The Development of Rolling Process for Strip

Mohd Zaidi Sidek

Thesis submitted for the degree of
Doctor of Philosophy
of
Imperial College London

Department of Mechanical Engineering
Imperial College London

October 2013
Abstract

This research aims to examine the feasibility of a new concept in section rolling of thick strip, which either could not be rolled at present due to cracking at bent corners. Whereas, the second moment of area of sections could be increased through sharpened corners and increased gauge thickness. A heat assisted section rolling process is proposed. This process is based on application of high intensity heat on the inner surface of the strip, immediately prior to rolling. To investigate the new section rolling concept, the following work has been carried out.

Firstly, the material property of the S450 steel has been determined using the Gleeble simulator, followed by thermal conductivity tests. Since a freon was used to increase temperature gradient, the heat transfer coefficient for the freon-hot surface interaction was determined. Finally, the four point hot bending tests were conducted to validate the simulation model. For this purpose, a hot bending test rig was designed and fabricated, utilizing an halogen heater as the heat source. The results between experiment and simulation were compared and a good correlation was found.

Then, finite element analyses of a single pass hot rolling process has been adopted to investigate the neutral axis shift and section thickening effects. It is revealed that localised heating creates bulging on the compressed surface. The bulged surface affects the both neutral axis and thickening of the formed parts.

This research has demonstrated that localised heating has a potential to be employed in section rolling operations. It shows that the neutral axis of the bent region shifted closer to the tensile surface would reduce the tendency for surface cracking. In addition, the increase in thickness that arises at a bend would enhance the stiffness of rolled sections. Ultimately a process window for heat assisted section rolling has been established.
Contents

List of Figures ................................................................. x
List of Tables ................................................................. xiv
Nomenclature ............................................................... xv

1.0 Research motivation

1.1 Introduction ............................................................. 1
1.2 Current needs and their requirements ......................... 1
1.3 Standards ................................................................. 2
1.4 Roll formed products .................................................. 3
1.5 Application of roll formed products ............................. 4
1.6 Essential feature of the roll forming process ................. 6
1.7 Production defects ..................................................... 9
1.8 Area of study .......................................................... 10
1.9 Aim and methodology .............................................. 12

2.0 Previous Research and Development on Section Rolling

2.1 Introduction ............................................................ 13
2.2 Cold roll forming research ......................................... 14
  2.2.1 Bending in cold roll forming ................................. 19
  2.2.2 Neutral axis shift ................................................ 20
  2.2.3 Relationship between neutral axis and stress-strain distribution .............................................. 22
2.3 Defect formation ....................................................... 25
  2.3.1 Thinning in the sheet metal bending ...................... 25
  2.3.2 Cracking in sheet metal bending .......................... 27
2.4 Elevated temperature sheet forming ............................ 28
  2.4.1 Forming by non-uniform heating ......................... 28
  2.4.2 Forming by uniform heating ............................... 29
  2.4.3 Effect of test-piece material ............................... 30
  2.4.4 Effect of hot forming mechanism ......................... 31
  2.4.5 Heat source ....................................................... 31
    2.4.5.1 Laser beam ................................................ 31
2.4.5.2 Infra-red ......................................................... 32
2.4.5.3 Induction heating ............................................ 33
2.4.5.4 Flame heating .................................................. 33
2.4.5.5 Resistance heating ............................................ 33
2.4.6 Heating mechanism .............................................. 34
2.4.7 Temperature distribution ...................................... 35
2.5 Process variables .................................................. 37
  2.5.1 Neutral axis movement ...................................... 37
  2.5.2 Sectional thickening .......................................... 38
2.6 Chapter summary .................................................. 39

3.0 Experimental work
  3.1 Introduction ...................................................... 40
  3.2 Material as received ............................................ 40
  3.3 Hot tensile tests ................................................. 42
    3.3.1 Equipment - Gleeble machine ......................... 42
    3.3.2 Test-piece preparation .................................... 43
    3.3.3 Test procedures ............................................. 45
  3.4 Heat transfer tests ............................................. 46
    3.4.1 The infra-red heater ....................................... 47
    3.4.2 Test-piece preparation .................................... 47
      3.4.2.1 Test 1 - Thermal conductivity tests .......... 48
      3.4.2.2 Test 2 - Heat transfer coefficient tests .... 48
    3.4.3 Test setup .................................................. 49
      3.4.3.1 Test 1 - Thermal conductivity tests .......... 49
      3.4.3.2 Test 2 - Heat transfer coefficient tests .... 50
    3.4.4 Test procedures ........................................... 51
      3.4.4.1 Test 1 - Thermal conductivity tests .......... 51
      3.4.4.2 Test 2 - Heat transfer coefficient tests .... 52
  3.5 Four-point hot bending ....................................... 53
    3.5.1 Test motivation ............................................ 53
    3.5.2 Test equipments ............................................ 54
      3.5.2.1 Press machine ........................................ 54
3.5.2.2 Test rig ................................................................. 54
3.5.3 Test-piece preparation .............................................. 55
3.5.4 Matrix of four-point hot bending tests ....................... 56
3.5.5 Test procedures .................................................... 57

4.0 Experimental results
4.1 Introduction .................................................................. 59
4.2 Hot tensile tests .......................................................... 59
4.3 Heat transfer test .......................................................... 63
  4.3.1 Test 1: Thermal conductivity .................................... 64
  4.3.2 Test 2: Heat transfer coefficient with spray cooling .... 66
4.4 Four-point hot bending test .......................................... 68
  4.4.1 Room temperature bending .................................... 68
  4.4.2 High temperature bending ...................................... 70

5.0 Numerical analyses
5.1 Introduction ............................................................... 72
5.2 Thermal conductivity tests .......................................... 72
  5.2.1 Finite element model ............................................. 73
    5.2.1.1 Geometrical model and meshing ....................... 73
    5.2.1.2 Material properties ....................................... 73
    5.2.1.3 Interaction properties .................................. 74
    5.2.1.4 Loading and steps ....................................... 75
  5.2.2 Comparison between experiment and simulation results ... 76
5.3 Heat transfer coefficient ............................................. 78
  5.3.1 Finite element model ........................................... 79
    5.3.1.1 Geometrical model and meshing ..................... 79
    5.3.1.2 Material properties ..................................... 80
    5.3.1.3 Boundary conditions ................................... 80
    5.3.1.4 Process steps ........................................... 80
  5.3.2 The measuring points ........................................... 81
  5.3.3 The simulation results ....................................... 81
6.0 Heating characteristics of the developed process

6.1 Introduction ................................................................. 94
6.2 Finite element analysis .................................................... 94
   6.2.1 Geometrical and meshing model .............................. 95
   6.2.2 Assumptions ........................................................ 96
   6.2.3 Material properties ............................................... 97
   6.2.4 Boundary conditions .......................................... 97
   6.2.5 Treatment of heat input ....................................... 97
   6.2.6 Time step .......................................................... 98
6.3 Simulation results ....................................................... 99
   6.3.1 Heating step ........................................................ 99
      6.3.1.1 Heat flux ............................................... 99
      6.3.1.2 Temperature gradient .................................. 100
   6.3.2 Bending step ...................................................... 103
      6.3.2.1 Neutral axis shift ................................... 104
      6.3.2.2 Sectional thickening .................................. 107

7.0 Numerical Investigations

7.1 Introduction ............................................................... 110
7.2 Type of analysis .......................................................... 110
7.3 Finite element model .................................................... 111
7.4 The primary parameters test ................................................... 113
  7.4.1 Heating band effects .................................................. 113
    7.4.1.1 The neutral axis shift ......................................... 113
    7.4.1.2 Sectional thickening ........................................ 114
  7.4.2 Heating time effects .................................................. 115
    7.4.2.1 The neutral axis shift ......................................... 116
    7.4.2.2 Sectional thickening ........................................ 117
  7.4.3 Bending speed effects ................................................. 118
    7.4.3.1 The neutral axis shift ........................................ 118
    7.4.3.2 Sectional thickening ........................................ 119
  7.4.4 Sensitivity analysis .................................................... 120
    7.4.4.1 Heating band sensitivity .................................... 119
    7.4.4.2 Heating time sensitivity .................................... 121
    7.4.4.3 Bending speed sensitivity .................................... 122
7.5 Secondary parameters test ..................................................... 123
  7.5.1 Bending radius ........................................................ 124
    7.5.1.1 The neutral axis shift ........................................ 124
    7.5.1.2 Sectional thickening ........................................ 124
  7.5.2 Part thickness ........................................................... 125
    7.5.2.1 The neutral axis movement ................................ 126
    7.5.2.2 Sectional thickening ........................................ 126
7.6 Process window .................................................................. 128

8.0 Conclusions and Future Research Recommendations
  8.1 Conclusion ........................................................................... 131
  8.2 Recommendations for future research................................. 134

References ................................................................................... 135
Appendices ................................................................................... 150
List of Figures

1.1 Steel production in year 2009 ................................................................. 2
1.2 Roll formed products ........................................................................ 3
1.3 Application of roll formed products in construction ...................... 5
1.4 Application of roll formed products in automotive ....................... 6
1.5 Typical set-up a roll sequence to bend a section from flat strip ...... 7
1.6 The strip is formed from an unreformed strip to a finished profile ... 8
1.7 Full roll forming system with pre-punch and post cut operation ...... 9
1.8 Common defects in the roll forming products ................................. 9
1.9 The concerned type of defects in the roll formed products ............. 10
1.10 Schematic view of the heat-assisted section rolling process ........... 11
2.1 Sheet metal deformation using shape function, S(x) ..................... 14
2.2 Deformation of a flat sheet metal at the first roll station .............. 16
2.3 a) Formation of a channel section
    (b) Typical cross-section of the formed product ............................ 17
2.4 The strip is formed by a bend angle in the contact zone between the rolls ... 18
2.5 Neutral axis definition .................................................................. 20
2.6 Neutral axis movement in strip bending .................................... 20
2.7 (a) Bending notation (b) The effect of an increase in curvature ...... 21
2.8 Neutral axis movement in plastic bending .................................. 22
2.9 Strain distribution in bending ....................................................... 23
2.10 Stress-strain distribution at small and large bending curvature ...... 25
2.11 The classification of laser heating mechanism ............................... 34
2.12 A thermal gradient mechanism of the laser bending:
    (a) heating process (b) cooling process .......................................... 35
2.13 Model geometry for laser forming ................................................. 36
2.14 Variation of surface temperature at different locations ................ 36
2.15 Temperature field obtained by a numerical method under the condition ... 37
2.16 Sectional thickening of 1.5mm mild steel .................................... 38
3.1 As received test-piece – steel grade S450 .................................... 41
3.2 Temperature effects galvanised steel at five tested temperature .... 42
3.3 The Gleeble simulator machine .................................................... 43
3.4 The test-piece and holder (a) the original specimen (b) the modified specimen ........................................................... 44
3.5 The test piece setting in the Gleeble machine ........................................................... 45
3.6 The hot tensile heating cycle ........................................................ 45
3.7 Main body of halogen heater ........................................................ 47
3.8 Thermocouple points for thermal conductivity test ........................................................... 48
3.9 Thermocouples points for heat transfer coefficient test ........................................................... 48
3.10 Thermal conductivity test- a)schematic diagram (b) actual setup ........................................................... 49
3.11 Heat transfer coefficient test - a)schematic diagram (b) actual setup ........................................................... 51
3.12 Process sequence in the heat coefficient test ........................................................ 52
3.13 Full assembly of the used test rig ........................................................ 55
3.14 Thermocouple location on specimen during 4PHBT ........................................................... 55
3.15 Setup for the 4PHBT tests ........................................................ 57
3.16 Specimen positioning inside the test rig during 4PHBT ........................................................... 57
3.17 Process sequence in the four-point hot bending test ........................................................... 58
4.1 Flow stress results of S450 steel a) Strain rate effects at $\dot{\varepsilon} = 1 \text{s}^{-1}$ b) Temperature effects at $T = 750^\circ\text{C}$ ........................................................... 61
4.2 Comparison of the Young modulus reduction factors at the elevated temperatures ........................................................... 62
4.3 Stress-strain relationship for the hot-rolled steel at the elevated temperatures ........................................................... 63
4.4 Determination of an optimum distance between infra-red heater and test-piece ........................................................... 64
4.5 Temperature history extracted from the thermal conductivity test ........................................................... 65
4.6 Temperature difference between the top and bottom surfaces when cooling gas sprayed at the back surface ........................................................... 66
4.7 The temperature measured on the back surface (a) Along the cooled area (b) At left and right location to the sprayed area ........................................................... 68
4.8 The bended test-piece from the four-point bending test at room temperature condition ........................................................... 69
4.9 The bended test-piece from the four-point bending test at high temperature condition ........................................................... 70
5.1 A symmetrical model of thermal conductivity test
(a) geometrical (b) meshes ............................................................73
5.2 Heat flux distribution as applied on the heating surface (a) The volume of heat flux applied on the respective rows
(b) The designated row in the model.................................................76
5.3 The measurement points in the heat transfer experiment ..................76
5.4 (a) Temperature history on the symmetry line
(b) Temperature history 5 mm away from the symmetry line .............77
5.5 Heat transfer coefficient from previous study ................................79
5.6 Heat transfer coefficient test (a) geometrical (b) meshed ...................80
5.7 The measurement points in the HTC validation .............................81
5.8 Comparison between simulation and experiment results at
the determined heat transfer coefficient = 1000 W/m².K .................82
5.9 Four-point hot bending test model (a) geometrical (b) meshes ..........84
5.10 Comparison of experimental and FE analysis at room temperature .....87
5.11 Test-piece’s edges (S) distance from the room temperature test ..........88
5.12 The temperature history during the four-point hot bending test
(a) at the heating stage (b) at the bending stage ..............................90
5.13 Comparison of experimental and FE analysis at high temperature .......91
5.14 Test-piece’s edges (S) distance from the high temperature test ..........92
5.15 The generated temperature inside the test-piece
during high temperature bending ..................................................92
6.1 The FE model of the HASR process, (a) geometrical (b) meshes ..........95
6.2 Combination of heat flux and peak temperature for different heating
width and part thickness at 0.5 sec heating time ...............................100
6.3 Temperature profiles from the half-section of symmetrical model
at the peak temperature 900°C ..................................................101
6.4 Temperature history at the two nodes—the heating zone node
(solid curves) and the back surface node (dash curves) .....................101
6.5 Temperature profile of the FE analysis for different heating width .......102
6.6 Axial stresses (S11) for the bended model after bending process .........103
6.7 Axial stress along the bending process at (a) the room temperature
(b)500°C (c)700°C (d) 900°C ..................................................105
6.8 Neutral axis shift against cylinder displacement for different
temperature setting ................................................................. 106
6.9 Sectional thickening effect after the hot bending process .... 107
6.10 Residual stress profiles for different peak temperature .... 109
7.1 Neutral axis shift during the bending process at
for different heating width ...................................................... 114
7.2 Sectional thickening (h/h₀) for different heating band .... 115
7.3 Temperature profiles at the end of heating stage
for different heating time configuration ................................. 116
7.4 Neutral axis shift during the bending process
for different heating time .......................................................... 116
7.5 Sectional thickening (h/h₀) during the bending stage
for different heating time .......................................................... 117
7.6 Neutral axis shift during the bending process
for different bending speed ...................................................... 118
7.7 Sectional thickening (h/h₀) during the bending stage
for different bending speed ...................................................... 119
7.8 Heating band sensitivity ;(a) Neutral axis movement
(b) Sectional thickness ........................................................... 121
7.9 Heating time sensitivity ;(a) Neutral axis movement
(b) Sectional thickness ........................................................... 122
7.10 Bending speed sensitivity ;(a) Neutral axis movement
(b) Sectional thickness ........................................................... 123
7.11 Neutral axis shift during the bending process
for different bending radius ...................................................... 125
7.12 Sectional thickening (h/h₀) due to bending
for different bending radius ...................................................... 125
7.13 Neutral axis shift during the bending process
for different part thickness ...................................................... 126
7.14 Plot of relationship between dimensionless variables between
the neutral axis shift and the heating band/thickness ratio .... 127
7.15 Plot of relationship between dimensionless variables between
the sectional thickening and the heating band/thickness ratio .... 128
List of Tables

1.1 Engineering standards related to the roll forming products and processes .... 3
1.2 Factors influencing roll forming process ........................................... 9
2.1 Three main laser types in the market ............................................ 32
3.1 Chemical percentage composition and properties of grades of S450 steel ... 41
3.2 Test-piece preparation for the heat transfer test ............................... 47
3.3 The four-point hot bending test plan ............................................ 56
6.1 Case studies for the four-point bending tests of 6 mm thick test-piece .... 98
7.1 Test matrix for sensitivity analysis ................................................... 111
7.2 Parameter setting of the developed FE models ................................... 112
7.3 Parameter used in FE models for bending radius & part thickness .......... 112
7.4 Hot bending conditions and the calculated process output values ........... 120
7.5 The process window for the heat-assisted section rolling process .......... 130
Nomenclature

Latin Symbols, uppercase

$A$ — The heated surface area (m$^2$)
$A_e$ — Area of the emitting body (m$^2$)
$Err$ — Error function
$F$ — Force (N)
$C_p$ — Specific heat (J/kg°C)
$J$ — Conductivity matrix
$L$ — Instantaneous length
$Lo$ — Original length
$T_x$ — Deformation length
$D_d$ — Height difference between the two load points
$E$ — Young’s modulus (MPa)
$G$ — Shear modulus (MPa)
$T_z$ — Flange length
$M_B$ — Applied bending moment per unit width during elastic loading
$Q_{tot}$ — Total heat transfer
$Q'$ — Input heat flux
$Q_{max}$ — Maximum heat flux
$Q_p$ — Heat generation due to the plastic work rate
$Q_i$ — Internal flux vector
$S$ — Shape function
$T_{a,b}$ — Temperature of the points on the adjacent surfaces.
$T_c$ — Cold surroundings absolute temperature (K)
$T_h$ — Hot body absolute temperature (K)
$T_{\infty}$ — Ambient temperature (°C)
$T_c$ — Calculated temperatures (°C)
$T_m$ — measured temperatures (°C)
$V$ — Vickers hardness
$Q_{sup}$ — Generated power (W)
$I$ — Current (Amp)
V  Voltage (Volt)
Iy  Second moment and
$C_D^{-1}$  Lumped capacitance matrix,
P  External force (N)

**Latin Symbols, lowercase**

$a_1, a_2$  Supporting points position.
$d_c$  Centre of deflection
$f$  Flexural rigidity
$i$  Radial distance from the power source beam center,
$r$  Bending radius
$k$  The gap conductance
$h$  Heat transfer coefficient, sheet metal thicknesses
$h_c$  Heat transfer coefficient for convection (W/(m$^2$ K))
$p$  Contact pressure
$n_h$  Power efficiency
$q$  Heat conductivity
$q_c$  Convection heat losses
$q_r$  Radiation heat losses
$i$  Heat flux vector
$i_o$  Maximum power output (W/m$^2$.sec)
$i_T$  Heat flux from the lamp filament of $T_o$
$i_r$  Heat flux received by a specimen at a temperature of $T_r$
$i_h$  Heat flux loss of heater system in W/m$^2$.sec
$i_e$  End-effects heat flux loss caused by heater design
$k_n$  Thermal conductivity normal to the surface (W/mK)
w  Heating band
t  Part thickness, heating time
$v$  Bending speed
Greek Symbols

\( \beta \)  Fraction of the plastic energy
\( \lambda \)  Isotropic heat conduction
\( \sigma \)  Stress (MPa)
\( \nu \)  Poisson ratio
\( \dot{e}_{ij} \)  Plastic strain rate
\( \varepsilon \)  Emissivity
\( \varepsilon_p \)  Plastic equivalent strain
\( \varepsilon_c \)  Engineering strain
\( \varepsilon_t \)  True strain
\( \tau \)  Shear strain
\( \sigma \)  Stefan–Boltzmann constant for radiation \( (5.669 \times 10^{-8} \, \text{W/m}^2\text{.K}^4) \)
\( \phi \)  Interaction conductivity constant
\( \theta \)  Bending angle
\( \rho \)  Curvature radius of the neutral axis
\( \rho_A, \rho_B, \rho_C \) Bending curvature
\( \gamma \)  Heating concentration factor
\( \psi \)  deflection of the workpiece

Operators

\( \Delta \)  Increment
\( \nabla \)  Divergence operator
\( \Sigma \)  Summations
\( \delta(x) \)  Dirac’s delta function
\[ \frac{\partial f_{NA}(w,t,v)}{\partial w} \] Neutral axis sensitivity with respect to heating band
\[ \frac{\partial f_{NA}(w,t,v)}{\partial t} \] Neutral axis sensitivity with respect to heating time
\[ \frac{\partial f_{NA}(w,t,v)}{\partial v} \] Neutral axis sensitivity with respect to bending speed
\[ \frac{\partial f_{st}(w,t,v)}{\partial w} \] Sectional thickening sensitivity with respect to heating band

\[ \frac{\partial f_{st}(w,t,v)}{\partial t} \] Sectional thickening sensitivity with respect to heating time

\[ \frac{\partial f_{st}(w,t,v)}{\partial v} \] Sectional thickening sensitivity with respect to bending speed

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI</td>
<td>American Iron and Steel Institute</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
<tr>
<td>BU</td>
<td>Buckling Mechanism</td>
</tr>
<tr>
<td>CRF</td>
<td>Cold Roll Forming</td>
</tr>
<tr>
<td>DIN</td>
<td>Deutsches Institut für Normung</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>HTC</td>
<td>Heat Transfer Coefficient</td>
</tr>
<tr>
<td>HASR</td>
<td>Heat assisted section rolling</td>
</tr>
<tr>
<td>JIS</td>
<td>Japanese Industrial Standards</td>
</tr>
<tr>
<td>LCS</td>
<td>Low Carbon Steel</td>
</tr>
<tr>
<td>TGM</td>
<td>Temperature Gradient Mechanism</td>
</tr>
<tr>
<td>UP</td>
<td>Upsetting Mechanism</td>
</tr>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>4PHBT</td>
<td>Four-point hot bending test</td>
</tr>
</tbody>
</table>
CHAPTER 1

RESEARCH MOTIVATION

1.1 Introduction

Sheet metal fabrication plays an important role in the manufacturing industry. It is extensively used to manufacture parts ranging from car body panel components to prismatic sections for structures in buildings. A variety of sheet metal technologies are available such as shearing, stamping, deep drawing, and incremental forming. One of them is cold roll forming, which is used to produce long and constant cross-sectional sheet metal products. This process is highly productive and versatile since certain operations such as punching, bending and welding can be included, resulting in ready-to-use products.

1.2 Current needs and their requirements

The quantity of cold roll formed and strip-based product is the third largest of all metal forming processes, world-wide. Industrially, this process is classified as ‘cold-rolled sheet and sections’ and based on the World Steel Association’s report released in 2011,
the total consumption of hot and cold rolled products reached 71.7 million tons in 2009. This volume consumes about 16% of the total steel consumption as can be seen in Figure 1.1.

![Steel production pie chart]

Figure 1.1: Steel production in year 2009 (World Steel Association, 2011).

1.3 Standards

All production activities in roll forming industries must comply with approved standards. By maintaining these, manufacturers are able to produce quality products that meet the customer needs and safety requirements. Moreover, implementations of the recognised standard in manufacturing activities are advantageous in terms of high productivity, low operating costs, and consistent product quality.

Standards applied to cold roll formed products are determined by the specific application and respective country's requirements. Selection of the standards depends on the specific requirements of particular regions of the world. For example, Table 1.1 shows standard designations to be used to produce certain products as parts for car bodies and household appliances. In implementing the new technology, the engineer or designer must make sure the final products comply with the standard requirements.
Table 1.1: Engineering standards related to cold roll formed products and processes

<table>
<thead>
<tr>
<th>Quality standard</th>
<th>EN 10130/91</th>
<th>EN 10311/92</th>
<th>DIN 1623 T1/83</th>
<th>JIS G3141/90</th>
<th>BS 1449 Part 1/83</th>
<th>UNO 5866/77</th>
<th>ASTM A1008/03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel grades</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe P01</td>
<td>DC 01</td>
<td>St 12</td>
<td>SPCC</td>
<td>CR SP 4</td>
<td>Fe P01</td>
<td>CS Type A</td>
<td></td>
</tr>
<tr>
<td>Fe P03</td>
<td>DC 03</td>
<td>RR St 13</td>
<td>SPCD</td>
<td>SR SP 3</td>
<td>Fe P02</td>
<td>DS Type A</td>
<td></td>
</tr>
<tr>
<td>Fe P04</td>
<td>DC 04</td>
<td>St 14</td>
<td>SPCEN</td>
<td>SR SP 2</td>
<td>Fe P04</td>
<td>DDS</td>
<td></td>
</tr>
</tbody>
</table>

Besides the above, other types of standard are available for different types of product. For examples, standards specific to construction products are:

- BS EN 10111:2008 Continuously hot rolled low carbon steel sheets.

Nowadays, there are new structural Eurocode standards specifically established for the construction industry which were fully implemented in Europe in 2010.

1.4 Roll formed products

Roll formed products can be classified by the geometry of their cross-sectional profile. These can include; angle, channel or corrugated profile. With another categorization roll formed products can be classified as open, closed, pierced, and welded. Examples of roll formed products typifying the categories are shown in Figure 1.2.

Open profiles are products with a prominent gap between the two extreme edges of the sheet metal strip. In contrast, a closed profile has greater complexity and is distinguished by the minimal gap between the two extreme edges of the strip. Pierced
profiles contain holes, punched through the strip during rolling. The fourth type, welded profiles represent more advanced products, in which roll formed edges have been joined using a continuous welding process during the roll forming process.

Roll forming offers a number of distinct advantages over other metal fabricating methods. Among them are:

a) Products with a substantial high strength-to-weight ratio.
   Savings in weight may be as much as 30-50% compared to casting and bulk forming, leading to appreciable savings in cost of transport and installation. (Johnson, 1975).

b) High precision products.
   Roll-formed products can be manufactured to very accurate tolerances and good surface finish. The dimensional accuracy of final products typically is ±0.3mm tolerance (Yu et al., 2009).

c) Better part strength especially on the bending line.
   During a cold work process the yield and ultimate strengths will be increased, but metal ductility will be decreased (Cubberly, 1989).

d) Cheaper products.
   Cold roll forming is a high productivity process and high volume production results in low cost-per-piece. Also roll formed products contain up to 94% of their raw material, resulting in less scrap (Gulceken, 2007).

1.5 Applications of roll formed products

Various industries use roll-formed products, especially those engaged in engineering applications, such as;

- Construction- Structural sections, door frames, guide channels and shutter laths.
- Building- window frames, roofs, gutters and curtain wall sections.
- Automobile- Stiffeners, bumpers, chassis, door frames and panel sections.
- Aircraft- airframe stringers, helicopter blade leading edges, and jet engine seals.
- Appliances- Handles for ovens, drawer rails, trims, and structural beams.
Furniture and fixtures—metal cabinets, shelves and display cases. 
Motorways and heavy construction—road signs, guard rails and piling.

In the construction industry, most structural components are produced by cold roll forming including, floor decking, roofs and wall claddings. The wide area of application of roll forming products in this industry can be seen in Figure 1.3.

![Figure 1.3: Application of roll formed products in construction](HighTechFinland, 2012)

Another important industry which uses cold rolled products is automotive manufacturing and the specific product applications can be seen in Figure 1.4. The automotive industry in particular has made extensive use of roll forming to produce body frames and trim, door headers, window guides, bumper reinforcements, seat tracks and door impact bars (Kevin & Ulrich, 2003).
Figure 1.4: Application of roll formed products in automotive (Chubu, 2008).

In addition to the above-mentioned applications, roll formed products are also important in other industries. For aerospace applications, roll formed products are used for window frames and helicopter blades (Ioannis, 2012). The domestic appliance industry also uses products such as handles, drawer slides, refrigerator shelves, ladder supports, and control panels (Lindgren, 2009). Further uses of these types of products can also be found in agriculture, transportation, and aerospace industry (Hisaki & Hiroshi, 2001).

1.6 Essential feature of the roll forming process

In industrial practice various types of roll forming machines, either conventional or customized designs are used. For a conventional roll forming machine, it consists of a wide steel base that supports the roll stations which are arranged in a single line. A set comprising top, bottom, and sometimes side rolls are fixed to each roll station. Basically, the main roll forming system consists of three sections; a raw material feeder, a series of stands for forming, and an additional process setup for punching and shearing. The typical arrangement of a roll forming line is shown in Figure 1.5.
As shown in the above figure, the roll forming process begins with the strip feeder at one end of the production line. The metal strip is then unrolled and fed into a machine in the form of a flat strip. During production, the feeder speed plays a major role in maintaining consistent strip supply to the machine. Generally, the normal production rate for most roll forming processes is around 30 m/min, but there are machines which can run up to 100 m/min (Sankar, 1996). The production rate depends greatly on the material thickness and the bend radius. It is also affected by shape complication and hence the number of stations, or steps required.

The number of roll stations required depends on section shape complexity, and their design has been largely a matter of skill and experience although nowadays computer-based expert systems and FE simulation software is available to aid a process planner. Figure 1.6 shows the development of a section shape through a series of rolls.
Figure 1.6: The strip is formed from an undeformed strip to a finished profile (Lindgren, 2005).

Strip is fed into a roll forming machine, where it is rolled continuously using successive sets of rolls. Rollers are located on the respective station together with the rotating system. The number of roll stations is not fixed, but depends on the final product geometry and the material used. In each station, a set of top and bottom rolls are fixed to the stand with the option of side rolls on the left and right. The side rolls rotate on vertical axes, and are used for producing vertical surfaces on parts.

In addition to a continuous section, intermittent features are sometimes added to the product, such as holes and notches. Therefore, the roll forming machine can have operations before or after the roll stands, such as punching, stamping or shearing. With these additional operations, roll forming lines can be set up to punch and cut off parts continuously. Depending on process convenience, the roll forming lines can be set up to use a pre-cut die where a single blank runs through the roll mill, or a post-cut die where the profile is cut-off at the end of the roll forming process. A simple arrangement of a conventional roll forming system with the attached press and cut-off machine is shown in Figure 1.7.