1. Introduction

Nickel free high nitrogen austenitic stainless steels with a base composition around 18%Cr–18%Mn and varying in C and N contents and processing conditions were evaluated for their mechanical behaviour. A range of mechanical properties from high strengths to ultra high strength levels could be obtained. The steels develop ultra high strength levels in the as-hot worked condition, hot work + cold work condition and solution treated + cold worked conditions. They show high strength levels with very good ductility and impact toughness levels in the solution annealed condition. The Hall–Petch parameters and DBTT obtained in the solution annealed condition were found to be influenced by the carbon content of the steel. The work hardening behaviour of the steels have been examined at various processing conditions. Nitrogen steels with high carbon content show good mechanical properties in the solution treated and subsequently cold rolled conditions. In the as-formed condition, the high carbon steels show inferior ductility due to grain boundary lamellar nitride precipitation.

Literature shows that predominantly low carbon varieties of these steels are evaluated in solution treated and subsequently cold rolled condition. The use of higher carbon containing nitrogen steels is expected to reduce the raw material and processing costs. This study investigates the effect of higher carbon containing nitrogen steels and mechanical processing conditions on properties of a base 18 wt%Cr–18 wt%Mn steel.

2. Experimental

A series of steel composition, prepared by air induction melting followed by conventional electroslag remelting technique, used for this investigation, is shown in Table 1. They were processed as per schematic shown in Fig. 1. Steels other than 2/1, were forged to 30 mm × 110 mm cross section slabs at temperature between 1100 and 1050°C in a one ton press. After finish forging at 1050°C, the steels were cooled in the ambient atmosphere. Steels M2, M3, M4 and M8, were evaluated in the forged and solution annealed condition. These steels were subsequently hot rolled at 1100°C to a finish rolling temperature around 1050°C, to get 6 mm thick sheet (73% thickness reduction). The sheets after rolling were cooled to room temperature in ambient atmosphere. The hot rolled sheets were further reduced in thickness by 40% by a subsequent cold rolling to 2.4 mm thickness. A part of the hot rolled sheet was subjected to solution annealing and were cold rolled to 40% thickness
reduction to get a thickness of 2.4 mm. Steels M2, M3 and M4 were cold rolled to intermittent thickness reductions as well. Samples from the 40% cold rolled 2.4 mm thick sheet steels 5/1, 5/2, 3/1, M4, M8 were solution treated at varying temperature and time to study the effect of grain size. Steel ingot 2/1, was hot forged to 25\(\times\)25 mm cross section bar (96% reduction in cross-section) at 1100 to 1050°C and evaluated for mechanical properties in the as forged and solution treated conditions only. Portions of solution annealed steels M2 and M3, were heated to 600°C for 1 h and were subjected to 40% thickness reduction by rolling in the warm condition followed by cooling in ambient atmosphere. The rolls were at room temperature. A part of the warm rolled steels, were further cold rolled to 10% thickness reduction.

The steels in all the above conditions were evaluated for room temperature tensile properties using an Instron machine (model 1185) with a maximum load 100 kN. Samples as per Fig. 2(a) were tested at a strain rate of 8.74\(\times\)10\(^{-4}\) for evaluation of Hall–Petch relation in rolled and solution treated samples. All samples in forged and subsequently in solution treated conditions conformed to Fig. 2(b) and were tested at a strain rate of 1.31\(\times\)10\(^{-3}\). The same type of sample was used for studying strain rate variation tensile properties of solution treated steel 5/2.

Impact testing of steels M2, M3 and 2/1 were carried out using the unit supplied by Tinius Olsen with maximum toughness values measurement of 30 kg-m, using standard Charpy V-notch specimen as per Fig. 2(d). The DBTT were examined in steels M2, M3 and 2/1. A cryostat with toluene media, was used for achieving temperature up to \(-90°C\) and liquid nitrogen was used for a temperature up to \(-196°C\).

The fractography of the broken tensile and impact tested samples at various conditions were analysed using a ISI-100A Scanning Electron Microscope unit.

3. Results and Discussion

The microstructures corresponding to the various processing conditions presented earlier\(^{17}\) can be referred to the properties presented here.

3.1. As-hot Formed Condition

The mechanical properties evaluated in this condition, in general, show ultra high strength levels as shown in Table 2, due to the highly deformed and strained grain structure that prevailed, after hot rolling followed by cooling to room temperature in ambient conditions. The microstructures of the low carbon steels\(^{17}\), corresponded close to those reported by Efimenko et al.\(^{18}\) and Andreev et al.\(^{14}\) The highly strained matrix and inadequate time to completely recrystallise the grains have contributed to the prevalence of high defect structure in the matrix resulting in ultra high strengths levels. Steels M2 and M3, with low alloying element contents showed significant ductility at ultra high strength levels. The ductility values of higher carbon steels M4 and M8 are significantly lowered, due to the formation of lamellar precipitates that formed during cooling the hot rolled steels\(^{17}\). The precipitation of lamellar nitrides in high carbon steels M4 and M8 was confirmed by mi-
croscopy and XRD studies.\(^\text{17}\) Though, the steel 3/1 had significant C content, along with high nitrogen, there was no precipitation of any kind detected in the XRD analysis. This contradicts the data of Ikegami \textit{et al}.\(^\text{16}\), according to whom grain boundary and lamellar carbides should precipitate. The steels studied by Ikegami had 2% Mo, 0.2% V which are strong carbide formers and 2 to 4% Ni. The presence of Ni in those steels could enhance formation of lamellar precipitates, due to positive interaction between Ni and N. The high carbon steel 2/1, evaluated in the as-hot forged condition, showed lamellar nitride precipitates in isolated regions\(^\text{17}\) and the mechanical properties exhibited lower ductility than in the solution annealed condition.

It is found that the tensile and yield strength increases with nitrogen content at almost similar rate in steels with about 0.1% C as shown in Fig. 3. The microstructure of all steels in this condition, showed precipitate free deformed austenite grain structure. With increasing carbon content and at about 0.8% N, the strength decreases as shown in Fig. 4, due to the formation of lamellar precipitate.\(^\text{17}\) The fall in yield strength is more pronounced. Though, lamellar precipitate was observed by Ikegami \textit{et al}. They reported that carbon has little effect on yield strength of the as-forged steels.\(^\text{16}\) However, the present study shows that carbon decreases strength due to lamellar nitride precipitate formation\(^\text{17}\) in accordance with earlier studies.\(^\text{19}\)

The work hardening behaviour evaluated as per Ludwik equation with strength coefficient \((K_y)\) and work hardening coefficient \((n_1)\) are shown in the Table 2. The \(n_1\) values, in general, were low indicating that the matrix may yield less to further deformation. The \(n_1\) values of steel M2 and M3 are unusually large and their ductility is also comparatively higher. The matrix seems to be amenable for further deformation processing and strengthening. The only difference these steels have with others, is that they have lower total alloying element contents.

The fractography of the low carbon steels showed completely dimple rupture as shown in Fig. 5(a). Some of the steels showed elongated dimples, slip steps within the dimple and serpentine glide, characteristic of a highly ductile steel.\(^\text{20}\) In steels with higher C contents, the fracture was quasi-cleavage type with shallow dimples indicative of poorer plasticity. In some of the high C steels such as M4 and M8, the fracture surfaces showed that fracture occurred along the lamellar precipitates as shown in Fig. 5(b). The high carbon as-forged steel 2/1, showed a quasi- cleavage appearance with non-uniform dimples as shown in Fig. 5(c). This forged steel had ductility values better than rolled high carbon steels. The lamellar precipitates were more scattered in steel 2/1 than other rolled high carbon steel.

### 3.2. Hot Rolled+Cold Rolled Condition

The mechanical properties of the steels in this condition shows ultra high strength levels of the order of 1500 to 1700 MPa, with ductility values 4 to 20% as shown in Table 3. Thus, in low carbon steels, solution treatment may not be prerequisite before cold rolling to attain ultra high strength levels. The high carbon steels (>0.22% C) could not be cold worked further without crack development in the material. This may be attributed to the formation of lamellar nitride precipitate,\(^\text{17}\) which induced crack nucleation sites during further deformation.

The mechanical properties of the steels, in general, showed a combination of ultra high strength levels with about 20% elongation, when the substitutional solid solu-

| CONDITION SAMPLES | UTS (MPa) | YS (MPa) | %E | %RA | HARDNESS (VHN) | K | n |
|-------------------|-----------|----------|----|-----|----------------|---|---|
| M2                | 1234      | 1128     | 37 | 18  | 446            | 2383| 0.30|
| M3                | 1203      | 1084     | 90 | 48  | 438            | 2628| 0.39|
| M4                | 1518      | 1463     | 3  | 4   | 514            | 1940| 0.04|
| M9                | 1485      | 1402     | 10 | 5   | 465            | 1977| 0.09|
| 1/1               | 1524      | 1477     | 42 | 29  | 520            | 1696| 0.06|
| 3/1               | 1400      | 1365     | 23 | 28  | 467            | 1736| 0.10|
| 5/1               | 1272      | 1220     | 20 | 20  | 444            | 1651| 0.06|
| 5/2               | 1257      | 1198     | 23 | 9   | 478            | 1819| 0.06|
| 2/1 As-Forged LONG| 1418      | 1175     | 17 | 10  | 446            | 1728| 0.06|

Fig. 3. Effect of nitrogen content on the strength in the as hot rolled condition in steels with about 0.1% C content.

Fig. 4. Effect of %C on strength in the as hot rolled condition in steel with about 0.8% N content.
tion in the steels were lesser. This, can be interpreted by comparison of data from steels M2 and M3, whose (Cr, Mn) content was in the range of 36% with those with 38% (Cr, Mn). The higher hardening associated with increased solid solution strengthening perhaps leads to lowering of elongation from 20% to 6%.

The strength levels, when compared with that in the as-hot rolled condition show about 200 MPa increment. The strengthening could be attributed to the slip lines generated within a highly deformed and partially recrystallised grain structure, indicative of high strain hardening of the matrix. The strain hardening coefficient values $n$ are also found to be lower than in the hot rolled condition as shown in Table 3 indicating that the material has limited plasticity for further deformation.

The fractographic features associated with the broken tensile test samples indicates complete ductile failure with very shallow dimples than other conditions as shown in Figs. 6(a)–6(b).

### 3.3 Solution Treated Condition

The mechanical properties of the solution treated steel bars are shown in Table 4 and that of rolled plates are shown in Tables 5(a) and 5(b). It can be seen that all the steels show high strength level (YS>550 MPa) with good ductility (>40%) values. The mechanical properties of the steels in the forged and solution treated bars were close to that of the rolled and solution treated plates as seen from the data for steels M2 and M3 in Table 4 and Table 5(b). Thus, in this condition, both forged and rolled materials were fully recrystallised and were free of precipitates leading to almost similar strength levels. The mechanical properties of forged bars in Table 4 and rolled plates in Table 5(b) exhibits uniform properties in the longitudinal and transverse direction after solution treatment due to their fully recrystallised grain structure. The mechanical properties of the solution treated steel plates with residual carbides in the matrix is shown in Table 5(a).
The presence of such carbides, were attributed to inadequate solution treatment temperature by Hsiao et al.\(^1\) The presence of these carbides enhanced strength moderately (50 to 70 MPa) compared to the carbide free steels shown in Table 5(b). Presence of carbides, however, may not be desirable for good corrosion resistance. It is further observed that by increasing C and N contents in solid solution enables achievement of ultra high strengths (<1000 MPa).

The increase in interstitial \(\%(C+N)\) content in the steel enhances strength as shown in Fig. 7. The lattice parameters of the solution treated steels, is also found to increase with interstitial content as shown in Fig. 8. The increase in interstitial content causes lattice expansion, which eventually resist deformation.\(^6\)\(^1\)\(^9\) The dependence of lattice parameter on yield strength is shown in Fig. 9. It is known that the substitutional solid solution elements in concentrations about 1 to 2% do not affect the lattice parameter similar to the interstitial elements.\(^1\)\(^9\)

The mechanical properties of the steel evaluated at varying solution treatment conditions as a function of grain size are shown in Table 6(a). A series of steel with varying carbon contents have been suitably solution treated to get a range of grain sizes\(^1\)\(^7\) and the Hall–Petch relation obtained. The variation of flow stress with grain size is shown in Fig. 10 and the Hall–Petch equation parameters are shown in Table 6(b). The study was carried out with flow stress because the effect of nitrogen on flow stress was reported to be more pronounced than tensile strength.\(^1\)\(^6\) The grain size dependence on mechanical properties, show that the parameter \(k_y\), in general, has a large value than conventional austenitic stainless steels due to planar dislocation pile-ups and Lomer–Cottrell barriers.\(^7\) It can be observed that the \(k_y\) value decreases with increasing carbon contents in the steels as shown in Fig. 11. This indicates that the material could undergo greater cross slip with increasing carbon contents. The strengthening associated with carbon due to lattice strain in austenite solution is counteracted by carbon contributing to weakening the steel by a decrease in \(k_y\) value in Hall–Petch relationship.

The work hardening characteristics of the steels was in-

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**Table 5(a).** Mechanical properties of hot rolled and solution treated nitrogen steel plates which showed presence of residual carbides.

| STEEL / CONDITION | UTS (MPa) | YS (MPa) | %E | %RA | HARDNESS (VHN) |
|------------------|-----------|----------|----|-----|----------------|
| M2 LONG (1050°C/5 hr) | 878 | 544 | 39 | 34 | 315 |
| M3 LONG (1050°C/5 hr) | 956 | 578 | 69 | 54 | 287 |
| M4 LONG (1150°C/75 hr) | 1135 | 656 | 81 | 49 | 307 |
| M4 TRANS (1150°C/75 hr) | 1157 | 645 | 76 | 43 | 307 |
| M5 LONG (1150°C/75 hr) | 1140 | 633 | 96 | 49 | 278 |
| M6 TRANS (1150°C/75 hr) | 1137 | 697 | 73 | 53 | 278 |

# Residual Cr23C6 type carbides detected in XRD phase analysis.

**Table 5(b).** Mechanical properties of solution treated plates with fully austenitic matrix.

| CONDITION / SAMPLE | UTS (MPa) | YS (MPa) | %E | %RA | HARDNESS (VHN) |
|--------------------|-----------|----------|----|-----|----------------|
| M2 LONG | 876 | 550 | 49 | 42 | 292 |
| M3 LONG | 932 | 521 | 78 | 54 | 277 |
| M4 LONG | 1060 | 709 | 40 | 48 | 295 |
| M5 LONG | 1069 | 646 | 43 | 48 | 288 |
| 1/2 LONG | 985 | 549 | 73 | 48 | 298 |
| 1/4 TRANS | 942 | 515 | 72 | 41 | 298 |
| 1/2 LONG | 955 | 597 | 69 | 44 | 274 |
| 3/4 TRANS | 1095 | 610 | 75 | 39 | 289 |
| 3/4 TRANS | 1072 | 630 | 55 | 29 | 289 |
| 4/4 TRANS | 940 | 557 | 62 | 50 | 291 |
| 1/2 TRANS | 939 | 570 | 73 | 55 | 291 |
| 5/4 TRANS | 961 | 596 | 76 | 58 | 274 |
| 5/4 TRANS | 959 | 593 | 78 | 53 | 274 |
| 5/2 TRANS | 957 | 598 | 61 | 57 | 266 |
| 5/2 TRANS | 987 | 598 | 73 | 48 | 296 |
| 3/2 AS-CAST | 987 | 917 | 9.5 | 12 | 280 |

**Fig. 7.** Influence of interstitial \%\((C+N)\) on yield strength in the solution annealed condition.

**Fig. 8.** Influence of interstitial \%\((C+N)\) on lattice parameter.

**Fig. 9.** Influence of lattice parameter of austenite on yield strength in the solution annealed condition.
vestigated by plotting log(σ) vs. log(ε) plots. A typical plot is shown for one of the steels studied in Fig. 12. It is observed that the steels exhibit a deviation from Ludwik equation at low strains. The data can be correlated using the model developed by Ludwigson,21) where a nickel free high nitrogen austenitic steel was used. At high strains the unmodified Ludwik equation is followed and at low strains there is appreciable deviation. According to this model, the plastic flow was given by the equation,

$$\varepsilon = K_1 \varepsilon_0^{n_1} + K_2 \varepsilon_0^{n_2} \cdot e^\varepsilon$$

A limiting strain value above which unmodified Ludwik equation was valid could be found. The first term in the equation have the same meaning as that in Ludwik equation. The term $\varepsilon_0^{n_1}$ is reported to correspond to proportional limit of the steel. The limiting strain is a value at which the planar glide behaviour decays and transient stage reported to occur in low stacking fault energy (SFE) materials. The term $n_2$ and the limiting strain can be correlated with the stacking fault energy of a material. Largest limiting strain and smallest negative $n_2$ value can be found in materials with lowest stacking fault energy. Since, it is well known that nitrogen decreases the stacking fault energy in a material, a qualitative correlation can be found for the dependence of nitrogen on SFE by analysing the nitrogen influence on parameter $n_2$. The Ludwigson parameters evaluated for the various steels are shown in Table 7. As %N increases, the parameter $n_2$ increases due to lowering of SFE by nitrogen as shown in Fig. 13. Further, it is observed that both $K_1$ and $n_1$, in the solution annealed conditions are higher than in other process conditions with values around 0.4 to 0.6. These high values indicate the ability to further work harden and would benefit fatigue and wear resistance properties of the material.
The fractographic examination in the solution treated condition, show complete dimple fracture at low carbon concentration as shown in Figs. 14(a)–14(b). There are some elongated dimples resembling worm holes, slip steps in the dimple and fine particles within dimple etc. in some of the steels. In high carbon steel 3/1, the fractography showed lot of transverse crack along the stress direction indicative of weak grain boundaries. However, the matrix still showed a complete dimple fracture as shown in Fig. 14(b). In the case of forged and solution treated steel 2/1, the fracture appears quasi cleavage as shown in Fig. 14(c). In general, as the carbon concentration increased, transverse cracks, occasional flaking of the grain indicating weak grain boundary, and unequal dimple sizes were observed.

The effect of strain rate on mechanical properties was studied in low carbon steel 5/1. The mechanical properties evaluated as a function of strain rate is shown in Table 8.

The effect of strain rate on flow strength is shown in Fig. 15. It is found that the flow strength increases significantly with strain rate. The specimen at room temperature did not show any kind of Jerky or serrated flow indicating that there was no dynamic strain aging at room temperature testing.

Unlike the conventional stainless steels, these steels exhibit ductile to brittle transition with temperature. This has been attributed to the increase in elastic modulus caused by increasing nitrogen content, which eventually increases cleavage stress more than plastic flow stress. Charpy V-notch impact testing was carried out in three steels M2, M3 and 2/1, which were processed as bars. The results are shown in Fig. 16. During room temperature testing, low carbon steels M2 and M3 did not break indicating very high toughness levels. The high carbon steel 2/1, showed a lower toughness value at room temperature.

Table 7. Ludwigsen model parameters as a measure of work hardening characteristics in the solution treated steels.

| Steel | K1    | n1   | K2    | n2   | sL  |
|-------|-------|------|-------|------|-----|
| M2    | 2022.97 | 0.6594 | 6.1466 | -7.412 | 0.2248 |
| M3    | 2073.43 | 0.4032 | 5.919  | -37.558 | 0.0658 |
| M4    | 2759.31 | 0.5687 | 6.3554 | -11.230 | 0.1769 |
| M5    | 3855.35 | 0.5761 | 6.3123 | -10.471 | 0.1844 |
| 1/1   | 2209.07 | 0.5910 | 6.1133 | -7.529 | 0.2217 |
| 1/2   | 2030.20 | 0.3652 | 6.0759 | -24.496 | 0.1215 |
| 3/1   | 2459.01 | 0.4558 | 6.1762 | -17.738 | 0.1422 |
| 4/1   | 2062.10 | 0.4626 | 6.9777 | -15.437 | 0.1511 |
| 5/1   | 2132.34 | 0.4906 | 6.0982 | -16.440 | 0.1482 |
| 5/2   | 2325.41 | 0.5402 | 6.1980 | -12.276 | 0.1710 |

Fig. 13. Influence of %N on Ludwigsen parameter n2 in steels with ~0.1% C.

Fig. 14. Fractographs of tensile tested samples.
(a) Rolled and solution annealed steel Mn(0.12% C).
(b) Rolled and solution annealed steel 3/1(0.33% C).
(c) Forged and solution annealed steel 2/1(0.62% C).

Table 8. Effect of strain rate on room temperature mechanical property of solution treated steel 5/2.

| STRAIN RATE (Sec^-1) | UTS (MPa) | YS (MPa) | %E | %RA |
|----------------------|-----------|----------|----|-----|
| 0.00665e-17          | 889       | 617      | 65 | 63  |
| 0.001312             | 846       | 734      | 52 | 50  |
| 0.01312              | 861       | 753      | 52 | 49  |
| 0.09057              | 840       | 813      | 39 | 47  |
| 0.13123              | 852       | 812      | 35 | 42  |
| 0.65617              | 950       | 873      | 57 | 42  |

Fig. 15. Effect of strain rate on room temperature strength of steel 5/2.
However, both the steels showed DBTT at lower temperatures. The DBTT values for steels M2 and M3 are 200 and 155 K respectively. The high carbon steel 2/1 had lower toughness at room temperature and it shows a DBTT value of 255 K. Thus, increasing carbon in these steel in the solution annealed condition increases DBTT. It is difficult to predict without additional studies, whether carbon has similar influence on cleavage stress as does nitrogen. Typical fractographic features of the broken impact tested samples is shown Figs. 17(a)–17(c). It can be observed that dimples are extremely shallow and cleavage facets predominated. Higher carbon contents and decreasing temperatures seem to promote more cleavage facets. The fractography in the present study, shows more facets in the cleaved region unlike plain featureless cleavage fracture reported earlier.\textsuperscript{(1)}

3.4. Solution Treated+Cold Rolled Condition

The room temperature mechanical properties in the cold rolled condition showed ultra high strength levels as shown
Table 9. Mechanical properties in the solution treated and subsequently cold rolled steel plates.

| SAMPLE/DEGREE COLD ROLLING | UTS (MPa) | YS (MPa) | %E | %RA | HARDNESS (VHN) | K | n |
|-----------------------------|-----------|----------|----|-----|----------------|---|---|
| M2 (29% CR)                | 1189      | 1115     | 25 | 38  | 406            | 1912 | 0.14 |
| M2 (40% CR)                | 1470      | 1448     | 4  | 21  | 2485           | 862  | 0.03 |
| M3 (13% CR)                | 1098      | 1014     | 41 | 57  | 385            | 1345 | 0.05 |
| M3 (40% CR)                | 1468      | 1438     | 8  | 26  | 455            | 834  | 0.02 |
| M4 (20% CR)                | 1336      | 1118     | 28 | 41  | 440            | 2475 | 0.25 |
| M4 (25% CR)                | 1468      | 1300     | 19 | 46  | 425            | 1600 | 0.08 |
| M4 (33% CR)                | 1626      | 1593     | 10 | 32  | 493            | 1913 | 0.04 |
| M8 (27.5% CR)              | 1522      | 1461     | 20 | 39  | 492            | 2062 | 0.16 |
| M8 (40% CR)                | 1857      | 1785     | 7  | 30  | 540            | 1890 | 0.03 |
| 1/1 (40% CR)               | 1700      | 1569     | 9  | 30  | 490            | 1857 | 0.02 |
| 1/2 (40% CR)               | 1654      | 1537     | 10 | 32  | 499            | 2202 | 0.06 |
| 3/1 (24% CR)               | 1481      | 1353     | 19 | 33  | 573            | 2255 | 0.12 |
| 4/1 (40% CR)               | 1581      | 1470     | 19 | 36  | 467            | 1979 | 0.03 |
| 5/1 (40% CR)               | 1908      | 1439     | 12 | 30  | 502            | 2096 | 0.05 |
| 5/2 (40% CR)               | 1602      | 1386     | 19 | 29  | 471            | 1979 | 0.05 |

Fig. 18. Influence of % cold rolling on mechanical properties of solution annealed steels M2, M3, M4 and M8.

in Table 9. Most steels were cold rolled to 40%, while steels M2, M3 and M4 were rolled at intermittent reductions as well. It is found from Fig. 18, that with increasing deformation, strength increases, ductility decreases and the difference between the ultimate tensile strength and yield strength narrows. The microstructure of the steel in this condition showed slip steps within the grain.17) The lattice parameter measurements showed a slightly reduced lattice parameter value than that in the fully solution treated condition. The phase analysis by XRD further confirmed the presence of a single austenite phase and complete absence of additional peaks for strain induced martensite formation in all steels.

In the case of steels with 38% (Cr+Mn) steels, the strength after 40% cold rolling shows that the interstitial (%(C+N) enhances strength as shown in Fig. 19. However, the effect of nitrogen alone on strength shows a moderate fall as shown in Fig. 20, although literature predicts that the strengthening due to nitrogen is more effective.15) Thus, carbon seems to have an influence over strengthening the steel in the cold rolled condition than nitrogen.

The work hardening behaviour shows that n1 values were similar to those the as-deformed condition and lower than in the solution treated condition. It further decreased with increasing deformation.

Typical fractographs on cold rolled steels showed completely dimple rupture in low carbon steel compared to the

Fig. 19. Effect of %(C+N) on strength of 40% cold rolled steels.

Fig. 20. Effect of %N on yield strength in ~0.1% C steels in the solution treated +40% cold rolled condition.

Fig. 21. Fractographs of tensile samples in solution treated+cold rolled condition.
(a) low carbon steel, 1/1. (b) high carbon steel, 3/1.
formation of transverse cracks in high carbon steels as shown in Figs. 21(a)–21(b). The weakening of grain boundaries due to higher carbon in the steels could be observed.

3.5. Warm Rolled Conditions

The mechanical properties of low carbon steels M2 and M3 warm rolled after prior heating at 600°C/1 hr condition show poorer ductility as shown in Table 10(a). The properties after further cold roll reduction also exhibits poorer properties in terms of ductility as shown in Table 10(b). This may be attributed to the weakening of the grain boundary due to carbide precipitation.17

4. Conclusions

The room temperature mechanical properties at various mechanical processing and thermal treatment conditions have been evaluated on a 18wt%Mn–18wt%Cr base steel with significantly varying carbon and nitrogen contents. Increase in C and N enhances strength from high strength to ultra high strength range in solution treated condition. Ultra high strength levels are achieved in the as-hot rolled, hot rolled+cold rolled and solution treated+cold rolled conditions. The steel exhibits detrimental mechanical properties on warm rolling at 600°C. In the solution treated condition, the steel exhibits DBTT, which was found to be a function of C content as well. The Hall–Petch constant $k_y$ decreased with carbon content. The fractography of low carbon steels in general show dimple fracture while the higher carbon steels show mixed mode fracture with transverse cracks indicating grain boundary weakness. The high carbon, nitrogen steel may find use at room temperature in the solution annealed and subsequently cold rolled conditions, while the other conditions show poorer ductility values associated with lamellar precipitates.

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