CHAPTER - X

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High Strength Steels and Their Applications
(A BRIEF REVIEW)

U. C. Patra
and
K. Bishoyi

Steels having a higher strength than those in general use irrespective of application have been termed as high strength steels. For a pretty long time plain carbon steels with a yield strength around 20 to 25 Kg/mm² were standard for almost all structural applications. A significant advance has been made, particularly in advanced countries about 30 years ago and a new family of steels termed as High Strength Low Alloy steels, with a yield strength of more than 30 Kg/mm² have emerged. In the recent years, with the process of development, much research has been made to improve the strength properties. Structure and property correlations have been well understood based on which steels with still higher strength have been developed classified as 'super strength' steels and 'ultra high strength' steels.

The designers have taken immediate advantage of this development and have tried to utilise this new family of steels in all structural applications to the maximum possible extent. This has led to more sound design with better reliability and considerable saving of weight. The steel industry has respected and responded to the demands made by the designers and has directed their resources in producing steels of the high strength group. Some companies, in fact, have entirely reoriented their production schedule and totally changed over to production of high and ultra high strength steels. Various national and international specifications including steels of patented grades have been developed to standardise the product of different industries.

In India, although, high strength steels were being produced by M/s. TISCO as 1950s and high strength low alloy steels by steel plants in the public sector like Rourkela Steel Plant for the last 10 years, no nationally accepted standards are available till today. This is partly because of the high demand for conventional structural steels by the users and partly due to the eagerness by a few privileged users to import whatever requirements of high strength steels. Lack of adequate technical facilities for production of super strength and ultra high strength steels and also in the fabrication technology of such steels have been a hindrance for.

Outlined below is a brief review of the types of high strength steels that are being commercially produced, their basis of development and end use:

The authors are with Steel Authority of India Ltd. R.S.P., Rourkela.
Types of high strength steels:

Based on the quantity and number of alloying elements added and the nature of the structures developed, high strength steels can be divided into the following sub-groups.

1. Niobium or vanadium bearing high strength low alloy steels.
2. Low manganese-vanadium-titanium bearing high strength low alloy steels.
3. Manganese and manganese-copper bearing high strength low alloy steels.
4. Manganese-vanadium-copper bearing high strength low alloy steels.
5. Copper-chromium-vanadium bearing high strength low alloy steels.
7. Precipitation hardening type high strength steels.
8. Supper strength structural steels.
9. Ultra high strength constructional steels
10. Abrasion resistant high strength steels.

1. Niobium or vanadium bearing HSLA steels:

These steels belong to a group which are conventionally known as HSLA steels. These are mainly of low carbon group with a carbon limit up to 0.30% but may be as low as .08%. Manganese is not normally considered as an alloying element in these type of steels, although, it is added to a maximum extent of 1.7%. Such steels are mainly of the silicon killed type with aluminium added for grain refinement and improvement of toughness properties. Niobium and vanadium are added from a very low percentage to as high as .05% Niobium and .15% vanadium. Some organisations deliberately add nitrogen to take advantage of nitride and carbonitride precipitates. These steels are sold in the market with yield strength from 30 to 50 Kg. per mm² and tensile strength ranging from 45 to 70 Kg/mm², with or without stipulation of toughness properties but with guaranteed weldability. The strengthening effect of these steels are due to one or more of the following mechanisms:
   a) Grain refinement
   b) Solution strengthening
   c) Precipitation hardening
   d) Dislocation hardening.

Grain refinement, solution strengthening and precipitation hardening are achieved through micro-alloying additions control of rolling temperatures and normalising treatment; whereas, the dislocation hardening is achieved principally by microalloying and control rolling. Some of the popular steels available in Indian market to-day are those produced by Rourkela Steel Plant under the brand name ‘Roustal’ group and those produced by M/s. TISCO under ‘LA’ group.

The principal uses of these steels consist of applications demanding weight saving, good weldability, for Transport vehicles, bridges, structural members, cranes and crane girders etc.

2. Low Manganese-Vanadium-Titanium bearing steels:

These steels also belong to the HSLA group but specific steels have as their principal features low carbon-manganese, (lower than those used in conventional...
HSLA steels), titanium in the order of 0.1% and vanadium in the order of 0.05% or a combination of two. The steels are either killed with silicon or with aluminium. Sometimes silicon is added to the extent of 0.5% for the purpose of strengthening. Zirconium and nitrogen are sometime added up to a maximum extent of 0.12% and 0.03% respectively. The strength range of these steels is similar to those of conventional HSLA steels, but they have superior formability and are available under the brand name Hyform, Maxiform, Ultraform, Superform etc.

Typical uses of these steels consist of automobile chassis members, frame and structures needing critical forming operations etc.

3. Manganese and Manganese-copper bearing steels:

Manganese bearing high strength steels are generally produced with a carbon content around 0.20% and manganese around 1.0% in quenched and tempered or in normalised condition. Strength changes obtained in these categories of steels are similar to those of HSLA steels. Nickel, Chromium, Molybdenum and Boron are sometime added in low percentages (in the order of 0.25% nickel or copper and 0.08% molybdenum and 0.001% boron) for improvement of hardenability.

Manganese-copper bearing steels contain a minimum amount of 0.2% copper which guarantee a minimum yield strength of 35 Kg/mm². Carbon and manganese, however, are kept on the higher side, carbon in the order of 0.25% and manganese in the order of 1.30%. These steels posses good atmospheric corrosion resistance. Costly alloying elements like niobium, vanadium and titanium can be dispensed with in such steels. The strength properties are achieved by transformation hardening and precipitation hardening mechanisms.

Manganese and Manganese-copper bearing steels are used in mining and earth moving equipment, hooks and shackles for marine blocks and tackle, coal conveyors, dump truck liner plates, ore chutes, shoes for cutting and turning soil etc.

4. Manganese-vanadium-copper bearing steels:

These steels have been specially developed to posses very good atmospheric corrosion resistance (corrosion resistance of this steel being approximately twice that of structural carbon steels), the composition range is similar to those of group 3 but with a minimum vanadium content of about 0.02%. The strength achieved by these steels is mainly due to precipitation of V (CN) and Eta Phase of copper.

American specification ASTM A 441 covers high strength low alloy structural steel shapes, plates and bars for welded, rivetted or bolted construction, intended primarily for use in welded bridges and buildings where saving in weight or increased durability are important. Leading manufacturers like M/s. TISCO in India have been marketing these steels since many years.
5. Copper-chromium-vanadium bearing steels:

These steels are produced with varying copper (as high as 1.25%) and chromium from 0.10% to 0.80%. Vanadium is added in small quantities with a maximum limit of 0.10%. Silicon is added up to the tune of 0.6 to 0.7% for improving strength. These steels possess excellent corrosion resistance (about 4 to 6 times that of plain carbon structural steels). The properties are achieved by normalising in certain cases and by quenching and tempering in others. During stress relief annealing the steel gets precipitation hardened and the tensile strength increases, which is an advantage for welded structures undergoing post weld heat treatment. Zirconium and titanium are some times added for inclusion shape control and for better formability of such steels.

These steels are generally used for automobile applications, structural members in a corrosive atmosphere etc.

6. Nickel-copper and phosphorus bearing steels:

Corten is one of the popular corrosion resistance steels belonging to this group, having a composition of carbon about 0.12%, Manganese 0.20 to 0.50%, phosphorus 0.07% to 0.15%, silicon 0.25 to 0.75%, copper 0.25 to 0.65%, nickel 0.65% and chromium 0.30-1.25%. These steels have been principally designed for enhanced atmospheric corrosion resistance combined with high strength. Steels possessing similar properties, but with different composition have also been developed at RSP under the trade name Roucor—A and Roucor—B. Although these steels develop strength on account of solution hardening, these can also be precipitation hardening.

The main advantage of these steels is that, they can be used in bare condition without any protective coating or painting. The tightly adherent oxide coating that forms on the steel, gives self protection and hence these are used in the exposed members of buildings, transmission towers etc.

7. Precipitation hardening type steels:

Precipitation hardening high strength steels covers a wide range of steels starting from HSLA steels to bainitic steels, maraging steels and ultra-high strength steels. In earlier days precipitation strengthening was believed to have deleterious effect in lowering impact resistance. Recent developments have combined precipitation hardening with grain refinement by use of niobium, vanadium, titanium, copper and aluminium and hence increased strength with improved toughness. The effectiveness of these elements depends on their solubility in austenite. Austenite formers like manganese and nickel are kept around 1 to 1.5% with copper also in the order of 1 to 1.5% in the low alloy group.

The maraging steels belong to the high alloy group and have got alloy content in the order of 20 to 30% with a yield strength varying from 100 to 220 Kg/mm². Precipitation hardened bainitic steels, in general, have yield strength around 45Kg/mm² in normalised condition which improves by about 5 Kg/mm² when subsequently tempered but without much improvement in tensile strength.
Precipitation hardened steels of ultra-high strength group are generally the products of advanced steel making technology where all types of impurities like sulphur, phosphorus and gases are kept to a minimum. Such steels find their principal application in aerospace industries. Low alloy precipitation hardening steels find their uses in bottom plates for loaders, coal cutting equipments, mine cars, scrapers, skip cars and hoists, rail, cars and truck frames etc.

8. Super strength structural steels:
These are low carbon multi-alloy steels containing nickel, chromium, vanadium, molybdenum, copper, aluminium, titanium, and boron in different proportions. Most of these steels are water hardenable type and also can be oil hardened. Subsequent tempering operations, either single tempering or double tempering impart the required strength and toughness. These steels are weldable and are required to possess high degree of cleanliness, very low level of sulphur, phosphorus and gaseous impurities.

With its existing facilities, Rourkela has developed quenched and tempered steels having the stipulated mechanical properties. The main application of these steels consist of crane parts, bridge members, chutes and conveyor parts, back-up plates dumpers and dozers and other earth moving equipments etc.

9. Ultra-high strength constructional steels:
Most of the ultra high strength constructional steels possess a minimum heat treated tensile strength of 150 Kg/mm².

These are of medium carbon, nickel-chromium - molybdenum - vanadium bearing steels and are produced by quenching, tempering and precipitation hardening methods. High degree of cleanliness and low gaseous impurity is a must for these types of steels.

Applications needing very high strength such as air craft landing gear, military equipments and oil well drilling equipment are the main areas of uses of such steels.

10: Abrasion resistant high strength steels:
Abrasion resistant steels are also from low alloy group with a medium carbon content although, for certain critical applications carbon in the higher ranges are also used. These are all chromium-molybdenum-boron bearing steels (chromium around 1.0%, molybdenum 0.40-0.60% and boron around 0.005%). hardened and tempered to the required hardness, typical of the application, which may vary from 300 to 400 Brinell.

The applications of these steels are limited to the areas where high abrasion resistances are required. Some of the typical applications can be power shovels, floor plates, ore cars and chute liners, dredgers and draw heads etc.

Conclusion:
It is probably correct to conclude that in general, a number of strengthening mechanisms are available for a metallurgist to choose. His skill lies in optimisation of design aspects which consist of a number of contradicting properties, cost and aesthetic appeal. The foregoing developments
TABLE

COMPOSITION, PROPERTIES AND USES OF SOME OF THE BRANDED HIGH STRENGTH STEELS

1. Niobium or Vanadium bearing steels:

<table>
<thead>
<tr>
<th>Brand Name</th>
<th>Composition % (Maximum)</th>
<th>Mechanical Properties</th>
<th>Remarks</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C  Mn  P  S  Si  Cu</td>
<td>V  min  Y.S.  U.T.S.  %E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Armco High Strength C-42 to C-65</td>
<td>.21/ .26</td>
<td>1.35 0.04 0.05 0.30 Opt. .005</td>
<td>— 30/35 42/52 15/20</td>
<td>5 grades; plates and shapes.</td>
</tr>
<tr>
<td>Inland Steel Company INX-42 to 70</td>
<td>.21/ .26</td>
<td>1.35 0.04 0.05 0.30 Opt. .01</td>
<td>— 30/50 42/60 14/20</td>
<td>7 grades; plates and shapes.</td>
</tr>
<tr>
<td>Bethlehem Steel Corp. Cb/V 45 to 65</td>
<td>.22/ .26</td>
<td>1.35/ 0.04 0.05 0.30 Opt. .005</td>
<td>— 30/50 42/52 16/25</td>
<td>5 grades, sheets.</td>
</tr>
<tr>
<td>V-42 to V-65</td>
<td>.22/ .25</td>
<td>1.25/ 0.04 0.05 0.30 Opt. —</td>
<td>0.02 30/45 42/52 15/20</td>
<td>5 grades; plate and shapes.</td>
</tr>
<tr>
<td>Jones and Laughlin Steel Corp. JLX 42 to 70</td>
<td>.22/ .26</td>
<td>1.00/ 0.04 0.05 0.30 Opt. .01</td>
<td>0.01 32/52 40/60 14/25</td>
<td>7 grades</td>
</tr>
<tr>
<td>VAN 50 to 80</td>
<td>.14/ .18</td>
<td>1.25/ 0.03 0.03 0.30/ Opt. .01</td>
<td>.02 35/56 45/68 18/25</td>
<td>4 grades</td>
</tr>
<tr>
<td>Republic X42W to X70W</td>
<td>.21/ .26</td>
<td>1.25/ 0.04 0.05 0.30/ Opt. .01</td>
<td>.01 32/52 45/60 14/25</td>
<td>7 grades</td>
</tr>
<tr>
<td>U. S. Steel</td>
<td>.13/ .26</td>
<td>0.90/ 0.04 0.05 0.10/ Opt. .01</td>
<td>— 32/50 42/60 14/25</td>
<td>14 grades sheets.</td>
</tr>
<tr>
<td>RSP Roustal 30 to 41</td>
<td>.20</td>
<td>1.30 .035 .035 .30 Opt. .03</td>
<td>.04 30 45/67 19/21</td>
<td>3 grades plates &amp; sheets</td>
</tr>
</tbody>
</table>

- Automobile Chassis frames Structures for buildings, bridges etc.
2. Low Manganese-Vanadium-Titanium Bearing Steels:

<table>
<thead>
<tr>
<th>Brand Name</th>
<th>Composition % (Maximum)</th>
<th>Mechanical properties</th>
<th>Remarks</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>Bethlehem Ultraform 50-80</td>
<td>0.12</td>
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<td>0.025</td>
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<td>Jones and Laughlin Super form</td>
<td>0.20</td>
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<td>0.025</td>
<td>0.030</td>
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<tr>
<td>Republic 35</td>
<td>0.12</td>
<td>.75</td>
<td>.04</td>
<td>.05</td>
</tr>
<tr>
<td>Hyform (RSP)</td>
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<td>.03</td>
<td>.03</td>
</tr>
<tr>
<td>42.52T</td>
<td>.17</td>
<td>1.20</td>
<td>.03</td>
<td>.03</td>
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3. Manganese and Manganese Copper bearing steels:

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<th>Brand Name</th>
<th>Composition % (Maximum)</th>
<th>Mechanical properties</th>
<th>Remarks</th>
<th>Uses</th>
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<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>Armco grades.</td>
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<td>.79</td>
<td>.04</td>
<td>.05</td>
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<tr>
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<td>.70</td>
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<td>.05</td>
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<td>Med-Mn.</td>
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<td>.04</td>
<td>.05</td>
</tr>
<tr>
<td>Republic-M</td>
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<td>.04</td>
<td>.05</td>
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<tr>
<td>MAX-Mi-Mang.</td>
<td>.28</td>
<td>1.10</td>
<td>.04</td>
<td>.05</td>
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4. Manganese-vanadium-copper bearing steels :-

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<th>Mechanical properties</th>
<th>Remarks</th>
<th>Uses</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>Armco High</td>
<td>.22</td>
<td>.85/</td>
<td>.04</td>
<td>.05</td>
</tr>
<tr>
<td>Strength B</td>
<td></td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bethelhem</td>
<td>.22</td>
<td>.85/</td>
<td>.04</td>
<td>.05</td>
</tr>
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<td>Steel Corp.</td>
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<td>1.25</td>
<td></td>
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<tr>
<td>Mn-V</td>
<td>.22</td>
<td>.85/</td>
<td>.04</td>
<td>.05</td>
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<td>US Steel</td>
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<td>.05</td>
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<td>Tri-Ten</td>
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<tr>
<td>Republic</td>
<td>.22</td>
<td>.85/</td>
<td>.04</td>
<td>.05</td>
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<tr>
<td>A 441</td>
<td></td>
<td>1.25</td>
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5. Copper-Chromium-Vanadium bearing Steels :-

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<th>Composition % (Maximum)</th>
<th>Mechanical Properties</th>
<th>Remarks</th>
<th>Uses</th>
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<tr>
<td></td>
<td>C</td>
<td>Mn</td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td>Bethelhem</td>
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<td>.75/</td>
<td>.04</td>
<td>.05</td>
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<tr>
<td>Steel Corp.</td>
<td></td>
<td>1.35</td>
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</tr>
<tr>
<td>Mayorri</td>
<td>.20</td>
<td>.75/</td>
<td>.04</td>
<td>.05</td>
</tr>
<tr>
<td>R50 - R60</td>
<td></td>
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<tr>
<td>Luken Steel Co.</td>
<td>.25</td>
<td>1.50</td>
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<td>.05</td>
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<td>42(C)-70(C)</td>
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<td>NAX-High Tensile.</td>
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<td>.90</td>
<td>.025</td>
<td>.03</td>
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<tr>
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<td>.80/</td>
<td>.04</td>
<td>.05</td>
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<tr>
<td>Steelcooly</td>
<td>.22</td>
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<td>50 - 70</td>
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6. Nickel-Copper and phosphorus bearing steels:

<table>
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<th>Brand Name</th>
<th>Composition % (Maximum)</th>
<th>Mechanical Properties</th>
<th>Remarks</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C  Mn  P  S  Si  Cu  Ni Others</td>
<td>Y.S. Kg/mm²  U.T.S. Kg/mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bethlehem Steel</td>
<td>.12 .75 .12 .05 .05 .50 .50 Cr-.40/ 1.00</td>
<td>35 49 18</td>
<td>Exposed members of buildings and transmission towers.</td>
<td></td>
</tr>
<tr>
<td>MayarR(a)</td>
<td>.12 .20/ .07 .05 .25/ .25/.65 Cr-.30/1.25</td>
<td>35 49 19</td>
<td>Medical members of buildings and transmission towers.</td>
<td></td>
</tr>
<tr>
<td>U. S. Steel Corp.</td>
<td>.12 .20/ .07 .05 .25/ .25/ .25 Cr-.35/1.20</td>
<td>35 49 22</td>
<td>Medical members of buildings and transmission towers.</td>
<td></td>
</tr>
<tr>
<td>Cr. Ten A RSP</td>
<td>.50 .15 .75 .55</td>
<td></td>
<td>Medical members of buildings and transmission towers.</td>
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<tr>
<td>Roucor A</td>
<td>.10 .25/ .07 .20/ .25/ .25 Cr-.35/1.20</td>
<td>35 49 22</td>
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<td>Roucor B</td>
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<tr>
<td></td>
<td>.20 1.25 .25/ .25/ .25 Cr-.49/ .70/ .35 V-.02/10</td>
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</tr>
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</table>

7. Precipitation hardening type steels:

<table>
<thead>
<tr>
<th>Brand Name</th>
<th>Composition % (Maximum)</th>
<th>Mechanical properties</th>
<th>Remarks</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C  Mn  P  S  Si  Cu  Mo Others</td>
<td>Y.S. Kg/mm²  U.T.S. Kg/mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Republic Steel Co. 70 - 80</td>
<td>.20 1.0 .04 .04 .15 1.00/ .20/ Ni-1.20/</td>
<td>49/56 63/70 18</td>
<td>2 grades</td>
<td>Bottom plates of loaders coal cutting equipments Mine cars, scrapers, skip cars, truck frames.</td>
</tr>
<tr>
<td>US Steel Corp.</td>
<td>.03 .40/.40/ .035 .04 .20/ 1.00/ Ni-1.20/</td>
<td>52/60 62/63 18</td>
<td>2 grades</td>
<td>Bottom plates of loaders coal cutting equipments Mine cars, scrapers, skip cars, truck frames.</td>
</tr>
</tbody>
</table>
### 8. Super strength structural steels:

<table>
<thead>
<tr>
<th>Brand Name</th>
<th>Composition % (Maximum)</th>
<th>Mechanical properties</th>
<th>Remarks</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
<td>Si</td>
<td>Cr</td>
</tr>
<tr>
<td>NAXTRA-75</td>
<td>.14/</td>
<td>.70/</td>
<td>.50/</td>
<td>.14/</td>
</tr>
<tr>
<td>to 150</td>
<td>.30</td>
<td>.85</td>
<td>.90</td>
<td>.18</td>
</tr>
<tr>
<td>Jolloy grade</td>
<td>.13/</td>
<td>1.00/</td>
<td>.15/</td>
<td>.10/</td>
</tr>
<tr>
<td>1 to 7</td>
<td>.60</td>
<td>1.65</td>
<td>.30</td>
<td>.20</td>
</tr>
<tr>
<td>US Steel Corpn. T-1</td>
<td>.20</td>
<td>1.00</td>
<td>.35</td>
<td>.50</td>
</tr>
<tr>
<td>steel</td>
<td>.20</td>
<td>.60</td>
<td>.40</td>
<td>.15</td>
</tr>
<tr>
<td>RSP Quenched &amp; tempered</td>
<td>.08/</td>
<td>1.20</td>
<td>.35</td>
<td>.15/</td>
</tr>
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</table>

### 9. Ultra - High Strength Construcional steels:

<table>
<thead>
<tr>
<th>Brand Name</th>
<th>Composition % (Maximum)</th>
<th>Mechanical properties</th>
<th>Remarks</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
<td>Si</td>
<td>Cr</td>
</tr>
<tr>
<td>AISI E4340</td>
<td>.38/</td>
<td>.65/</td>
<td>.20/</td>
<td>.70/</td>
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<tr>
<td>AMS 6427 B</td>
<td>.28/</td>
<td>.60/</td>
<td>.20/</td>
<td>.65/</td>
</tr>
<tr>
<td>6428</td>
<td>.33</td>
<td>1.00</td>
<td>.35</td>
<td>1.00</td>
</tr>
<tr>
<td>Tricert</td>
<td>.40/</td>
<td>.65/</td>
<td>1.45/</td>
<td>.70/</td>
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<tr>
<td></td>
<td>.47</td>
<td>.90</td>
<td>1.80</td>
<td>.95</td>
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</tbody>
</table>
# Abrasion resistant High strength steels:

<table>
<thead>
<tr>
<th>Brand Name</th>
<th>Composition % (Maximum)</th>
<th>Hardness</th>
<th>Remarks</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C  Mn  P  S  Si  Cu  Cr  Mo  Others</td>
<td>BHN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bethlem Steel Corpn.</td>
<td>.12/ .40/ .035/ .15/ .80/ .15/ B-.001 005</td>
<td>321/400</td>
<td>16 grades</td>
<td></td>
</tr>
<tr>
<td>XAR-30 (b)</td>
<td>.30  .60  .04  .04  .09  .45/.85  .30  Zr-.05</td>
<td>360</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Steel Corpn.</td>
<td>.10/ .60/ .035 .04  .15/ .15/ .40/ .40/ Ni-.70/1.00</td>
<td>321/360</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-1321-360</td>
<td>.20  1.00  .35  .50  .65  .60  V-.03/.08  B-.000/.006</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Effect of dual phase on the mechanical properties and microstructure of a plain C steel and Nb-bearing HSLA steel

U. C. Patra and R. I. Ganguly

ABSTRACT

The present work aims at determining an optimum treatment by which suitable mechanical properties are obtained in plain C and HSLA steels displaying dual phases.

It is concluded that the enhanced strength properties in the dual phase steels are controlled both by the amount of martensites formed and final ferrite grain size obtained in the structure.

INTRODUCTION

Duel phase steels are a new class of HSLA sheet steels. The structure here consists of about 80-90% soft, ductile polygonal ferrite and rest martensites. There may also be a small amount of pearlites, bainite or/and retained austenite. The Unique properties obtained are:

(a) Continuous yielding behaviour (No Yield point)
(b) Low yield strength
(c) High tensile strength
(d) High work hardening exponent
(e) High uniform and total elongation

The cooling rate should be such that About 5-20% of martensite should be formed and pearlitic transformation is to be avoided.

In view of the attractive mechanical properties and the simplicity in the composition and heat treatment already achieved, the low carbon steels are now receiving greater attention.

In order to control the microstructure, heat treatment parameters are varied. The structure may be obtained by either of the following processes.

(i) Heating above A₃ --- cooling between A₃ and A₁ and then quenching.
(ii) Heating between A₃ and A₁ and then quenching to room temperature.

EXPERIMENTAL

Steel used was of the following composition
C—0.21%, Si—0.20%, Mn—0.55%, P—0.04%, S—0.04% by weight.

Standard tensile samples for Monsanto tensometer were made. They were given the following heat-treating schedules—

A. Austenitised at 950°C (Soaked for 15 minutes)

\[
\begin{array}{ccc}
\text{Cooled to} & 780°C & \downarrow 15 \text{ or } 60 \text{ or } 90 \\
\text{min. hold} & \text{min. hold} & \text{min. hold} \\
\text{Quenched} & \text{Quenched} & \text{Quenched} \\
\text{in brine} & \text{in brine} & \text{in brine}
\end{array}
\]

B. Austenitised at 950°C (for 15 minutes)

\[
\begin{array}{ccc}
\text{Cooled to} & 740°C & \downarrow 15 \text{ mins. or } 60 \text{ mins. or } 90 \text{ mins.} \\
\text{holding} & \text{holding} & \text{holding} \\
\text{Quenched} & \text{Quenched} & \text{Quenched} \\
\text{in brine} & \text{in brine} & \text{in brine}
\end{array}
\]

Experiments were repeated for two other austenitisation temperatures, namely 900°C and 850°C.

After treatment, mechanical properties like Y.S., T.S., % Elongation, % R.A. and hardness values were measured and microstructures are examined.

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Manuscript received at H. O. on 9.11.1982

RESULTS AND DISCUSSION

The mechanical properties obtained are listed as follows:

The steel in the as received condition containing ferrites and pearlitic as rolled structure, possessed mechanical properties as follows:

- Y.S. 576 N/mm², T.S. 667 N/mm², % Elong. 13.5, % R.A. 50%, hardness 212 HV. Most of the strength properties obtained for the dual phase structure were superior in comparison to as received rolled steel.

In order to have a quantitative effect of these variables on properties, a matrix was formed from the experimental Table I and is given below.

<table>
<thead>
<tr>
<th>No.</th>
<th>Aust. temp. °C</th>
<th>Aust. time Mts.</th>
<th>Intermediate temp. where samples were held °C</th>
<th>Intermediate time where sample were held Mts.</th>
<th>Y.S. N/mm²</th>
<th>T.S. N/mm²</th>
<th>% Elongation</th>
<th>%RA</th>
<th>HV</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>850</td>
<td>15</td>
<td>740</td>
<td>15</td>
<td>604</td>
<td>748</td>
<td>14</td>
<td>40</td>
<td>207</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>368</td>
<td>530</td>
<td>17</td>
<td>65</td>
<td>157</td>
</tr>
<tr>
<td>3</td>
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<td></td>
<td>90</td>
<td>348</td>
<td>520</td>
<td>19</td>
<td>63</td>
<td>157</td>
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<td>787</td>
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<tr>
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<td></td>
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<td></td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>780</td>
<td>15</td>
<td>540</td>
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<td>35</td>
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</tr>
<tr>
<td>11</td>
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<td></td>
<td></td>
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<td>776</td>
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<td>230</td>
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<tr>
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<td>950</td>
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<td>686</td>
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<tr>
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<td>740</td>
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</tr>
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<td></td>
<td></td>
<td></td>
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<td>983</td>
<td>9.3</td>
<td>34</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>90</td>
<td>803</td>
<td>842</td>
<td>8.5</td>
<td>34</td>
<td></td>
</tr>
</tbody>
</table>

TABLE I—Mechanical properties for various treatment combination obtained for the steel:
The regression equations obtained from the above matrix are as follows:

\[
Y.S. = 657.5 + 113X_1 + 85X_2 - 47X_3 + 18X_1X_0 + 21X_2X_3 - 53.3X_1X_2X_3 \ldots 1
\]

\[
T.S. = 779.8 + 59.7X_1 + 82.5X_2 - 50.5X_3 \ldots 2
\]

\[
\%\text{Elong.} = 11.54 - 1.913X_1 - 0.46X_2 + 1.08X_3 \ldots 4
\]

\[
\%\text{RA} = 37.0 - 6.62X_1 - 2.63X_2 + 1.12X_3 - 1.62X_1X_2 \ldots 5
\]

Both Y.S. and T.S. increase with temperature of austenitisation and temperature of holding in the intermediate range. The austenitisation temperature in comparison to the intermediate holding temperature, has 1.5 times greater influence on the Y.S. (Eq. 1) where as the holding at the intermediate temperature between A_1 and A_3 has 1.5 times greater influence on T.S. (Eq. 2). One of the objectives of designing the dual phase structure is to have a higher T.S. than Y.S., in other words to have lower Y.S./T.S. ratio. Therefore it will be advisable to use a higher holding temperature (i.e. keeping above 760°C) rather than increase the temperature of austenitisation beyond 900°C. Holding time has much less severe effect compared to holding temperature. In fact it reduces both Y.S. and T.S. if it is increased beyond 1 hour (i.e. above the base level). This is expected since, increasing holding time results more separation of soft phase like ferrite.

Of the three variables employed, austenitisation temperature and holding temperature (between A_1 and A_3) affect Y.S./T.S. ratio (equation 3). Here again, the effect of austenitising temperature is 3.5 times more than that of holding temperature. All these results suggest that to meet the requirement expected out of dual phase, it will be preferable to adjust the variables such that lower Y.S./T.S. ratio is obtained.

The effect of process variables on the ductility properties (i.e. % Elong. and % R.A.) are shown in equations 4 and 5. The effect of individual variable is just the reverse as is seen in the strength equations. Here we find that increasing the austenitisation temperature has the worst effect. Therefore, in order to achieve a good or compromise between the properties

```
TABLE II—Matrix of design of the type 2³ with response obtained for various treatment combination obtained.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y. S. N/mm²</td>
</tr>
<tr>
<td>Aust. temp. °C, X₁ (code value)</td>
<td>Intermediate temp. °C, X₂ (code value)</td>
</tr>
<tr>
<td>950</td>
<td>780</td>
</tr>
<tr>
<td>950</td>
<td>740</td>
</tr>
<tr>
<td>950</td>
<td>740</td>
</tr>
<tr>
<td>950</td>
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<td>950</td>
<td>740</td>
</tr>
<tr>
<td>850</td>
<td>740</td>
</tr>
</tbody>
</table>
```
Effect of dual phase on the mechanical properties and microstructure of a plain C steel and Nb-bearing HSLA steel

of strength, ductility and Y.S./T.S ratio, it is recommended to have an austenitisation temperature of 900°C, holding temperature around 760—780°C and holding time of 1 hour.

Figs. 1 and 2 represent micrographs of the sample, austenitised at 950°C for 15 minutes cooled to 780°C and kept for 15 and 60 minutes respectively and finally quenched in brine. The difference in microstructure lies mainly in the amount of ferrite. Fig. 1 shows martensitic structure with insignificant amount of ferrite whereas Fig. 2 shows presence of an appreciable amount of ferrite and martensite.

Figs. 3 and 4 compare the microstructure for similar situation as before except for a different intermediate holding temperature (740°C). The difference in microstructure can be discussed in the same manner as above. Here two characteristics are revealed:

(i) The amount of ferrite is always more.
(ii) Grain size of ferrite formed is smaller.

Figs. 5 and 6 show the micrographs of steels austenitised at 900°C for 15 minutes, held at 780°C for 15 minutes and 60 minutes and then quenched in brine. The different amount of ferrite and martensite may be observed here again.
Fig. 1 Microstructure of the sample austenitised at 950°C for 15 minutes and intercritically held at 780°C for 15 minutes followed by brine quenching. 100 x

Fig. 2 Microstructure of the sample, austenitised at 950°C for 15 minutes, intercritically held at 740°C for 60 minutes followed by brine quenching. 100 x

Fig. 3 Microstructure of the sample, austenitised at 900°C for 15 minutes, intercritically held at 780°C for 15 minutes followed by brine quenching. 100 x

Fig. 4 Microstructure of the sample, austenitised at 950°C for 15 minutes, intercritically held at 740°C for 60 minutes followed by brine quenching. 100 x

Fig. 5 Microstructure of the sample, austenitised at 900°C for 15 minutes, intercritically held at 780°C for 15 minutes followed by brine quenching. 100 x

Fig. 6 Microstructure of the sample, austenitised at 900°C for 15 minutes, intercritically held at 780°C for 60 minutes, followed by brine quenching. 100 x
Study of the Effect of Process Variables on the Mechanical Properties and Structure in Microalloy Dual Phase Steels

U. C. PATRA, R. I. GANGULLY and K. S. SINGH

ABSTRACT

Studies were made on steels with three different compositions. The mechanical properties and dual phase structures produced in these three categories of steel are compared and their work hardening co-efficients evaluated. Quantitative effects of time and temperature during treatment have been brought out in the form of regression equations. The effect of cooling rates on the microstructure and mechanical properties of the steels has been studied and the micro-structures obtained for various treatment combinations have been examined and compared.

INTRODUCTION

Dual Phase Steels are a new class of high strength low alloy steels characterised by a micro-structure containing a dispersion of about 10-20% of hard martensite phase in a soft ductile ferrite matrix. These are high strength steels possessing good formability and third use in transportation equipment including automobiles can lead to significant saving in fuel and energy consumption. These steels have a number of unique properties like low Y.S./T.S. ratio, high strain hardening co-efficient and high uniform elongation.

Composition of the dual phase steel should be so chosen that the desired microstructure can be easily obtained with some variation of the experimental condition. The microstructure should essentially contain clean polygonal ferrite with martensite containing about 0.3-0.4% C. Adequate hardenability should be ensured by addition of Cr, Mn, and Mo. Manganese, in particular, helps in strengthening the ferrite without affecting the ductility.

The present investigation has been made to evaluate the quantitative effect of intercritical annealing temperature and time on the mechanical properties of three different low alloy steels. The effect of cooling rate after intercritical annealing on the mechanical properties was also studied.

EXPERIMENTAL

Three different grades of steels were chosen for investigation, and these were obtained from the Rourkela Steel Plant. Chemical composition of the steels is given in Table I.

<table>
<thead>
<tr>
<th>Steel No.</th>
<th>%C</th>
<th>%Mn</th>
<th>%Si</th>
<th>%Cr</th>
<th>%V</th>
<th>%Nb</th>
<th>%Ni</th>
<th>%Cu</th>
<th>%P</th>
<th>%S</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.12</td>
<td>1.50</td>
<td>0.60</td>
<td>0.15</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.031</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0.17</td>
<td>1.40</td>
<td>0.12</td>
<td>—</td>
<td>0.036</td>
<td>0.04</td>
<td>—</td>
<td>0.029</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>0.18</td>
<td>0.70</td>
<td>0.46</td>
<td>0.15</td>
<td>—</td>
<td>0.47</td>
<td>0.15</td>
<td>0.029</td>
<td>0.035</td>
<td></td>
</tr>
</tbody>
</table>

Samples for the Charpy and tensile tests were cut from the bulk of the materials. Sheet samples were made in the laboratory rolling mill with intermediate anneal-

U. C. Patra and K. S. Singh are with SAIL, Rourkela Steel Plant, Rourkela, and R. I. Gangully is with REC, Rourkela. Original manuscript received on 25.9.84, revised manuscript received on 1.5.85 and manuscript received at H.O. on 16.8.85.
Initially the soaking temperature was varied from 730 °C to 830 °C at intervals of 20 °C and the soaking time was kept constant. To study the quantitative effect of the intercritical time and temperature of annealing on the mechanical properties of dual phase structure, a few experiments were planned and carried out in the sequence given in Table II. All the samples were quenched in oil after annealing. In the last phase of experiments, the samples from steel-I and steel-II were heat treated at 830 °C for 7 minutes and rapidly cooled in different medium, namely, air, oil and water. This was done to study the effect of cooling rate after annealing on the mechanical properties of the steel.

Tensile testing of round samples was carried out at room temperature in the Monsanto tensometer at very slow strain rate with 12 mm gauge length. The sheet samples were tested in the Instron testing machine. The charpy tests were carried out for a particular heat treatment schedule at room temperature. Metallography samples were cut from broken tensile pieces and then mounted in bakelite. The samples were polished and etched in 2% nital.

RESULTS AND DISCUSSION
Keeping in view the attractive mechanical properties of dual phase steel, different producers have specified different compositions in the range of C: 0.06-0.12%, Mn: 0.9-1.5%, Si: 0.25-2.0%.

Table I indicates the composition of the steels used in the present investigation. The carbon content of 0.12-0.18% is higher in comparison to the carbon content of dual phase steels specified by various manufactures. However, the Mn content, cited in the table is not far off from the specified range though Si content is somewhat lower. Steel-II shows the presence of V and Nb. The role of these elements in the formation of ferrite and austenite during short period of inter critical annealing is not very clear. However, it is believed that V and Nb may act as grain refining elements. These elements increase the hardenability of steel and thus help in suppressing the formation of pearlite. V in particular is believed to reduce the carbon content of ferrite by forming interstitial compound and thus lowers the carbon content of the austenite from which martensite is formed. Steel-III contains Cu and Ni. These elements do not contribution significantly to the formation of dual phase structure during heat treatment of steel. However, they do not have any harmful effect either. To achieve the properties of dual phase steels, the temperature and time of intercritical annealing were adjusted since there is a complex interaction among temperature, time and composition of steel. In the first phase of experiments, the intercritical annealing temperature alone was varied. The time of annealing was kept constant at 5 minutes. It is normally difficult to attain phase equilibria at the production stage when Mn is present. Based and the experimental procedure followed by other investigators and studying the equilibrium and CCT diagram for Mn bearing steel, the heat treatment parameters were decided.

Figs. 1 and 2 show the variation of mechanical properties like yield strength, tensile strength, percentage elongation and reduction in area, and CVN values obtained after being treated at different intercritical annealing temperatures. There is a drop in both yield strength and tensile strength for steel-I and Steel-II with increase in intercritical annealing temperature, but the trend is reversed for Steel-III. Similarly, % elongation, % RA and CVN values show an increase for Steel-I and Steel-II.

It is seen that the strength properties increase with increase in intercritical annealing temperature for Steel-III and so this steel does not offer any advantage as dual phase alloy.

To study the combined effect of time and temperature, a design matrix was set for Steel-I and Steel-II. Since only two variables were considered, a matrix of design was set consisting of only four experiments.
Table II shows the matrix of design with the mechanical properties obtained for Steel-I and Steel-II. By regression analysis of response variables (vide Table II) equations 1 to 6 are obtained.

\[ Y_{ts} = 395.75 - 31.75 x_1 + 24.25 x_2 + 1.25 x_1 x_2 \]  
\[ Y_{ts} = 652.25 - 3.75 x_1 + 13.75 x_2 - 2.75 x_1 x_2 \]  
\[ Y = (Y S / T.S. = 0.606 - 0.0457 x_1 + 0.024 x_2 + 0.005 x_1 x_2 \]  
\[ Y_{% Elong} = 25.5 - 0.5 x_2 + x_1 x_2 \]  
\[ \text{Applied temp. °C} - 800°C \]  
\[ \text{Where, } x_1 = \frac{\text{Interval of time (mts) - 10 mts.}}{30°C} \]  
\[ x_2 = \frac{5 \text{ mts.}}{\text{and Y is the response obtained.}} \]

It is possible to calculate Y.S, T.S., and % Eelong. for Steel-I from the equation by inserting the coded value for \( x_1 \) and \( x_2 \). The coded values for \( x_1 \) and \( x_2 \) are obtained with the help of equations 5 and 6. The validity of the equations are restricted within the range of variation of the variables. Equations 1-4 are obtained for Steel-I.

Equation 1 indicates that, if the temperature of annealing is increased beyond 800°C, Y.S. drops sharply. This is desirable since dual phase steels should have lower yield point. The magnitude of decrease in Y.S. is 31.75 N/mm² for a rise of 30°C above 800°C (ie) 1.058 N/mm² per degree °C rise of temperature.

An increase in the time of intercritical annealing above 10 minutes increases the Y.S. by 24.25 N/mm². The interaction co-efficient (ie co-efficient attached to \( x_1 x_2 \) of equ. 1) is very insignificant and is found to be positive. Thus this equation is linear in nature.
By studying eq. 2 it is observed that like eq. 1, tensile strength is affected in a similar manner. However, the magnitude of the co-efficient of eq. 2 is much less in comparison to that of eq. 1. Here again, and increase in annealing temperature causes lowering of T.S., but the decrement is much less severe.

Annealing beyond 10 minutes increases T.S. It is thus seen that while increasing the annealing temperature beyond 800 °C causes faster decrement of Y.S., the T.S. decreases at much slower rate and hence causes higher T.S. to Y.S. ratio. An annealing time beyond 10 minutes causes greater increase in Y.S. than in T.S. It is therefore desirable to keep the time of annealing between 5-10 minutes and the temperature of annealing around 830 °C to get the required properties in the steel. The effect of temperature and time of annealing is best understood by considering eq. 3. Here again, it is seen that a higher Y.S. to T.S. ratio is obtained by increasing the time of annealing and decreasing the temperature of annealing. The effect of variables on percentage elongation is not very much pronounced (vide Eq. No. 4). The equation shows that there is hardly any contribution of the variables towards the total percent elongation, though the increase in time of annealing to 15 minutes lowers the percent elongation by 0.5%. Determination of percentage elongation accurately within 0.5% by the present technique of measurement may be doubted and hence the coefficient may be considered insignificant. The only conclusion drawn from Eq. 4 is that the total percentage elongation is affected by a change in the annealing time rather than in the annealing temperature.

Equations 7-10 are obtained by regression analysis of the response variables shown in Table II. The equations obtained are:

\[ Y_{\text{ts}} = 477.5 + 40x_1 + 2.5x_2 x_3 \]  
\[ Y_{\text{ys}} = 690.0 - 2.0x_1 + 22.0x_2 - x_1 x_2 \]  
\[ Y_{\text{(Y.S./T.S.)}} = 0.688 + 0.00375x_1 + 0.03375x_2 \]  
\[ Y_{\%E} = 14 - 0.5x_1 + x_2 - 0.5x_1 x_2 \]

Equation 7 indicates that Y.S. increases significantly with increase in the holding time beyond 10 minutes. The temperature does not affect the Y.S. and the interaction between the time and the temperature of intercritical annealing is also not very prominent. Eq. 8 indicates that T.S. is slightly lowered by increasing the austenitising temperature above 800 °C, but this decrease is not very significant. The interaction between the time and the temperature of annealing is also not very significant. Thus out of the two variables selected, the time of annealing has more pronounced effect.

If equations 7 and 8 are compared with the corresponding equations 1 and 2, it will seen that the annealing temperature has significant contribution in lowering Y.S. and to some extent also in lowering T.S. for Steel-I, but the Y.S. is very much increased by increasing the time of annealing beyond 10 minutes. The time of annealing should be kept within 5 to 10 minutes to avoid any increase in Y.S. so that the Y.S. to T.S. ratio is lowered. It is concluded that for both the steels, the temperature of annealing should be kept around 800 °C and the time should be restricted to 5-7 minutes. The equations 4 and 10 show that none of these variables effectively change the percentage elongation. Thus, these equations give some quantitative estimate of the effect of the variables on the mechanical properties of the steels. Further, the equations also help in selecting the operating variables for some desirable properties of this heat treated steel.

The work hardening index is an important parameter for evaluating the properties of a dual phase steel. The work hardening index is also numerically equal to the uniform elongation at necking\(^6\) and hence it was decided to determine the value of work hardening index (n) for the three different steels. A comparison of the properties of Steel-I, II and III, treated at 830 °C for 7 minutes and quenched in oil can be made by referring to Table III.

**TABLE III—Comparison of the properties of Steel-I, II and III treated at 830°C for 7 mts. and quenched in oil.**

<table>
<thead>
<tr>
<th>Steel</th>
<th>Y.S. N/mm²</th>
<th>T.S. N/mm²</th>
<th>Y.S./T.S.</th>
<th>Total % elongation</th>
<th>Uniform % elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>355</td>
<td>658</td>
<td>1.85</td>
<td>27.5</td>
<td>20.120</td>
</tr>
<tr>
<td>II</td>
<td>430</td>
<td>670</td>
<td>1.56</td>
<td>19</td>
<td>12.7</td>
</tr>
<tr>
<td>III</td>
<td>560</td>
<td>690</td>
<td>1.23</td>
<td>15</td>
<td>9.4</td>
</tr>
</tbody>
</table>

It will be seen that Steel-I has all the desirable properties of a dual phase steel.

The cooling rate after intercritical annealing, changes the microstructure considerably. The knowledge of CCT diagram for each composition of steel is very essential since there is a requirement of minimum cooling rate to obtain ferrite (Polygonal) and martensite (15%) structure in the steel. The approximate minimum cooling rate is calculated using equations 13-14\(^11\).
Log (Cooling rate °C/Sec.) = 1.73 Mn equi (%) + 3.95

Mn% Equi (%) = % Mn + 1.3 × %Cr + 2.6%Mo .. [14]

The minimum cooling rate for Steel-I and Steel-II is given below

Steel-I — — — 11 °C/Sec.
Steel-II — — — 31 °C/Sec.

Steel-I gives desirable structure at lower cooling rate whereas the other steels have to be cooled faster. Without the knowledge of the actual CCT diagram for the present compositions, it is not possible to control the properties and structures accurately. In order to have comparative studies, Steels-I and II were treated at 830 °C for 7 minutes and cooled in water, oil and air. The mechanical properties obtained after these treatments are listed in Table IV.

TABLE IV

<table>
<thead>
<tr>
<th>Steel No.</th>
<th>Heat treatment</th>
<th>Y.S. N/mm²</th>
<th>T.S. N/mm²</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Air cooling</td>
<td>359</td>
<td>645</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Oil quenching</td>
<td>370</td>
<td>650</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Water quenching</td>
<td>380</td>
<td>658</td>
<td>26</td>
</tr>
<tr>
<td>II</td>
<td>Air cooling</td>
<td>420</td>
<td>580</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Oil quenching</td>
<td>430</td>
<td>670</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Water quenching</td>
<td>462</td>
<td>790</td>
<td>15</td>
</tr>
</tbody>
</table>

It is revealed from the table that air cooling after intercritical annealing is suitable for obtaining optimum properties for Steel-I. However, there is no marked change in the mechanical properties of Steel-I by cooling in oil or water. Steel-II behaves like the conventional plain carbon steel where the strength increases with increasing severity of cooling with corresponding drop in ductility. The microstructure of the samples after different treatments is shown in Figs. 3 to 5.

These figures show the microstructure of Steels-I, II and III intercritically annealed between 730 °C and 830 °C and quenched in oil. The photographs show the phases present in actual tensile samples for which the mechanical properties are shown in Figs. 1 and 2. As expected, there are two phases, bright ferrite and dark martensite. The amount of martensite is seen to vary considerably for Steels-II and III with the change in intercritical annealing temperature. The morphology seems to differ a little, though the segregation of martensite is located along the grain boundaries. The ferrite is polygonal and the martensite is of lath type.

Fig. 3 Microstructure of Steel-I intercritically annealed for 5 minutes at 770°C and oil quenched X 500.

Fig. 4 Microstructure of Steel-II intercritically annealed at 750°C for 5 minutes and oil quenched X 500.

Fig. 5 Microstructure of Steel-III intercritically annealed at 810°C for 5 minutes and oil quenched X 500.
The microstructure also reveals ferrite with two different shades. The bright regions of ferrite perhaps indicate newly formed ferrite.

CONCLUSIONS
(1) Out of the three dual phase studied steels, Steel-I is found to be better suited for dual phase purpose.
(2) Higher carbon (C>0.12) is not desirable for attractive properties in the dual phase steel.
(3) Increasing intercritical annealing temperature causes lowering of yield strength considerably for Steel-I without affecting T.S. appreciably, thus ensuring a lower Y.S. to T.S. ratio. Steel-II also shows decreasing trend for Y.S. and T.S. with increasing intercritical annealing temperature though there is no marked decrease in the ratio of Y.S. to T.S. For Steel-III both Y.S. and T.S. increase with increasing temperature of intercritical annealing.

ACKNOWLEDGEMENTS
The authors would like to express their sincere thanks to the management of Rourkela Steel Plant for the kind permission to publish the work. Further, the author are indebted to Prof. S. Mishra, Principal, Regional Engineering College, Rourkela for his kind consent to carry out the experiments in the laboratory of the college.

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STUDY ON THE QUANTITATIVE EFFECT OF CARBON AND INTERCRITICAL ANNEALING TEMPERATURE ON PROPERTIES OF CARBON-MANGANESE STEELS BY APPLICATION OF STATISTICAL DESIGN OF EXPERIMENTS

U. C. PATRA, R. I. GANGULY & K. S. SINGH

The classical data obtained from the works carried by Speich and Miller was analysed by applying Design Matrix. The regression equations were obtained from input variables, i.e. from carbon content and intercritical annealing temperature for yield strength, tensile strength, uniform elongation and total elongation, reduction in area, volume fraction of martensite and carbon content of martensite. The effect of carbon content ($X_1$) and intercritical annealing temperature ($X_2$) in their coded form, was quantified. The calculated properties at base level of carbon content of 0.16% and intercritical annealing temperature 760°C were compared with the actual properties obtained by the authors. It is possible to find out the optimum carbon content in steel and intercritical annealing temperature required to obtain a specific desired properties.

INTRODUCTION

Dual Phase Steel is a composite of hard martensite phase distributed in the matrix of clean, soft and ductile ferrite. The proportion of hard phase is about 15-20% of the total phase mixture. The previous workers have shown that the mechanical properties of these steels depend only on the distribution and volume fraction of the hard phase but not on the carbon content of martensite, i.e. carbon content of the steel. Speich and Miller have shown clearly that the properties of dual phase steel depend considerably on the amount and carbon content of martensite which are largely controlled by the inter/critical annealing temperature and carbon content of steel. The authors have also experienced from their previous work that if carbon content exceeds 0.15%, the mechanical properties obtained from the dual phase structure are not beneficial. Thus it will be helpful to an alloy designer to know the quantitative relationship between carbon content and the mechanical properties of a dual phase steel in the form of regression equations.

Since the intercritical annealing temperature interacts with the carbon content of steel in a complex manner, it is also essential to develop regression equations connecting mechanical properties with the carbon content of steel and the intercritical annealing temperature.

Speich et al. have shown systematically the effect of carbon on the mechanical properties of manganese bearing steel but this does not give any quantitative effect.

The present paper attempts to develop regression equations by arranging the data of Speich et al. in the form of design matrix and by bringing out quantitative relationship between composition and heat treatment parameters with the mechanical properties. Once such equations are developed, they may be utilised to optimise the mechanical properties by adjusting the variables. Also these

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Study on the Properties of Carbon-Manganese Steels

equations give choice to a designer to select the carbon content of steel and control the heat treatment parameters such that he gets the alloy with the desirable properties.

ANALYSIS OF RESULTS

Using Tables 1, 2 and 3 of Speich et al, the design matrices are constructed with carbon content and intercritical annealing temperature as input variables and properties obtained as response variables. Table 1 shows design matrix consisting of two variables, namely carbon content and annealing temperature as input variables. Since each variable is varied into two levels, a total of 4 Nos. of experiments are arranged. Here the carbon content is varied between 0.06% and 0.16% keeping the base level at 0.11% C whereas the annealing temperature is varied between 740°C and 780°C keeping the base level at 760°C.

Regression equations are developed by the method described in text. The equations (1) to (7) below are developed from the matrix shown in Table 1 and the equations (8-14) are developed from the matrix shown in Table 2.

\[
\begin{align*}
Y_{YS} &= 377.25 + 62.5x_1 + 10.25x_2 + 0.25x_1x_2 \\
Y_{TS} &= 754.25 + 141.75x_1 + 20.75x_2 + 3.25x_1x_2 \\
Y_{%Eu} &= 119.5 - 2.425x_1 + 0.075x_2 \\
Y_{%Et} &= 208.75 - 5.875x_1 + 1.625x_2 + 0.375x_1x_2 \\
Y_{%RA} &= 425.5 - 130x_1 + 3.15x_2 + 2.7x_1x_2 \\
Y_{%Pm} &= 343.75 + 9.575x_1 + 4.72x_2 + 1.525x_1x_2 \\
Y_{%Cm} &= 0.312 + 0.062x_1 + 0.042x_2 + 0.012x_1x_2
\end{align*}
\]

where \(x_1\) and \(x_2\) are coded values for % carbon content and intercritical annealing temperature respectively.

In order to calculate the response for any input variable, coded values have to be inserted in the equations.

A similar design matrix is constructed and is shown in Table 2. Here carbon is varied between 0.12% min and 0.20% max while the temperature of annealing was varied between 740° and 780°C, keeping 0.16% C and 760°C temperature as base level.

\[
\begin{align*}
Y_{YS} &= 445.5 + 560x_1 + 180x_2 + 15.5x_1x_2 \\
Y_{TS} &= 94025 + 16075x_1 + 33.25x_2 + 24.75x_1x_2 \\
Y_{%Eu} &= 10.28 - 2.0x_1 + 1.05x_2 - 0.85x_1x_2 \\
Y_{%Et} &= 160 - 50x_1 + 3x_2 - x_1x_2 \\
Y_{%RA} &= 27.75 - 10.95x_1 + 5.66x_2 + 0.05x_1x_2 \\
Y_{Pm} &= 43.65 + 6.95x_1 + 7.15x_2 - 0.45x_1x_2 \\
Y_{Cm} &= 0.378 + 0.028x_1 - 0.063x_2 + 0.0075x_1x_2
\end{align*}
\]

where \(x_1\) and \(x_2\) are coded values for % carbon content and intercritical annealing temperature respectively.

Table 1 — Design Matrix for Lower Carbon Content

<table>
<thead>
<tr>
<th>SI. No.</th>
<th>Input variables</th>
<th>Response variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% carbon content</td>
<td>YS Mpa</td>
</tr>
<tr>
<td>1</td>
<td>0.16 (1)</td>
<td>780</td>
</tr>
<tr>
<td>2</td>
<td>0.06 (-1)</td>
<td>780</td>
</tr>
<tr>
<td>3</td>
<td>0.16 (1)</td>
<td>740</td>
</tr>
<tr>
<td>4</td>
<td>0.06 (-1)</td>
<td>740</td>
</tr>
</tbody>
</table>

VOL. 8 NO. 2 OCTOBER 1985
**DISCUSSION OF RESULTS**

Analysis of equations (1) and (2) reveal that both yield strength and tensile strength properties of dual phase structure increase with the increase of carbon content and intercritical annealing temperature. However, the contribution of carbon is more severe, when compared with the contribution of intercritical annealing temperature (6-7 fold), as indicated by coefficients of \( x_1 \) and \( x_2 \) in equations (1) and (2).

The larger contribution of carbon content on the strength properties in comparison to the intercritical annealing temperature can be understood by considering equations (6) and (7). Equation (6) shows that while the increase of carbon content and intercritical annealing temperature increase the volume percent of martensite, the effect of the former variable is twofold in comparison to the latter one (by comparing the coefficients attached to \( x_1 \) and \( x_2 \) of equation 6). Equation (7) shows that while percentage carbon content in martensite increases with the increase of carbon content in steel, the carbon content of martensite is lowered by increasing the intercritical annealing temperature (vide positive coefficient of \( x_1 \) and negative coefficient of \( x_2 \) in equation 7). Thus increasing carbon content not only increases the amount of martensite to a larger extent but also increases the carbon content in martensite. This explains why the coefficient attached to \( x_1 \) is having a higher value than the coefficient attached to \( x_2 \) (vide equations 1 and 2).

Both the variables (i.e. carbon content and annealing temperature) have greater effect on the tensile strength than on the yield strength. The percent uniform elongation and the total elongation are affected adversely by the increase of carbon content (negative coefficient of \( x_1 \) in equations 3 and 4) of steel. The increase of intercritical annealing temperature is helpful since it increases both uniform and total elongation percent (positive coefficient of \( x_2 \) in equations 3 and 4). Similar trend is seen for the percent reduction in area also (vide comparing the coefficients of \( x_1 \) and \( x_2 \) in equation 5).

All these behaviour thus help us to conclude that carbon content of martensite in the dual phase structure has great influence in controlling the properties of dual phase steel.

Equation (8) to (14) are developed from the analysis of the response obtained from the design matrix indicated in Table 2. Similar trend was observed for higher carbon content design matrix from equations (8) to (14).

It can be further discussed that if equations (6) and (13) are compared, the effect of carbon content compared to annealing temperature is significant for volume fraction of martensite (coefficients of \( x_1 \) and \( x_2 \) vide equation 6). But this is reversed for higher level of carbon content (vide coefficients of \( x_1 \) and \( x_2 \) of equation 13).

To find out the validity of the equations, the properties, at base level of 0.16% C and annealing...
Study on the Properties of Carbon-Manganese Steels

Table 3 — Comparison of Properties at Base Level at 0-16% C and 760°C

<table>
<thead>
<tr>
<th>Y.S.</th>
<th>T.S.</th>
<th>% Eu</th>
<th>% Et</th>
<th>% RA</th>
</tr>
</thead>
<tbody>
<tr>
<td>940-25</td>
<td>10-275</td>
<td>16-00</td>
<td>27-75</td>
<td></td>
</tr>
</tbody>
</table>

Calculated from 445-05 equations (8) to (12)

Experimental vide 448 Table 2 of Speich et al.

5. The total elongation is decreased by 1-6 to 3-6-fold with carbon compared to annealing temperature.
6. Percent reduction in area is decreased (2 to 4-fold) with carbon content compared to annealing temperature.
7. The volume fraction of martensite is increased both with carbon and intercritical temperature. But at lower levels of carbon, the effect is about 2-fold compared to annealing temperature and at higher carbon level, the intercritical annealing temperature has greater effect than carbon.

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Effect of Intercritical Annealing Treatments on Structure and Properties of C-Mn Steels

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R I Ganguly, Non-member
B S Prasad, Non-member

The present work aims to determine the quantitative relationship between process variables and mechanical properties for two steels. The effect of initial microstructure on the heat-treatment parameters is also systematically studied. The regression equations developed can be utilized to design heat treatment parameters for specific properties of steel.

INTRODUCTION

Though the dual phase structure (ferrite and martensite) was known to early metallurgists, the emphasis on producing this structure has increased during the last decade. The excellent formability (i.e., higher work hardening index and greater uniform elongation) for dual phase steels with lower carbon content makes it possible to be used by automobile industries in industrially advanced countries like the USA, Japan, and the USSR. The simplicity of heat treatment operation further attracts technologists to produce steels for specified applications.

In the present investigations, the authors have tried to find the variation in properties of carbon-manganese steels by treating at various combinations of intercritical annealing temperature and time, from initial microstructures of ferrite and pearlite, austenite and martensite. The mechanical properties were evaluated using a Hounsfield tensometer and regression equations have been developed relating response variables (i.e., mechanical properties) with austenitising temperature, annealing temperature and time (i.e., process variables).

It is concluded that though dual phase structures can be produced from steels with higher carbon content, it is not encouraging when the property requirements of these types of steels are concerned.

EXPERIMENTAL PROCEDURE

The chemical compositions of the steels selected for the trial are given in Table 1.

| TABLE 1 CHEMICAL COMPOSITION OF SELECTED STEEL |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| C%   | Si%   | Mn%   | S%   | P%   |
| Steel I | 0.25  | 0.16  | 0.55  | 0.040 | 0.040 |
| Steel II | 0.19  | 0.15  | 1.02  | 0.035 | 0.028 |

Tensile samples were prepared as per standards for a Hounsfield tensometer. The samples were treated in the laboratory furnace with a temperature accuracy of ± 5°C. The specimens were protected for surface oxidation. They were given the following heat-treatment cycles as schematically represented in Fig 1.

Steel I (a) step quenching: austenitised at 850°C, 900°C, 950°C, soaked for 15 min, cooled to 740°C (or 780°C) and held for 15 or 60 or 90 min and quenched in water.

(b) intermediate quenching and (c) intermediate air cooling: austenitised at 900°C for 15 min, quenched/
normalised to room temperature, intercritically annealed at 740°C or 760°C or 780°C for 20 min and quenched in water.

Steel II (c) intermediate air cooling: austenitised at 900°C for 15 min, normalised to room temperature, annealed at 720°C or 740°C or 760°C for 20 min and quenched in water.

(d) direct quenching: hot rolled steel, annealed at 760°C or 780°C or 800°C or 820°C for 30 or 90 min and quenched in water.

After heat treatment, mechanical properties, namely yield strength; tensile strength, percentage elongation, percentage reduction in area and hardness values were determined and are shown in Tables 2 and 3. Microstructures were also examined.

RESULTS AND DISCUSSION

Tables 2 and 3 list the mechanical properties of steel I heat treated in accordance with the procedure outlined in experimental (a), (b) & (c) and are schematically represented by Fig 1. Table 2 shows that ultimate tensile strength and yield strength
increase with increasing austenitisation temperature and intercritical annealing temperature. While the austenitisation temperature has greater influence on yield strength than ultimate tensile strength, the effect of intercritical annealing temperature is more on ultimate tensile strength than on yield strength. It is also observed that both ultimate tensile strength and yield strength are reduced at higher holding time especially at lower intercritical annealing temperature. This is expected because longer holding time at the austenitisation temperature helps in attaining phase equilibrium and this results in the formation of new soft ferrite.

Table 3 shows the mechanical properties of steel I annealed at different temperatures. Here the samples were given initial treatment before annealing intercritically at various temperatures. This is done to study the effect of initial microstructure on the mechanical properties of dual phase steel produced by intercritical annealing. The results of Table 3 show that the toughness produced by intercritical annealing for the steel with martensite as initial structure is always inferior to the toughness of intercritically annealed steel, having initial microstructure ferrite and pearlite produced by normalising.

Similar experiments are conducted with steel II, i.e., experiments (c) and (d). The different results obtained are graphically shown in Figs 2 to 6. Figs 2 shows variation of yield and tensile strength of the steel being intercritically annealed at different temperatures for two different times of holding. Beyond 780°C yield strength and tensile strength do not change appreciably for the steel held for longer period of time but the strength properties increase continuously with increasing intercritical annealing temperature for shorter period of time of holding. This is probably due to stabilisation of austenite during annealing at higher temperature for longer period of holding time.

Fig 3 shows effect of annealing temperature on total and uniform elongation percent of steel II being held at annealing temperatures for 15 min. This treatment is preceded by an initial treatment (i.e., austenised at 900°C for 15 min followed by quenching in water). Both total and uniform elongations decrease slightly with increasing annealing temperature between 720°C and 740°C but the elongation percent rapidly increases and the difference between total elongation and uniform elongation decreases at higher holding temperature. Figs 4 and 5 show that both yield strength and tensile strength increase linearly with increasing intercritical annealing temperature with normalised structure as per treatment schedule (c) of Fig 1.

The mechanical properties of dual phase steels are affected by various treatment combinations (namely, austenitisation temperature, intercritical annealing tem-
TENSILE STRENGTH
• YIELD STRENGTH

INTER CRITICAL ANNEALING TEMPERATURE °C

Fig 5 Effect of intercritical annealing temperature on tensile and yield strength after normalising

INTER CRITICAL ANNEALING TEMPERATURE °C

Fig 6 Effect of intercritical annealing temperature on total and uniform elongation after normalising

So quantitative estimates are made by regression analysis 6-8, of the data of Table 2 arranged in a design matrix (vide Table 4) where range of variations of process variables is shown.

The equations 1, 2 and 3 are obtained by regression analysis 9,10 for response variables.

\[
Y_1 = 653.3 + 113.0X_1 + 85.3X_2 - 45.5X_3 + 1.8X_1X_3 + 0.66X_1X_2 - 0.04X_1X_3 - 0.9X_2X_3 + 0.46X_1X_2X_3 \quad (1)
\]

\[
Y_2 = 778.5 + 59.8X_1 + 82.5X_2 - 50.5X_3 - 2.25X_1X_2 - 6.6X_1X_3 - 20.5X_2X_3 - 44.88X_1X_2X_3 \quad (2)
\]

Here \( X_1, X_2 \) and \( X_3 \) are coded values, and are defined as:

\[
X_1 = \frac{\text{Austenitising Temperature °C} - 900°C}{50°C}
\]

\[
X_2 = \frac{\text{Annealing Temperature °C} - 760°C}{20°C}
\]

\[
X_3 = \frac{\text{Annealing time (min)} - 52.5 \text{ (min)}}{37.5 \text{ (min)}}
\]

\[
Y_3 = 11.54 - 1.8X_1 - 2.5X_2 + 1.08X_3 + 0.66X_1X_3 - 0.04X_1X_3 - 0.9X_2X_3 + 0.46X_1X_2X_3 \quad (3)
\]

These equations reveal the quantitative effect of the process variables on the mechanical properties of dual phase structure. These equations will help the alloy designer to determine the treatment combinations for obtaining desirable properties in the steel by the adjustment of process variables.

Quantitative estimates of mechanical properties of steel II are similarly made utilising data of Table 6.

Regression equations obtained analysing process variables for different response variables are shown on equations (4) to (6).
### TABLE 6 MECHANICAL PROPERTIES OF STEEL II OBTAINED BY DIFFERENT TREATMENT COMBINATION

<table>
<thead>
<tr>
<th>(PROCESS VARIABLES) TREATMENT COMBINATION</th>
<th>RESPONSE VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANNEALING TEMP, °C (X₁)</td>
<td>ANNEALING TIME, min (X₂)</td>
</tr>
<tr>
<td>820 (+1)</td>
<td>90 (+1)</td>
</tr>
<tr>
<td>720 (-1)</td>
<td>90 (+1)</td>
</tr>
<tr>
<td>820 (+1)</td>
<td>30 (-1)</td>
</tr>
<tr>
<td>780 (-1)</td>
<td>30 (-1)</td>
</tr>
</tbody>
</table>

Note: YS = yield strength and UTS = ultimate tensile strength.

\[
Y(YS) = 1224.3 + 29.8X₁ - 9.75X₂ - 20X₁X₂ \quad (4)
\]

\[
Y(TS) = 1599.5 + 108.5X₁ - 53.0X₂ - 82.0X₁X₂ \quad (5)
\]

\[
Y(\%E) = 9.38 + 1.63X₁ + 0.38X₂ - 0.63X₁X₂ \quad (6)
\]

Here, \(X₁\) and \(X₂\) are coded values and are defined as

\[
X₁ = \frac{\text{Austenitising Temperature (°C) - 800°C}}{20°C}
\]

\[
X₂ = \frac{\text{Annealing times (min) - 60 (min)}}{30 (min)}
\]

and \(Y(YS)\), \(Y(TS)\) and \(Y(\%E)\) are response variables for yield strength, tensile strength and % elongation.

The equations can be utilised for optimising mechanical properties of steel through adjustment of process variables by suitable computer programming.

### CONCLUSIONS

1. Both yield strength and tensile strength are increased by increasing the austenitisation and intercritical annealing temperatures for steel I. The austenitisation temperature has greater influence on yield strength than tensile strength (comparing the coefficients of regression equations (1) and (2)).

2. The result indicates that toughness of the intercritically annealed steel starting with martensite structure is always inferior to the toughness of the steel given similar heat treatment with normalised structure.

3. The results revealed that dual phase structure obtained for steel I (C-0.25% and Mn-0.55%) by step quenching (i.e., austenitising at 900°C followed by intercritical annealing at 740°C for 90 min and water quenching) gave superior properties compared to the other treatment combinations.

4. For steel II, both yield strength and tensile strength increase linearly with increasing intercritical annealing temperature. The total and uniform elongations increase rapidly with higher annealing temperature and the difference between them is decreased at higher holding temperature.

5. Quantitative relations are developed for both the steels in the form of regression equations. These equations can suitably be utilised for designing heat treatment parameters for suitable mechanical properties. However, the equations are valid only in the range of variations of the variables.

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