

Challenges in Special Steel Making

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Abstract : Special bar quality [SBQ] is a long steel product where an assured quality is delivered by the steel mill to its customer. The bars have enhanced tolerance to higher stress application and it is demanded for specialised component making. The SBQ bars are sought for component making processing units such as closed die hot forging, hot extrusion, cold forging, machining, heat treatment, welding operations. The final component quality of the secondary processing units depends on the quality maintained at the steel maker end along with quality maintained at the fabricator end. Thus, quality control is ensured at every unit process stages. The various market segments catered to by SBQ steel segment is ever growing and is reviewed. Steel mills need adequate infrastructure and technological capability to make these higher quality steels. Some of the critical stages of processing SBQ and the critical quality maintenance parameters at the steel mill in the manufacture has been brought out.

1. INTRODUCTION:

Steel long product produced, may be divided into Merchant Bar Quality [MBQ] and Special Bar Quality [SBQ]. MBQ steels, is manufactured to specified sizes with appropriate chemical limits to meet a set of properties, where the end use is non-critical. MBQ bars, is made from unconditioned billets. The bars may have liberal tolerances controls. The surface and core defects are wide and not well quantified. The bar manufacture may involve mild bending, hot forming, punching and welding. The quality norms in terms of internal porosity, surface seams are also liberal.

Special Bar Quality is a term used in long product industry, where an assured stress level in the application can be met by the steel [1,2]. They are long steel products manufactured to meet tough applications. Stress tolerance of the steel is enhanced which provide higher level of consistency and integrity. To achieve the desired level of performance chemical composition and cleanliness of the steel are critical to achieve the desired mechanical properties. While the chemistry achieved is as per the alloy design principles, the achievement of cleanliness levels is critical to achieve the special bar quality and they have a direct impact on the dynamic properties such as fatigue life of a component. The SBQ steel bars, are produced using processes that enhance quality parameters required for end use and customer specifications. The quality in the bars produced may be required to meet with the lowest levels of chemical segregation, inclusion rating, internal defects and surface defects.

Heterogeneity in a bulk steel is inherent in the manufacturing processes of the steel and SBQ has minimal heterogeneity acceptable to a customer. The heterogeneities in a steel include non-metallic inclusions [3,4], macro-segregation [5], micro segregation [6], micro-void or discontinuities that was generated in the casting [7] and that did not heal during subsequent hot deformation processes [8,9]. There is a quantified and assured acceptance level of the heterogeneity in the steel in terms of the quality of the steel bars. In terms of application, the SBQ steel performs in a highly loaded condition due to lower level of defect initiation sites. Hence, several safety critical high warranty prone components, where strength, fatigue life and durability requirements are there, fall in this category. The components are subjected to rotation, twisting and bending type of load application calls for SBQ steels.



SBQ steels are at the higher end of the quality spectrum in terms of both metallurgical consistency and dimensional accuracy. Some end uses of these steels may require superior surface quality, or special chemical restrictions, metallurgical characteristics, heat treatment or surface finishes. The internal quality of these steels is very important since machining and bending activities are involved during the processing of these steels in subsequent stages. In order to achieve the desired metallurgical quality, the steel has to be particularly clean. This makes the production route of these steels, a bit complex. Steel with high cleanliness is, achieved through the integrated steel making route or through an additional secondary steel refining process. The inputs have cleaner iron bearing inputs into an EAF in a mini mill. Internal metallurgical quality and consistency is, achieved by a meaningful reduction during the rolling process. These steels are, produced in fixed cut lengths or as wire rod coils.

2. Market Segments for SBQ:

The market segments for SBQ involves carbon steel, microalloyed steel, Low alloy heat treated steels, tool and die steels, high alloy steels, free cutting steels, case hardening steels, and stainless steels. These steels are functional grades, that is supplied, in different forms that include round bars, round corner squares, flats, round corner flats, hexagons, tubes, and special shapes. The products may also include hot rolled steel bars or cold finished steel bars. The SBQ steels have guaranteed with precise dimensions, metallurgical properties and chemistry. These steels have superior mechanical properties, defect free surface and internal quality. The products from the special bar quality steel line adapt to the customer's specific requirements, including those related to chemical composition, malleability, hardness, ductility and steel surface condition. SBQ steels are generally machined, forged or cold drawn during subsequent processing. The steel grades, is subjected to heat treatment such as direct hardening, carburizing, induction hardening, and/or nitriding. The SBQ bars are supplied as input raw material for closed die forging or open die forging, machining directly, cold working operations, wire drawing, extruded or further heat treatment etc.

The SBQ alloy steels meet critical levels of hardness and/or hardenability, strength, ductility, toughness, fatigue resistance, fracture resistance, wear resistance, machinability, and formability. Few grades are, applied to elevated temperature applications that demand high temperature strength, thermal fatigue, creep, oxidation etc. The market segments involved for use of SBQ steel for typical applications is, shown in Table 1. The various types of components made from SBQ steels are, listed. The steels include carbon steel, alloy steel and stainless steels as well. The bars are used in transportation sector [automotive, railways, marine etc.]; energy sector [thermal power, hydro power, nuclear power, wind power etc.]; strategic defence, nuclear and aerospace sectors; Oil and Gas industry, tool and die industry, mining industry and Industrial Machinery etc.

3. Attributes Demanded in a Special Steel:

SBQ steels are required when certain input steel quality is, demanded for a fabrication process such as hot forging, cold forging, machining, heat treatment etc. Use of merchant bar quality may lead to failure to achieve target properties in application or excessive defect in the processing that may lead to component failure. The process of manufacturing SBQ removes excessive pipe formation, chemical inhomogeneity, surface defects and internal core defects. The bars are, inspected and conditioned at every stage of the production process. The frequency and the degree of surface defects is influenced by chemical composition, type of steel, and bar size. Resulphurized grades, certain low C killed steels, and boron (B) treated steels are most susceptible to surface defects. Some end uses or fabricating procedures can necessitate one or more extra requirements. These requirements include special hardenability [11], internal soundness, non-metallic inclusion rating, and surface condition and microstructure and properties described in the standards. The quality specification for bars to which only one of these special requirements is applied is the 'restrictive requirements' of the quality. The restrictive requirements can be a single special restriction or more. Multiple restrictive requirement SBQ bars are those to which two or more restrictive requirements are applied.

Table 1 Market segments of SBQ steels and components made from long bar products

Automotive LCV, MCV & HCV
<p><u>Engine Components:</u> Crankshaft, conrod, rocker arm shaft, cam shaft, piston pin, ring gear, monotherm Piston, Cam followers, Cam rollers, Valve rocker arms, Valve rocker arm shafts, Valve springs, Push rods, Diesel injection systems components, Gudgeon pins, timing gears, fuel injection pumps forging for diesel engines, bearings</p> <p><u>Transmission:</u> Mission gear, differential gear, output shaft, shift fork, CVT Pulley, forged parts going into drive shafts, Gear Counter shaft, gear boxes Coupling sleeves Carriers Gear shift shafts Shafts Planetary gears Sun gears Ring gears, Differential gears Crown wheels Planetary gears Sun gears Ring gears, Gears Levers, Constant velocity joint, Transmission shafts, Joint Yoke, bearings</p> <p><u>Chassis Components:</u> Front axle, steering knuckle, Rack for Pinion gear, shock absorber spring, steering, suspension and hydraulic components, Ball joint, blades, eyes for hydraulic cylinders, Gears, Starter rings, stub axle, yokes, rings, rear axles, bearings, seamless tubes, fastners, steering suspension, hydraulic component</p> <p><u>Wheel Assembly:</u> Wheel Hub unit, rear axles Couplings, Carriers Drive shafts, Flanges for universal driving shaft, Pinions Thrust washers Break arms, Wheel nuts and bolts; cable wires, tyre beads</p>
Railways
Axles, rails, wheel forgings, fastners, piston rods, flange, housing pieces, wagon parts like screw couplings and other for wagons, cushioning device components, pin and steel liners, traction gears; wheels, axles, brake disks, drive unit mechanisms, and joints, for high speed rail transport, fastners, crankshafts, Portal axles for rails, connecting rod for diesel engine, claw lock for rails.
Marine / Ship Building
Propeller Shafts, Rudder Stock, Intermediate Shaft, Pinion Shaft, Forged Plates, Forged Rounds and others. Crank shaft, connecting rod, Marine engine Bolts, crank shaft, connecting rod
BioMedical
Surgical stainless steel [316, 440, 420]
Mining Equipment
Shafts, crusher forgings, bearing, drill rigs to drill bits, Rock drilling equipment, Crusher Shafts, Excavator Shaft, Transmission Shafts, Grinding Mill Rolls, Pinions, front spindle, etc.
Agriculture
parts for loaders, farm equipment, land diggers, ploughs, gears, shafts, levers and spindles to tie-rod ends, spike harrow teeth and cultivator shafts.
Steel Mill Components
Rolls & Roll Blanks used in rolling mills like, Table Rolls, Coiling Rolls, Leveller Rolls, Descaler Rolls, Work Rolls, Backup Rolls, chain steels, hooks
Oil & Gas
<p>Mud pump forgings, Body Block Forgings, Cross Forgings, Forged Valves, X - mas tree Forgings, Well Testing Forgings. oil string</p> <p>Surface: Gate valve Body surface, casing head surface, shell surface, blow out preventor, Annular BOP for surface and sub-surface drilling</p> <p>Sub Sea : Spool body, sub sea Christmas tree, connector for sub sea drilling, Mandrel for sub sea Christmas tree, Shale Gas: crankshaft for fraction pump, fluid end fraction pump, machined fluid end</p>
Thermal Power Plant
High temperature fastner, valve forgings, turbine forgings, valves, pipes and fittings, hydraulic shafts, flanges, valve bodies and stems, tees, elbow reducers, saddles, rock cutter bits, drilling hardware, and high-pressure valves and fittings, shafts, Rotor, Turbine Shafts and others. valves, pipes and fittings, hydraulic shafts, steam turbine rotors [High Pressure, Intermediate pressure], steam turbine excitor shaft, heat exchanger tube sheet
Hydro turbine
Generator Shafts, Rotor, Turbine Shafts, fastners

.....Contd. Table 1 Market segments of SBQ steels and components made from long bar products

Wind turbine
Components for Windmills, Windmill Main Shafts, wind turbine components, bearings and seamless tubes, transmission gear blanks, Transmission rings, crane wheel drives, gear box hollow shafts
Chemical & Petrochemical
Pressure vessel for crude refining, Shafts (Round and Square) in Fertiliser Plants, Refinery, Petrochemical, Cement, Sugar, Chemicals, valves and pipeline couplings for oil extraction
Defence
Barrels, shafts, shell forgings, gears, bearing, Tie rod, missile components, rifle triggers to nuclear submarine drive shafts. Heavy tanks, missiles, armoured personnel carriers, shells and other heavy artillery
Nuclear
Nuclear flask component, heavy forgings for reactor pressure vessels, steam turbines and generators, but extends to other engineered component, turbine rotor, generator shaft, retainer rings, reactor pressure vessel, nozzle, shells, shell flanges, Forgings for both Nuclear Island and Turbine Island
Aerospace
Landing gears, Missile parts, forgings are widely used in commercial jets, helicopters, piston-engine planes, military aircraft and spacecraft, bulkheads, wing roots and spars, hinges, engine mounts, brackets, beams, shafts, landing gear cylinders and struts, wheels, brake carriers and discs and arresting hooks, shafts, couplings, manifolds, wheel lever forging, fan forging, landing gear main leg forging
Industrial
Hook, Chains, Mooring chains for offshore platform, Input/output shafts, Pump Bodies, Wheel hubs and spindles, Ring gears and pinions, Valve bodies, Balls, Tees, Seats, Hammer union nuts, Check valves, crane wheels, and machine parts. , pins, studs, bolts, gears, shafts, axles, bolts, studs, crane wheels, and machine parts.
General Engineering
engine and transmission parts, variety of gears, sprockets, levers, shafts, spindles, ball joints, wheel hubs, rollers, yokes, axle beams, bearing holders and links. blanks, blocks, connecting rods, cylinders, discs, elbows, rings, T's, shafts and sleeves.
Tool & Die steel
Hand tools and hardware: Pliers, hammers, sledges, wrenches and garden tools, as well as wire-rope clips, sockets, hooks, turnbuckles and eye bolts, Dies for plastic moulds, die casting, forging tools and dies, hammers, screwdrivers and wrenches

SBQ quality steel bars can be produced using rimmed, capped, semi-killed, or fully killed deoxidation practice. The appropriate type is dependent on chemical composition, quality, and customer specifications. In addition, specification may demand quantified austenitic grain size, microstructure and mechanical properties and dimension. The tensile strength ranges in SBQ is similar to those applicable for the MBQ steels, while there could be enhanced fracture resistance properties such as impact or fracture toughness. There no specified size ranges established for SBQ steels. The bars can be squares, rounds, ovals, half-ovals, half-rounds, octagons, and other special special shapes such as beam blanks. A customer needed to give specific quality parameters for his application in unambiguous numerical value of acceptance depending on his end use application. Some of the typical parameters sought for SBQ steel quality is, given in Table 2. The Table brings out the quality parameters, typical equipment needed, critical parameters that need to be controlled and the requirements to qualify the steel under SBQ category. The SBQ steels have to pass through narrow chemistry bands and higher levels of customer specification. More than cost performance is the basis a customer evaluates a SBQ producer. Grade wise even simple carbon steels are enabled to perform at higher performance levels [life or load enhancement], when it is subjected to SBQ processing.

Table 2 Typical quality and control parameters demanded in a SBQ steel.

Quality Parameters	Equipment/ Processing	Critical Parameters	Requirements
Compositional	Ladle furnace	Steel making	Meeting very narrow band of chemistry
Size range	Ingot, Caster & Rolling Mill	Roll pass; Kocks or PSM mill	Strict dimensional control
Tolerances on dimension	Rolling Mill	Roll pass	European standards, for round bars EN 10060. Better than DIN/3
Manufacturing lengths	Rolling Mill	Decide by the Rolling mill	6,000 mm (+200 mm) 10% of bar below specs
Roundness / squareness	Rolling Mill	Roll pass	Out of roundness = [max dia- min dia]. Desired at most 2/3 of the diameter tolerance.
Straightness	Rolling Mill & Bar straightening machines	Rolling Mill; Cooling condition post hot rolling	Straightness is measured as the maximum height of arch, i.e. the largest deviation from the straight line. Normally the test length is 1.0 metre. Standard deviation of straightness is 2 mm/meter maximum.
Surface quality	Hot eye during rolling; Magna flux; MPI; Dye penetrant at times; ECT for peeled bar	Caster; Rolling; Cooling bed	Standard surface crack depth is max. 1% of dia.[mutually agreed]. Bars are inspected by magna flux leak detection or magnetic particle method. Normally, surface quality class D can be achieved for diameters up to Ø 80 mm and C for diameters up to Ø 120 mm complying with EN 10221.
End executions	Hot saw ; Hot shear; Chamfer machine	Steel hardness	Smaller sizes rolled products up to Ø 75-90 mm are cold sheared. Larger sizes are hot sawn or abrasive cut. Deburred at end
Decarburisation & excessive scaling	Reheating furnace; Rolling Mill	Temperature, time, Air:Fuel mixture; coating	Good surface quality and Yield losses to be reduced
Banding	Steel Grade; EMS, super heat; Caster; Rolling Mill	Columnar to equiaxed zone in concast; Degree of deformation;	Banding in alloy steels is minimized. The hardness difference between adjacent layers <5BHN
Non-Metallic Inclusion Rating	Ladle furnace; Tundish; Caster; Rolling Mill	LF melting; Casting temperature, super heat, mould powder.	Devoid of oxide inclusion rating Type B and Type C Thin and Thick series to be <0.5 ; sulphide as grade demands; Silicates Nil values
Macro inclusion	Ladle furnace; Casting	Exogeneous inclusion	Demand on extreme value statistics; Flaw size determination on Immersion UT testing at high frequency
Microstructure	Steel Grade; Caster; rolling; heat treatment	Processing & Heat treatment [Grain size; phases]	ASTM Grain size No.8 and higher to improve strength, toughness & FATT
Hardness	Steel grade; rolling; heat treatment	Microstructure	Depends on fabrication input. Mostly around 260BHN for eased of machining
Heat treatment supply condition	Heat treatment furnace	Microstructure	Required heat treatment such as annealing, normalizing or hardening & tempering

Contd..... Table 2 Typical quality and control parameters demanded in a SBQ steel.

Quality Parameters	Equipment/ Processing	Critical Parameters	Requirements
Hardenability [Jominy specs]	Steel chemistry; Hot Rolling	Chemistry; grain size	As per application it is specified
Mechanical Properties	Rolling/ heat treatment	Phase constitution Microstructure, grain size & inclusion	Strength, toughness, ductility at room temperature or high temperature, Impact toughness, FATT, Fracture toughness, Fatigue properties, creep properties etc.
Internal Soundness	Caster; Hot rolling Mill	Casting & rolling parameters	Internal defect size measured by Ultra sonic testing as per 2 to 8 mm FBH based on product thickness.

4. Processing of SBQ

In the manufacture of SBQ, one has to assess the type of infrastructure a plant has towards manufacture of the same. It is necessary to have infrastructure that has quality control at every stage of its operation. The infrastructure should address to some of the enhanced quality requirement demanded by the steel. JSW Salem works is a leading SBQ steel producer in India. The steel plant should have a means to produce steels with lowest levels of impurities within a narrow chemistry range. The infrastructure the plant has towards making SBQ has to be, examined by a customer. The typical processing route of JSW Salem Works is, given in Fig.1. The steel in the plant is made through, the blast furnace route with controlled input charge material, with quality control at every unit process with adequate equipment. The steel in JSW is made from the blast furnace – EOF route with least addition of external scrap, which is a source of certain defect causing tramp impurities such as Cu, Sn, As. Excess residual Cu can lead to surface defects that defeats the purpose of SBQ [12]. The steel made from blast furnace route is devoid of harmful residual elements unlike a recycled EAF steel.

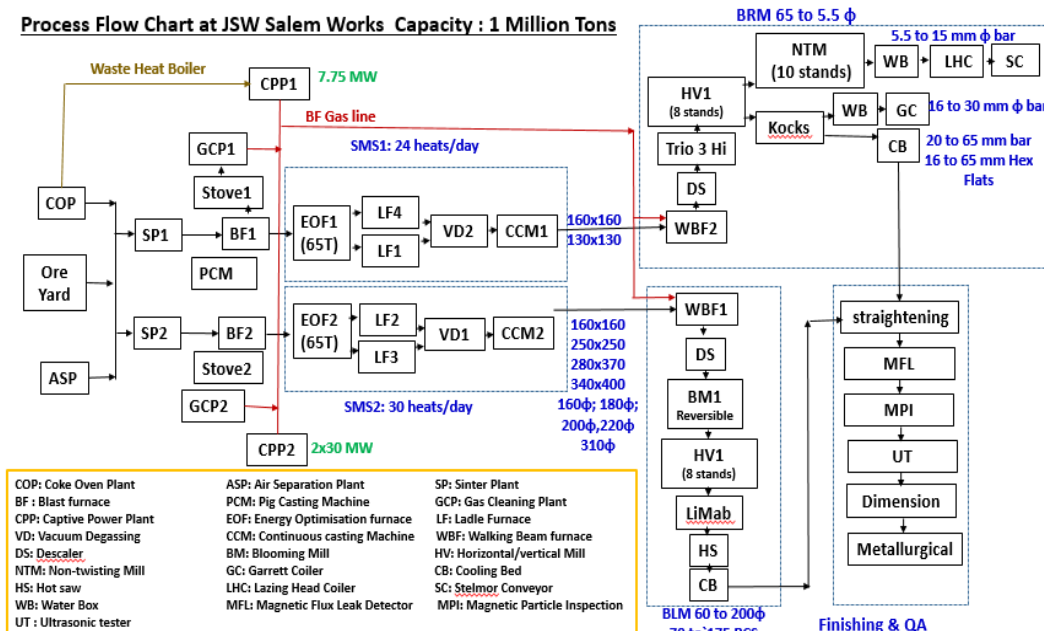


Fig.1 Process Flow chart of JSW Salem Works

4.1 Steel Making

The blast furnace hot metal pig iron is, extracted with the desired level of Si content [0.5 to 1.2%] and carbon content [$\sim 4.3\%$]. Lower levels of P, S and Ti, is desired for SBQ steels. The exothermic oxidation of the carbon and Si with oxygen in an EOF produces heat sufficient for steel making. The oxidation of all solute elements in hot metal, is carried out in the EOF. The elements with higher oxide stability [lower standard free energy of oxide] preferentially get oxidised first. While all the alloying elements are oxidized, the iron purity increases to $>99.5\%$ pure iron with dissolved oxygen. It is, desired to ensure that the tap carbon level is controlled, to achieve the lowest possible equilibrium oxygen in the bath. It is desirable to maintain EOF melt oxygen <600 ppm for SBQ type clean steel. The low phosphorous levels required by the SBQ steels is, generated by promoting P mass transfer from molten steel to slag at this stage. Some of the stringent mechanical property requirement in power plant, aerospace and defence sectors, demand extremely low P level as low P content enhances the fracture toughness and DBTT of the of the heat treated alloy steel [13]. The levels may be as low as 0.007% in power plant rotor steel forgings. The slag basicity and FeO content is controlled, to ensure dephosphorisation at the primary melting stages such as EOF furnace [14]. The FeO content in the slag has to be maintained so that the equilibrium oxygen in the pure iron tapped does not increase. If the FeO content in slag is large then, the equilibrium oxygen in steel bath is higher during tap. This promotes more number of inclusions in the steel at the secondary steel making stage. Low inclusion levels are desired by SBQ steels in ladle furnace process ensure management of easily reducible oxides (FeO+MnO) towards lowest levels.

The steel from EOF is, transferred to a ladle with deoxidisers to bring down the initial dissolved oxygen in steel. Here, there are several strategies to control the inclusions. Addition of carbon along with the tapping stream, prevent ingress of air to molten steel bath due to carbon oxidation. In some of the experimental heats made by the author, observed, a high Al recovery along with high carbon pick up. This implied that the carbon is able to go into solution in molten steel and contributes to the lowering of oxide inclusions in the bath. The residual oxygen in the tapped steel is killed with a combined Si-Mn deoxidation or with large amounts of Al additions in the ladle. This initial deoxidation during tapping is called as blocking the steel heat, which brings down the oxygen level in molten steel, low enough, so that alloying elements added subsequently are fully recovered without oxidation. The initial Al killing gives lowest oxygen levels during blocking [15]. Alloying using quality controlled ferroalloys is carried out in ladle furnace, depending on the steel grade. In some practices, initial slag skimming followed by synthetic slag addition is carried out [16, 17]. The slag in LF has to have adequate lime content $>50\%$ to ensure a white slag practice, the reducing condition along with good basicity for refining reaction. Vacuum Degassing with a pressure <1 mbar is carried out, where excellent degassing is promoted by intense gas stirring under reduced pressure. Nitrogen levels fall down along with hydrogen to low values and in SBQ steel [18]. The FeO content of the slag falls to very low levels $<0.5\%$ [reducing condition], which along with high slag basicity, promote excellent desulphurisation. Some of the steels, where transverse toughness properties are critical sulphide inclusions have to be reduced and hence very low levels of S $<0.005\%$ is targeted [19]. Desulphurisation takes place intensely at vacuum degassing stage where again the FeO content is monitored to the lowest level possible to achieve low dissolve oxygen content in the bath [20]. In the case of resulphurised steel, sulphur wire is subsequently added to meet the required sulphur levels [21]. Usually, deoxidant addition, especially Al is carried out within vacuum as this is the element most reactive and may fluctuate in Ladle furnace. After Vacuum degassing treatment, a period of soft rinsing, at low Ar flow rates has to be carried out. Here, the flow rate of Ar has to be at low rates, which ensure formation of large plume of fine bubbles. Each of this bubbles as they ascend through the melt provide heterogeneous interfaces for inclusions to interact with each other and float to melt surface. Often, stirring efficiency is a parameter optimised during alloying and soft rinsing [22]. It must be ensured, that the duration of soft rinsing does not result in temperature fall that warrants re-arcing. Appropriate initial ladle temperature should be maintained to, account for this loss in temperature.

If there is a requirement of Ca treatment, the LF processing window is adjusted with suitable slag tailoring and Ca addition maintaining a Ca/Al ratio suitable enough to promote $\text{CaO} \cdot \text{Al}_2\text{O}_3$ inclusion which is liquid

at the temperature of steel making [23]. If the required liquid phase is not achieved high temperature calcium aluminate inclusions populate the steel bath as inclusions. Usually, for high quality steel, after VD arcing is not permitted as, it exposes the melt to atmospheric oxygen during turbulent arcing. After VD the steel is very clean with least amount of gaseous elements. Sometimes, deoxidant addition such as Al content is specified and this has to be made up preferably in the VD stage only. The residual Al is important depending on the grade as this combines with N to form fine AlN inclusions that ensures fine grain sizes desired in an SBQ [24]. Fine grain sizes enhance the strength and toughness and optimum level is required.

4.2 Casting of Steel

SBQ involves both ingot and continuous casting processes and the later process predominates due to higher yield, productivity and quality in certain areas. Ingot casting is preferred where the product requires highly recrystallized grain size that warrants high reduction ratio.

Once the liquid steel is made, it is important to maintain its quality during subsequent processing. The tundish has to have a good refractory that is stable and least reactive to the melt chemical and physical interaction and should have flow behaviour where macro inclusions float out [25]. The refractory with high MgO content is preferred. It is subjected to pre-determined prolonged heating to ensure that the lining is free of moisture. The molten bath, when transferred to tundish may react with moisture to introduce hydrogen and oxygen [26]. Hydrogen measurement at this stage is a critical parameter. Appropriate post processing treatments such as stack cooling or anti flaking treatments depend on the hydrogen levels at this stage [27]. Also the nitrogen pick-up at this stage is monitored as there is a correlation between N pick up and oxygen pick up from atmosphere [28]. Casting is carried out with proper tundish flux through an SEN. Free opening of the ladle is desired and the SEN is properly shrouded to prevent ingress of air to oxidise the bath. The SEN with upward angle nozzle is preferred as the flow is smoothened and the flow pattern enables flotation of inclusion towards the top mould surface layers, where the mould powders have the ability to absorb inclusion [29]. The mould powder choice is critical to the grade. For example, the peritectic grade demand a different condition of solidification compared to a high carbon steel grade [30,31]. The wrong choice of mould powder can lead to sub-surface seams that may escape the notice during surface grinding yet show up during hot rolling. The super heat needs to be optimised [32]. High super heat favours inclusion flotation during casting, but macro segregation and centre line porosity tends to enhance. Too low a super heat tends to clog the nozzle and prevent inclusion from floating. Appropriate parameters of casting speed, primary and secondary cooling are to be ensured [33, 34, 35]. The casting mould is subjected to proper oscillation frequency to ensure smooth stripping of the billet and improper choice of condition may lead to severe ripples in the steels in surface, especially at the corners. It may also lead to transverse crack and hooke defect [36]. Another important phenomenon that will ensure proper solidification with freedom from surface and sub-surface inclusions is, obtained by the electromagnetic stirring in the mould or strand. The stirring ensures better heat transfer that gives better solidification macro structure and the lighter inclusions are, pushed to the core due to the centripetal force acting on the particles [37, 38]. Different grades have different characteristics in secondary cooling. In-appropriate choice of this parameter again results in seam cracks. The temperature during unbending in certain grades leads to embrittlement associated with AlN precipitation [39]. Automatic mould level controller is another control parameter that ensure proper turbulence free meniscus solidification [40] that results in superior surface quality with mould powder smoothly filled between the solidifying steel shell and water cooled mould.

The bloom or billet solidification structure is usually heterogeneous with a chill layer, columnar zone and core equiaxed zone [41]. The columnar zone is minimised and efforts to maximize equiaxed grains. The deformation of columnar zone product results in banded microstructure with anisotropic mechanical properties especially transverse toughness and ductility. Efforts to maximize the equiaxed zone is maximised by proper choice of superheat, casting speed, primary and secondary cooling in a continuous casting process. The structural banding is an important aspect of alloy steel and it is seldom possible to completely eliminate the banded microstructure caused by the interdendritic region rich in solute and dendrite core devoid of alloying elements [42, 43]. The acceptable level of banding is specified to be about 5 BHN difference in

some of the standards. Depending on the grade, one may encounter core central porosity or macro segregation. Efforts to minimize the same by optimising super heat of the grade being cast, casting speed, and EMS current.

Secondary cooling characteristics govern the initiation of surface cracks and one needs to optimise the parameters of the same for a given grade. There could be formation of embrittling phases during unbending in continuous casting that can initiate surface flaws [44]. Although much lower in volume, special steels produced by Electro-slag remelting, vacuum arc remelting etc. Are, classified under SBQ type steels. These steels may be demanded for use in high end applications in nuclear, defence and aerospace.

4.3 Hot Rolling of Steel

The cast blooms or billets made are hot scarfed, in some plant, while they are subject to cold grinding before being hot rolled [45]. In some plants hot charging is carried out which, enables conservation of energy apart from preventing phase transformation during complete cooling that involves volume changes and associated stresses in the bloom or billet [46, 47]. The blooms have to be heated appropriately before hot deformation in reheating furnace as a temperature gradient will result in non-uniform flow strength and inhomogeneous deformation. The thermal cycling is such that the core achieves the required temperature [48]. During the bloom re-heating, apart from choice of heating parameters, oxidation of the bloom and the surface decarburisation are important aspects that are crucial to SBQ product [49]. Scales generated in the reheating operation reduces the steel yield, which needs to be curtailed, and in some grades can be potential sites for crack initiation. The choice of the burning fuel and fuel:air ratio are factor optimised in a furnace. The soaked bloom is, subjected to initial deformation in a blooming mill where the cast structure is heavily broken down. The deformation at this stage is large enough to convert the cast dendritic microstructure to recrystallized grain structure. Phenomenon such as static, dynamic and metadynamic recrystallization refines the grain structure [50]. The reduction ratio is a monitored measure of the extent of deformation that has enabled the cast product to become a wrought product. The fine grain structure obtained has to be retained especially after the finish rolling. The deformation strain, pass schedule and rpm are critical parameters apart from the surface and core quality of the input bloom. Post rolling, the blooms are cooled in cooling table or slow cooling boxes or pits or vermiculite, to ensure achievement of suitable hardness and also diffusing out hydrogen in steel in some grades. The final hardness achievement in the bars, suitable for machining, may be specified by some of the customer, where slow cooling needs to get a softer product. Certain high alloy steel prone for hydrogen flaking needs to be given a proper anti-flaking heat treatment below A_1 temperature [51]. Hydrogen level in excess of 1.2 ppm in high hardenability steel such as C-Mn, Cr-Mo and Ni-Cr-Mo steels are prone for hydrogen flaking problem.

4.4 Heat Treatment Testing & Quality Control:

Many of the SBQ steels should show favourable response to heat treatment. They have specified hardenability, fine grains, flawless surfaces etc. This has to be consistently maintained by the steel mill to ensure consistent heat treatment response and mechanical property requirements in production at customer end. Some of the SBQ steels are inclusion engineered, where inclusion modification is carried out using Ca, Te, Pb or re-sulfurised [52 to 54]. They form fine evenly distributed secondary phases, which can enhance machinability. SBQ may also have non-heat treated steel grades such as microalloyed steel [55]. These steels, post forging achieves high strength properties.

In terms of quality control, the steels have to conform to chemistry, inclusion rating, grain size, microstructure, macrostructure, surface flaw by Magnaflux or MPI, core defect by ultra-sonic testing, decarburisation, banding level and mechanical properties at the customer specified conditions. There are other physical attributes such as the dimension, multiple length, straightness, ovality in round product or rhomboidity in a square product [56]. Steel mills, which make SBQ has the specialised infrastructure to ensure dimension and defect free surfaces. The machines include straightening machines, surface grinding machines for blooms, annealing, peeling units etc.

Often SBQ steels undergo direct machining or further processing such as closed die forging, extrusion operation or cold drawing operation in a spheroidize annealed condition [57] or a heat treatment after fabrication or surface hardening heat treatment post fabrication. Quality steel mill understands the requirement of subsequent processing industry and tailors the SBQ steel bar quality to suit the end use applications so that the products can be realized with consistency and least failures.

SBQ steels are, subjected to annealing, normalising, hardening and tempering heat treatments. Minimising defect initiation sites in the steel making operation enable achievement of consistent properties. Properties such as transverse impact or fracture toughness are superior in SBQ steels. The embrittlement generating impurities are least in the steel. There is a good microstructural homogeneity due to control over parameters such as hardenability. In inclusion engineered steels, there is a consistency in terms of machinability. Surface heat treatment response of the SBQ steel bars show consistency in the hardness and depth of layers and grain size in processes such as, carburising, nitriding, induction hardening etc, [58-59]. The surface quality of the bars influence the flaws generated in heat treatment and these steels and that is one reason SBQ is preferred for heat treated products.

In spite of additional costs associated with additional infrastructural necessity in manufacture and testing, productivity losses associated with higher refining times, and yield losses due to higher discards, the customer prefers SBQ to ensure assured performance. The SBQ steel market is growing. Customers generally assesses, the capability of the product by its performance in final applications.

5 Conclusion:

A review of various processing conditions in a steel mill in the manufacture of SBQ steels has been brought out. Special bar quality requires assured mechanical and quality parameters which needs to be adhered to by the steel mills. Proper infrastructure and processing technological capability and scientific understanding is needed for the manufacture of SBQ. JSW is a leading producer of SBQ with excellent infrastructure for the manufacture and quality assurance of the products.

6. References:

- [1] Timken steel <http://www.timkensteel.com/what-we-make/high-performance-steel/sbq-steel-bars-and-billets#sthash.K0FnkHql.dpuf>
- [2] Newquist Don E, Watson Peter S., Rohr David B., Brunsdale Anne E., Crawford Carol T. and Nuzum Janet A., "Certain special quality hot-rolled and semi-finished Carbon and Alloy steel products from Brazil", Determination of the Commission in, Investigation No. 731-TA-572, USITC Publication 1992, July, I6-I8, 2537.
- [3] Zhang Lifeng and Thomas Brian, "State of the art in the control of inclusions during steel ingot casting", Met Trans B., 2006, V.37B, Oct., p.733-800.
- [4] Zhang Lifeng, and Thomas Brian, XXIV National Steel making symposium, Morelia, Mich, Mexico, 26-28, Nov.2003, p.138-183.
- [5] Howe A A, "Segregation and phase distribution during solidification of carbon alloy and stainless steel", Catalogue No. :CD-NA-13302-EN-C, Pub by the Commission of the European Communities, Luxemborg.
- [6] Won Young-Mok, and Thomas Brian, " Simple model of microsegregation during solidification of steel", Met Trans A, 2001, V.32A, July, p.1755.
- [7] Pfengfei U, "Numerical modelling of porosity and macrosegregation in continuous casting of steel", Doctoral Thesis, 2013, University of Iowa, <https://ir.uiowa.edu/etd/2482;ir.uiowa.edu/viewcontent.cgi?article=4610&context=etd>
- [8] Liu Yazheng, Jiang Bo, Liu Guanglei, Wang Zhilin, Zhang Chaolei, Zhao Zhigang and Sun Jianlin, "Void Closure and the Sensitivity Analysis of the Process Parameters during Forging of Large Steel Ingot",

8nd International Conference on Physical and Numerical Simulation of Materials Processing, ICPNS'16, Seattle Marriott Waterfront, Seattle, Washington, USA, 2016, October, 14-17.

- [9] Yu, H., Tieu, A. K., Lu, C. & Godbole, A. R. (2014). Investigation of closure of internal cracks during rolling by FE model considering crack surface roughness. *International Journal of Advanced Manufacturing Technology*, 75 (9-12), 1633-1640.
- [10] Kor G. J. W., and Glaws P. C., "Ladle Refining and Vacuum Degassing", Chapter 11, *Steelmaking and Refining Volume*, Copyright © 1998, The AISE Steel Foundation, Pittsburgh, PA. <http://studylib.net/doc/8246142/chapter-11---ladle-refining-and-vacuum-degassing>
- [11] Doyuglas V. Doane, "Application of hardenability concepts in heat treatment of steel ", *J. Heat Treating*, Vol. 1, No.1, p.5. http://www1.diccism.unipi.it/Valentini_Renzo/slides%20lezione%20met.%20meccanica/hardenability.pdf
- [12] V. Leroy, R. D'Haeyer, J. Defourny, T. Hoogendoorn, J. P. Birat, H. J. Grabke, W. B. Morrison, N. G. Henderson, R. D. Longbottom, T. Laux, I. Les "Effects of tramp elements in flat and long products", European Commission technical steel research, EUR Report No. CGNA16672ENC_0
- [13] Cheruvu N S and Seth B B, "The influences of impurity content, tensile strength, and grain size on in-service temper embrittlement of CrMoV steels", *Met Trans., A*, Nov, 1989, V.20 no.11, pp.2345-2354
- [14] Somnath Basu, "Studies on dephosphorisation during steel making", Doctoral Thesis, School of Industrial Engineering and Management, Dept of Material Sci. & Engg., Material Process Science, Royal Institute of Technology, SE-10044, Stockholm, Sweden, 2007. P.7-19 & 32-39.
- [15] Socha Ladislav, Bazan J, Styrnal Pwetr, Pilka Vaclav, Piegza Zbygnev, Melecky Jan, Michalek Karel, Tkadleckova Marketa, "Evaluation of steel desulphurisation in the ladle during the utilisation of briquetting fluxing agent for slag" *Proc of Conf Metal-2012*, 5.2012 Brno, Czech Republic, EU, 2013, p. 23.-25.
- [16] Gavanescu Adrian, *Annals of Faculty Engineering Hunedoara – International Journal of Engineering*, IX, 2011, p.177. <http://annals.fih.upt.ro/pdf-full/2011/ANNALS-2011-4-37.pdf>
- [17] Socha L, Michalek K., Bazan J., Gryc K., Machovec P. AK', Opler A., Styrnal P., *Archives of Metallurgy and Materials*, Volume 59, 2014, Issue 2, p.809-813
- [18] Turkdogan E T, "Fundamentals of Steel making", Pub by Institute of Materials, UK, 1996, p.277-284.
- [19] Bul'ko B, Kijac J and Domovec M, "Optimization slag composition in ladle furnace Considering to effective steel desulfurisation", *Acta Metalurgica Slovaca*, 2009, 15, 2, p.93-99
- [20] Stephen Famurewa Mayowa, "Improvement of the desulphurization process by slag composition control in ladle furnace", Master Thesis, Lulea University of Technology, Dept of Chem Eng & Geo Sciences, Division of Process Met., 2009. P.9-14 & p.27-44
- [21] Crawford G. P., "Wire injection or metallurgical powders into molten metal", *INFACON 6, Proceedings of the 6th International Ferroalloy Congress*, Cape Town, Vol.1. Johannesburg, SAIMM, 1992. pp, 271-277
- [22] Shen Jiandong, Zhao Yong, Han Guijin, "Design on Optimization of Argon Bottom Blowing of Molten Steel ladle", *Procedia Engineering*, Volume 16, 2011, p. 284-290.
- [23] Lind Minna, "Mechanism and kinetics of transformation of Alumina inclusions in steel by calcium treatment", Doctoral thesis, Helsinki University of Technology Publications in Materials Science and Engineering, 8., Sept., 2006. P. 1-22 and p. 58-60.
- [24] Cheng Leon M., Hawbolt E. Bruce, Ray T and Croft Meadow, "Dissolution and coarsening of aluminum nitride precipitates in low carbon steel — distribution, size and morphology", *Canadian Metallurgical Quarterly*, 2000, Vol 39, No 1, pp 73-86.

- [25] SahaiYogeshwar and EmiToshihiko, “Tundish Technology for Clean Steel Production”, World Scientific Publishing Co. Pte. Ltd., 2008, p.17-73.
- [26] Dekkers, R., Blanpain, B., Plessers, J., and Wollants, P., “Steel cleanliness and hydrogen in liquid steel”. VII International Conference on Molten Slags Fluxes and Salts, The South African Institute of Mining and Metallurgy, 2004, p.753
- [27] VoronenkoB. I., “Hydrogen and flakes in steel”, Metal Science and Heat Treatment, 1997, Vol. 39, Nos. 11 - 12, p.462-470.
- [28] Doostmohammadi M, Andersson M, Karasev A and Jonsson P G, “ Use of computational thermodynamic calculations in studying the slag/steel equilibrium during vacuum degassing” ,Steel Research Int., 2010, 81, V.1, p.31 – 39.
- [29] Realá Cesar, Hoyos Luis, Cervantes Francisco, Mirandac Raul, Palomar Pardavéa Manuel, and Gonzalez Jesus, , “Sensitivity analysis of the three dimensional flow dynamics in the continuous casting submerged entry nozzle “, Mechanica Computational V.XXVI, 2007, p.1292-1310. www.amcaonline.org.ar
- [30] Görnerup, M., Hayashi, M., Däcker, C.-Å., And Seetharaman, S,” Mould fluxes in continuous casting of steel—characterization and performance tuning”, VII International Conference on Molten Slags Fluxes and Salts, The South African Institute of Mining and Metallurgy, 2004, p.745.
- [31] Majumdar B, “ A process for developing continuous casting mould powder for steel industries“, Journal of Scientific and Industrial Research,1999, V.58, Oct., p.773-780.
- [32] ZhangJian, ChenDengfu, WangShuigen, and LongMujun, “Compensation Control Model of Superheat and Cooling Water Temperature for Secondary Cooling of Continuous Casting”, steel research int., 2011, 82, No. 3, p.213-221.
- [33] FalkusJ, Miłkowska-Piszczyk K, “Strategy of cooling parameters selection in the continuous casting of steel”, Arch. Metall. Mater., 2016, Vol. 61, No.1, p.329-334.
- [34] Štetina Josef, Kavicka František, Mauder Tomáš, Klimes Lubomír, Masarik Miloš, Šanab Zdeněk, Optimization of secondary cooling In order to achieve higher surface temperatures at the slab unbending point”, Metal 2012, Brno, Czech Republic, EU , 5, 23- 25.
- [35] SpuyD. deV. van der , Craig I K and Pistorius P C, “An optimization procedure for the secondary cooling zone of a continuous billet caster”, The Journal of The South African Institute of Mining and Metallurgy JANUARY/FEBRUARY , 1999, p.49-54.
- [36] CibulkaJ., KrzokR., HermannR., BocekD., Cupek J. and MichalekK., “Impact of oscillation parameters on surface quality of cast billets”, Arch. Metall. Mater., 2016, Vol. 61, No 1, p.283–288.
- [37] Stránský Karel, Kavička František, Sekanina Bohumil, Štětina Josef, Dobrovská Jana, Stransky, Lubomir, Brně V, and oceli Výroba, Hutnické listy č. 3/2009, p.26.
- [38] ChaoXiao, Jiong-Ming Zhang, Yan-zhaoLuo,GdongWei Xiao, LianW U, Shun-XiWang, “Control of macrosegregation behavior by Applying Final Electromagnetic Stirring for Continuously Cast High Carbon Steel Billet”, Journal of Iron and Steel Research, International, 2013, 20(11),p.13-20.
- [39] DarsouniA, Bouzabata B and MontheilletF, “Hot Ductility of a Microalloyed Steel in the Intermediate Temperature Range”, Journal De Physique IV Colloque C7, supplement au Journal de Physique 1995, 111, Volume 5, November C7, p.347.
- [40] Smutný Lubomír, Farana Radim, Víteček Antonín, Kačmář Dalibor, “ Mould level control for the continuous steel casting”, <https://pdfs.semanticscholar.org/24f7/2089ed3cd4f29dea6707f5d3ed1e83634628.pdf>

- [41] White C V, Krauss G and Matlock D K, “ Solidification structure and the effect of hot reduction in continuously cast steel fro bars and forgings”, <https://www.forging.org/uploaded/content/media/143-white.pdf>
- [42] Grange R A, “ Effect of microstructural banding in steel”, Met Trans., 1971, V.2, p.471.
- [43] Herring Daniel H, “Segregation and Banding in Carbon and Alloy Steel“, <http://www.industrialheating.com/ext/resources/Issues/October2013/Treat/ih1013-hidr-fig1-615.jpg>
- [44] Mišičko R., Embrittlement of continuously cast steel products and its microstructural effects , Acta Metallurgica Slovaca, 2008, 14, 1, p.50 – 58.
- [45] Zhou Xiaoxu and ThomasBrian G., “Modeling Steel Slab Heat Transfer during Scarfing Processing”,Continuous Casting Consortium Report to POSCO, Department of Mechanical Science and Engineering University of Illinois at Urbana-Champaign, 2010, p.1-8 & p.19-31.
- [46] Abernethy K and CindereyR J, “ Effect of hot charging on steel properties“, European Commission Technical steel research, Report No. EUR 14943 EN , 1995, p.23-74.
- [47] John Guerard, “Considerations for the hot charging of billets ” , Proceedings of the International Symposium on direct rolling and hot charging of strand cast billets,Montreal, Canada Edited by J.J. Jonas, R.W. Pugh S.Yue, 1988, August 29-30, p.53
- [48] Rahul S Nalawade, Prafull P P, . Balachandran G and Balasubramanian V, “Void Closure in a Large Cross Section Bars Hot Rolled from a Low Alloy Steel Ingot Casting”, Trans Indian Inst. Met, 2016, V.69(9), p.831.
- [49] Vander Voort George F., “Understanding and measuring decarburization”, Advanced Material Processes, Feb, 2015, p.22.
- [50] Bianchi J H and KarjalainenL P, “Modelling of dynamic and meta dynamic recrystallisationduring bar rolling of a medium carbon spring steel”, Journal of Material Processing Technology, 2005, 160, p.267-277.
- [51] Hodge J M, Orehoski M A, and Steiner J E, “Effect of Hydrogen content on susceptibility of flaking”, Trans Met Soc., AIME, 1964, V.230, Aug., p.1182-1193
- [52] Wilson Alexander D, “ Clean Steel Technology – Fundamental to the development of high performing steels” , Advances in the production and use of steels with improved cleanliness,, ASTM STP 1361, J K Ed by Mahaney Jr , p. 73.
- [53] MapelliC., Vedani M. and Zambon A., “On microstructure development and inclusion generation in a continuously cast resulphurised steel”, Lat. Am. appl. res. v.32 n.3 Bahía Blanca jul./sept. 2002, p.9.
- [54] Popova L. V., Lebedev D. V., and Nasibov A C, “Properties of steel 16G2AF with microadditions of tellurium”, I. P. Bardin Central Scientific-Research Institute of Ferrous Metallurgy. Translated from Metallovedenie i Termicheskaya Obrabotka Metallov, 1983, No. 3, pp. 21-22.
- [55] Van Tyne C J, Matlock D K and Speer J G, “Microalloyed forging steels”, Colarado School of Mines, https://www.forging.org/uploaded/content/media/_376VanTyne_0_0.pdf
- [56] JSW Brochure Down loads in <http://www.jsw.in/steel/special-steel>
- [57] Nandita Gupta and Sen S. K.,” Spheroidisation Treatment for Steels”, Defence Science Journal, 2006, Vol. 56, No. 4, October, pp. 665-676
- [58] Boyle I E, NorthwoodD.O., Bowers R, Sun X, Bauerle P, Materials Forum V.32 – 2008, Edited by J.M. Cairney, S.P. Ringer and R. Wuhrer Pub. by © Institute of Materials Engineering Australasia Ltd., p.44
- [59] Otto Fredrick J and Herring Daniell H, “Gear Heat Treatment”, Heat Treating Process, July/Aug, 2002, p.1-5.

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