0.1, 1 S^{-1}. Three Specimens Were Tested For Each Condition. The Engineering Stress Vs. Engineering Strain Curves Of C-Mn440 Steel Are Given In Fig. 3(A). It Is Observed That In Line With Natural Expectation For Most Common Metallic Materials, Theflow Stress Increases With Increase In Strain Rate. The Variations In The Magnitudes Of %Uniform Elongation (%UE) And %Total Elongation (%TE) Are Also Shown In Fig. 4 Which Show That Both %UE And %TE Decrease Steadily With Increase In Strain Rate. The Flow Curve Of Metals And Alloys In The Regime Of Uniform Plasticdeformation Can Be Expressed By Various Empirical Relationships Proposed By Hollomon[$\Sigma= K\epsilon^{n}$], Ludwick[$\Sigma=C_1+C_2\epsilon^{c}{}_{3}$], Swift[$\Sigma=C_1(C_2+\epsilon)^{C}{}_{3}$], Hockett[$\Sigma=C_2-(C_2-C_1)Exp(-C.\epsilon^{c}{}_{4})$]Where K Is The Strength Coefficient And N Is The Strain Hardening Exponent And C_1, C_2, C_3, And C_4 Are Modelling Parameters. It Can Be Seen From Fig. 5 That Rather Than Hollomon's Model, All The Above-Mentioned Model Fit Well To Predict The Plastic Flow Behaviour Of The Investigated Steel.

Table 1: Effect Of Strain Rate On Tensile Properties Of The Investigated Steel



Strain rate	$0.0001s^{-1}$	$0.001s^{-1}$	$0.01s^{-1}$	$0.1s^{-1}$
Strain hardening exponent (n)	0.19	0.18	0.17	0.15
Strength coefficient (K), MPa	692	750	784	864
Ultimate tensile strength MPa	450	466	481	495
Yield strength (MPa)	316	328	350	359

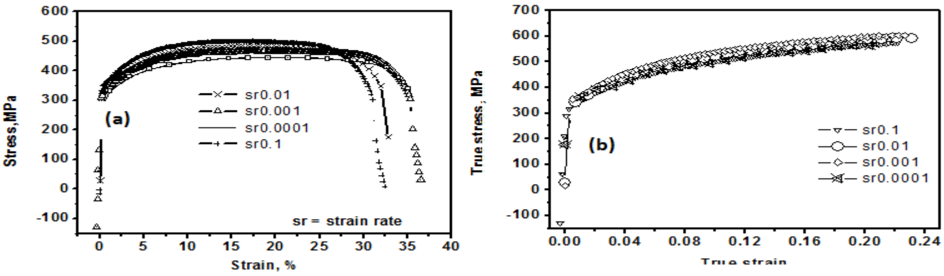


Fig. 3:(a) Engineering stress – engineering strain diagram and (b) true stress – true strain diagram.

It Is Found That *N* Strongly Depends Upon Strain Rate. As Shown In Table 1, *N* Decreases With Increasing Strain Rate.

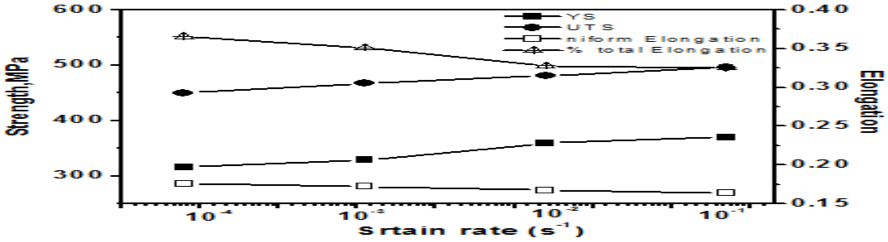


Fig.4. Effect of strain rate on strength and elongation

The Increase In Flow Stress With Increase In Strain Rate Can Be Rationalized From The Viewpoint Of Dislocation Activity During The Process Of Plastic Deformation. The Initial Dislocation Density And Dislocation Configurations Were Constant, Fixed By The Processing Condition Of The Thin Sheet From Which The Tensile Specimens Have Been Fabricated. The Increase In Flow Stress With Increase In Strain Rate Is Governed By The Equation: $\epsilon' = B\rho V$where, B Is The Burger's Vector, ρ Is The Mobile Dislocation Density And V Is The Average Dislocation Velocity [1]. To Maintain The Higher Imposed SR, V Needs To Be Increased With Simultaneous Increase In Flow Stress According To The Relationship: $V=A\sigma^{m'}$ [1].

Xiong Et Al. Have Reported That Yield Strength And Ultimate Tensile Strength Increase In TWIP Steel While Elongation Decreases With Strain Rate [5, 6]. Similar Phenomenon Can Also Be Observed For The Investigated Steel.

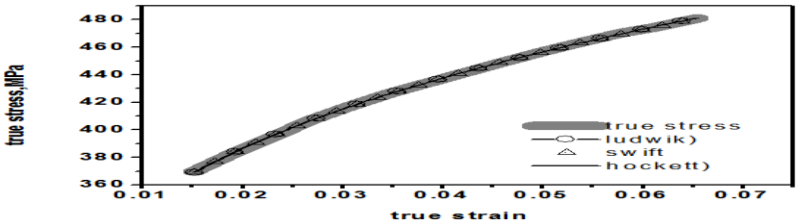


Fig.5. Ludwick, Swift and Hockett fit curves for the investigated material.

3.4 Void Characterization By Optical Microscopy And Correlation With Tensile Properties:

As Indicated In Section 1, The Micromechanism Of Ductile Fracture Is Usually Associated With Formation Of Voids In The Subsurface Of The Material. In View Of Formation Of Voids And Its Morphology During Tensile Loading Under Varying Strain Rates, Thorough Investigation Was Carried Out On Fractured Tensile Specimens At Several Levels Of True Strains, Using Optical Microscopy. Typical Void Generation Map Is Shown In Fig. 6. The Voids As Appeared In The Micrograph Were Composed Of Elongated Shapes. Fig. 7(A) And 7(B) Represent The Variations In Void Count And Void Density Respectively With True Strain Of The Fractured Tensile Specimens For All The Investigated Strain Rates. It Can Be Observed From Fig. 7(A) That The Rate Of Development Of The Void Population With Strain Is Initially Low, And Then Increases Rapidly With High Strains On Approaching The Fracture Surfaces. For The Same Amount Of True Strain, The Void Density Fraction Was Found To Be Higher For The High Strain Rate Specimen Than For The Low Strain Rate. Also, To Reach The Same Amount Of Void Density Fraction, The Higher Strain Rate Specimen Needs A Lower Amount Of Accumulated True Strain Than The Lower Strain Rate. This Is In Accordance With Some Published Reports On AISI 304LN Stainless Steel [7].

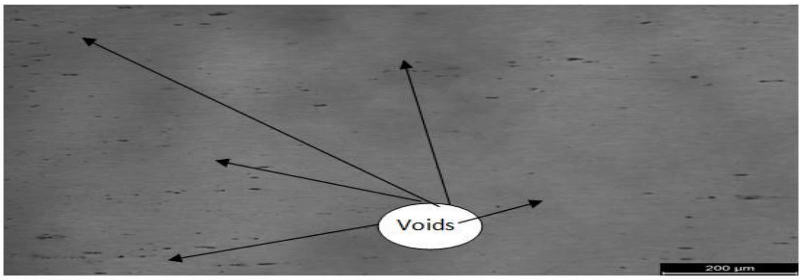


Fig 6.Optical micrograph showing presence of void at sub-surface of fractured tensile specimen don under strain rate0.1s-1

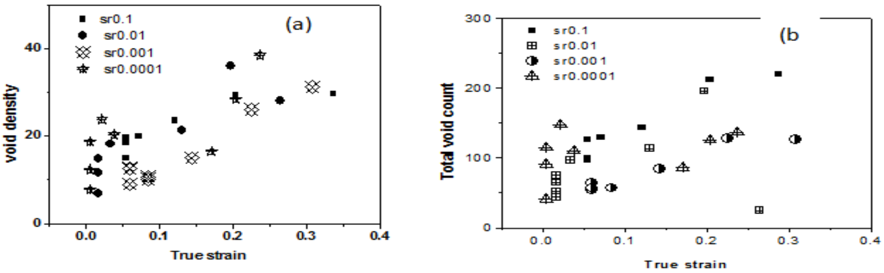


Fig.7. At different strain rate (a) variation of void density with true strain (b) Total void count

Stress State, Voids Grow, Coalesce And Finally Form The Continued Fracture Surfaces With Dimples. The Dimples Show The Evidence Of The Initiation Points At The Particles. Inclusions Play An Important Role In This Failure Process In Many Materials, Even Though They Are Present In A Relatively Small Quantity [8].

3.5Fractographic Analysis For Cmn440 Steel

Analyses Of The Fractographs Obtained From The Fracture Surfaces Of The Four Different Samples Reveal That There Exists Elongated Dimples At The Specimens Belong To Low Strain Rates, But At Higher Strain Rates More Amount Of Equi-Axed Dimples Were Found. Typical Fractographs Are Shown In Figure 8(A) And 8 (B) For The Employed Highest And Lowest Strain Rates Respectively. Typical Metrices Of Coalesced Microvoids On Tensile Fracture Surfaces Have Been Obtained Through Extensive Image Processing Of Representative Fractographs. It Is Observed The Minimum Being At The Lowest Strain Rate (0.0001 S^{-1}). It Has Been Demonstrated Elsewhere [7-9] That Deformation And Fracture Are Influenced, To A Large Extent, By The Same Set Of Factors, Then The Fracture Surface Keeps An Imprint Of The Entire Deformation Process. Figure 8clearly Elucidate That The Mean Size Of The Dimples Constituting The Final Fracture Changes Depending Upon The Strain Rate. It Was Noted That, With Decreasing Strain Rate, Number Of Fine Dimples Becomes Predominant, And With Increasing Strain Rate, The Fine Dimples Is Gradually Replaced By Larger Dimples.

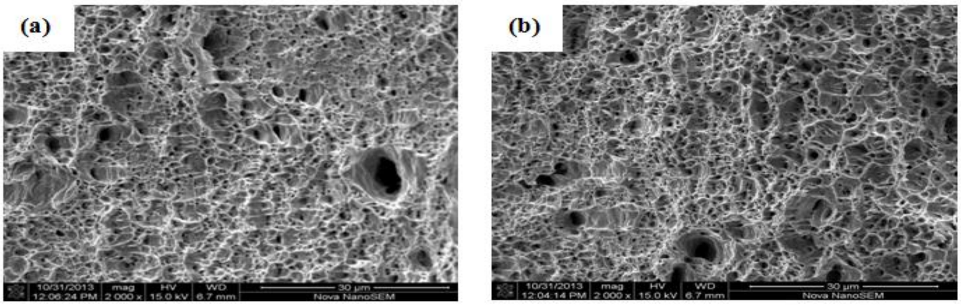


Fig.8. Typical fracture surface obtained from tensile done at strain rate of
(a) strain rate 10-1s-1(b) strain rate 10-4s-1

IV. CONCLUSIONS

The Obtained Results And Their Pertinent Analyses Related To Different Strain Rate Deformation Behavior Of Cmn440 Steel And Its Associated Variations In Property Assist To Infer

- Both Yield Strength (YS) And Ultimate Tensile Strength (UTS) Increase When Experiments Are Conducted Under Increasing Strain Rate. On The Other Hand, % Uniform Elongation And % Total

Elongation Decrease With Increasing Strain Rate, As Expected. It Has Been Observed That Parameters Like Strain Hardening Exponent (N), Strength Coefficient (K) Increase With Strain Rate; These Have Been Obtained Using Empirical Equations By Ludwik, Swift And Hockett. It May Be Mentioned That Hollomon Equation Remains Unfit To Represent The Plasticity Region Of All The True Stress-True Strain Curves.

- Fractographic Investigation Reveals Typical Ductile Fracture Characteristics Associated With Dimples Of Bimodal Size Distribution. A Comparative Assessment Of Dimple Geometry On The Fracture Surfaces Clearly Reveals That With The Increase In Strain Rate, Average Dimple Diameter Increases And Dimple Density Decreases And *Vice Versa*.
- The Void Accumulation (I.E., Void Density) In The Subsurface Of The Material (Near The Fracture Surface) Increases With The Increase In True Strain For All Strain Rates. At The Initial Stage Of Strain, Void Density Increases Slowly And At The Later Stage, Void Density Increases Rapidly

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