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The production of high-strength low-alloy steels in the hot-rolled condition

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SYNOPSIS

The production of high-strength low-alloy (HSLA) steels containing either niobium or vanadium as the principal micro-alloying element is discussed, including recent developments in steelmaking practice that have had a great effect on the development of HSLA steels; strengthening mechanisms, as well as the principles of thermomechanical treatment during controlled rolling on a hot-strip mill; and the results of production heats with various amounts of micro-alloying elements.

SAMEVATTING

Die produksie van hoëtreksterkte-laelegeringstaal (HSLL-staal) wat niobium of vanadium as die hoofmikrolegerings element bevat, word bespreek, insluitende die jongste ontwikkelings in staalvervaardigingspraktyke wat 'n groot uitwerking op die ontwikkeling van HSLL-staal gehad het; versterkingsmeganismes asook die beginsels van termomeganiese behandeling tydens beheerde walsing op 'n warmbandwalsery; en die resultate van produksiesmeltings met verskillende hoeveelhede mikrolegeringselemente.

Introduction

During the past two decades, the technology of micro-alloyed steels has been refined to a high degree. In addition, new steelmaking techniques provide an excellent means for the mass production of low-carbon micro-alloyed steels, e.g. aluminium-treated niobium, niobium–vanadium, and niobium–titanium types.

At the beginning of the development of structural steels, carbon was the most important alloying element required to achieve the desired tensile properties. Markedly changing criteria[1] for structural steels led the way to the development of high-strength low-alloy (HSLA) steels. Some of the more important criteria are listed below.

(1) The use of welding, rather than riveting, as a method of joining necessitated a lower carbon content.

(2) Failure by brittle fracture of welded structures resulted in a recognition that impact or fracture toughness was essential, and thus the need for a low impact-transition temperature became apparent. It was also recognized that high yield strength was more important than high tensile strength. Thus, the carbon content was lowered further, and the manganese was maintained at high levels. The advantages of high manganese-to-carbon ratios for impact toughness were also appreciated, and the significance of grain size was at last established.

(3) The refinement of grain size by grain-refining additions such as aluminium was then introduced.

(4) Further increases in yield stress were then achieved by precipitation hardening, and further grain refinement by niobium, vanadium, and titanium additions, especially when controlled rolling was done.

(5) The general formability was improved by a lowering of the sulphur content and/or control of the shape of the sulphides and oxides by the addition of calcium, zirconium, or cerium.

Steelmaking Routes

Two basic steelmaking routes are used:

Arc-furnace Route (Fig. 1)

In *primary refining*, the scrap mixture is made up of fairly large percentages of heavy scrap and pit scrap (about 40 per cent). Sheets and plates make up another 25 per cent, and high-carbon mould or pig iron about 5 per cent, the balance being light-to-medium purchased scrap. The alloy scrap is kept separately in pits and charged on alloy grades as required. The same refining practice is followed on all grades, the only exception being that HSLA steels are tapped at higher temperatures to accommodate subsequent secondary refining.

No lime is charged on heats destined for ladle treatment; only low-cost raw dolomite is used to limit slag-line erosion due to the higher tapping temperatures. HSLA steels are decarburized to between 0,04 and 0,08 per cent carbon in the furnace. During tapping, bulk alloys and desulphurizing slag are added, while argon purging in the ladle aids in better mixing. The steel is further purged after tapping for homogenization and some degree of desulphurization. To achieve low oxygen levels, HSLA steels are tapped into basic ladles so that no oxygen is supplied to the steel from siliceous refractory material.

To achieve the high cleanliness associated with most HSLA steels, either an extended refining time in the melting furnaces or some form of ladle refining is required. As the former option is very expensive, with high-powered, highly productive furnaces, *secondary refining* units are used for the final refining. This is done in a vacuum-arc degassing (VAD) and/or a Thyssen Niederrhein (TN) injection plant. Where good formability is required, ladle refining procedures aim to assist in achieving isotropic properties by reducing the oxygen and sulphur contents and modifying the remaining inclusions with calcium through the injection of calcium silicate in the TN plant. Manganese sulphate and alumina mixtures, which are rolled out into stringer-type inclusions in the rolling direction during rolling, are

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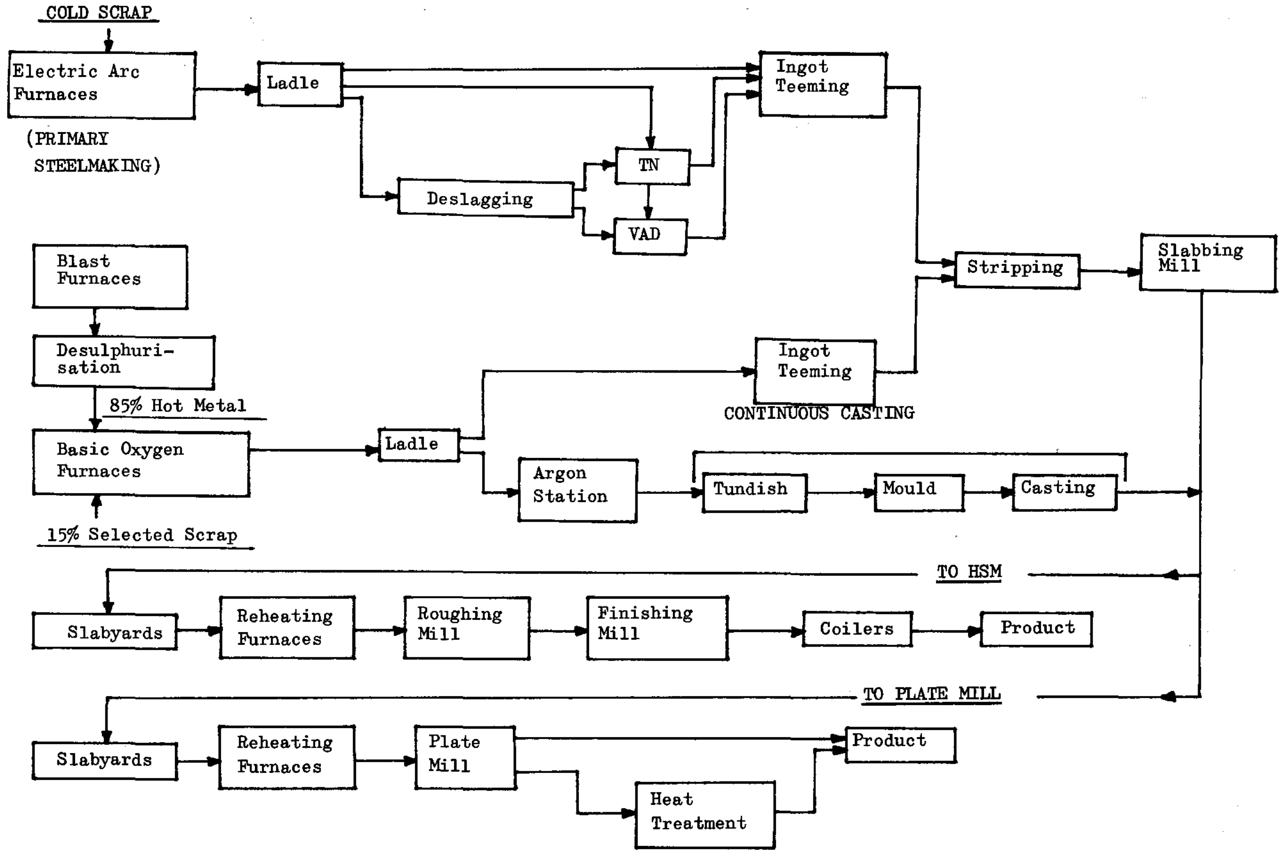

Fig. 1—Schematic production flow diagram

transformed to isolated non-plastic inclusions of $(CaO)_m(Al_2O_3)_n.CaS$.

Trimming additions and micro-alloys such as vanadium, niobium, titanium, and zirconium are added in the VAD under vacuum. As correct teeming temperatures are vital for good cleanliness, the VAD plant also serves to adjust steel temperatures through its capacity of three-phase arc heating under partial vacuum (40 kPa). Last, but not least, on hydrogen-sensitive steels such as HSLA steels with a high ratio of yield to tensile strength above certain plate thicknesses, the VAD serves to minimize hydrogen embrittlement by extended vacuum degassing at pressures of approximately 80 Pa.

Sulphur levels of 0,005 per cent maximum and phosphorus levels of 0,02 per cent maximum are produced regularly, whereas total oxygen levels on aluminium-killed TN/VAD steels are usually below 20 p.p.m. HSLA steels are usually top-poured into moulds, but the highest qualities are bottom cast for further improved cleanliness, as well as for improved surface quality.

The ingots, after being soaked in soaking pits, are rolled down into slabs ranging from 150 to 360 mm in thickness and 700 to 1900 mm in width for final hot rolling through the hot-strip mill or plate mill.

BOF Route (*Fig. 1*)

In the *hot metal treatment*, hot metal with a temperature of approximately 1275°C is first desulphurized by the injection of calcium bicarbonate in the torpedo car in which the hot metal arrives from the blast furnaces. It is further desulphurized in the hot-metal transfer ladle with soda-ash. The full charge is then transferred to another hot-metal ladle to enhance mixing. Slag is thoroughly skimmed off with a mechanical scraper. The end-point sulphur following steelmaking is approximately the same as the final sulphur obtained in the hot metal.

The *BOF practice* involves approximately 85 per cent hot metal and 15 per cent selected scrap. Lime, burnt dolomite, and fluorspar are also charged to achieve the correct type of slag. The predicted bath temperature is adjusted by variation of the amounts of iron ore or raw dolomite in the charge.

The sublance is lowered approximately 3 minutes before the predicted end of blow to measure the bath temperature and carbon content. This gives more accurate end-point control, thus avoiding over-oxidation and excessive temperatures, which both contribute to a high content of inclusions. The measurements gained by the sublance also assist in the calculation of the quantity of coolant required to correct the end-point temperature.

Ferrosilicon is normally used for deoxidation in the ladle, and in the *ladle treatment*, micro-alloys are added mainly as ferroniobium or ferrovanadium. Other alloying elements such as carbon and manganese are also added.

The temperature of the steel arriving at the *argon-*

stirring station is about 1600°C. Additions of aluminium are made, and stirring is done by argon through a refractory-shrouded lance. When the ladle analysis is available, final corrections to the analysis are carried out with a final stir to homogenize the steel. The temperature is adjusted with a suspended slab in the ladle while stirring to approximately 1570°C for an aimed tundish temperature of 1530 to 1535°C. Argon stirring has the further advantage of enhancing the flotation of inclusions. A further development will be the feeding of calcium wire to desulphurize and modify the sulphide inclusions.

In the *casting and slab handling*, a thermal-insulation powder is used on the tundish, which also prevents oxidation of the steel surface. The mould powder absorbs alumina inclusions, prevents oxidation, and forms a lubricant between the steel and the surface of the mould.

Two strands are cast on one machine in thicknesses of 240 mm or 210 mm, depending on the rolling mill's requirements. Owing to the relatively small cross-section of the cast slab and the rapid solidification rate, segregation is kept to a minimum. After being cast, the slabs are air-cooled to approximately 300°C, machine-scarfed, and inspected before being rolled in either the plate mill or the hot-strip mill.

Major Strengthening Mechanisms

To aid in an understanding of the metallurgical mechanisms that play a part in the hot rolling of HSLA steels, attention is briefly drawn to the main strengthening mechanisms that are of importance in the production of this kind of steel.

Grain Size

The dependence of the yield stress on the grain size is given by the Hall–Petch relationship[1]

$$\sigma_y = \sigma_i + k_y d^{-1/2},$$

where d is the grain diameter, σ_y is the yield stress, σ_i is the friction stress opposing the movement of dislocations in the grains, and k_y is a constant. The unique feature of grain-size strengthening is that it is the only strengthening mechanism that simultaneously increases both the yield stress and the toughness with a decrease in grain size.

Precipitates or Second-phase Particles

Depending on their size and whether the precipitate itself deforms during yielding of the steel, precipitates or second-phase particles can have a significant effect on the yield and tensile strength of the material. Precipitates, depending on the temperatures at which they precipitate, can instigate grain growth, as well as hampering grain growth by pinning grain boundaries. In general, precipitates have a negative influence on toughness.

Hot Rolling in a Semi-continuous Hot-strip Mill (Fig. 1)

To make the steel more readily deformable, it is heated prior to being rolled. It has been determined that a more uniform microstructure is obtained when final rolling is carried out just above the A_3 line on the Fe–C diagram. To obtain this temperature on thin final gauges, reheating temperatures of above 1200°C must be used.

In HSLA steel, reheating to 1200°C or higher is also utilized, mainly to make it more easily deformable, with the additional advantage that all the nitrides and carbides of the micro-alloyed elements will be fully dissolved in the austenite matrix. As the steel is deformed and the temperature drops, the micro-alloying elements precipitate at various temperatures, thereby improving the mechanical properties of the steel in a direct or indirect way.

Fig. 2 indicates a typical temperature profile over the hot-strip mill during production and the roles played by the various micro-elements at various stages in this profile. It should be noted that finishing temperatures of 860 to 890°C are being used, instead of the very low finishing temperatures (less than 850°C) that were initially recommended for this kind of steel in the literature. With low finishing temperatures there are production penalties, the main ones being

(a) bad shape of the material,
(b) dimensional limitations due to an increase in rolling forces,
(c) accentuation of anisotropy by the deformation in the ferrite–austenite two-phase region.

New steelmaking technologies offer an excellent means of alloying with various micro-alloy elements and the control of detrimental sulphides and oxides, and because local conditions do not need steels with ultra-low impact-transition temperatures. A strategy of rather higher finishing temperatures is used that is accommodated much more easily in the normal rolling schedules.

Role of Micro-alloying Elements in Hot Rolling

Although aluminium is used as a deoxidizing element, it is also a micro-alloying element. As it combines with nitrogen, it not only removes the free nitrogen and so improves the toughness properties, but AlN also precipitates in the austenite, thus preventing the growth of austenite grains, with the ultimate result of a finer ferrite grain and thus better mechanical properties. When aluminium-treated steels are coiled after hot rolling at temperatures below 600°C, AlN precipitates are finely dispersed in the ferrite grains and can be very beneficial after cold rolling if proper annealing is done.

Niobium precipitates markedly retard recrystallization during hot rolling, and the particles of Nb(CN) also inhibit grain growth; thus, strengthening of the material is achieved by grain-size control and precipitation.

Vanadium as VN is very effective as a grain refiner while also strengthening the iron matrix due to the precipitation of V_4C_3. It is generally accepted that niobium strengthens mainly by grain refinement, whereas vanadium strengthens mainly by precipitation hardening.

As reductions in the hot-strip mill's finishing train are heavy and occur in quick succession, they greatly assist the micro-elements in achieving small ultimate ferrite grain sizes, thus enabling the production of steels with high mechanical properties in the as-rolled condition. Laminar cooling after the final reduction prevents grain growth, and coiling at temperatures around 600°C aids in auto-tempering of the material. Coiling at various temperatures, depending upon the amounts of alloying

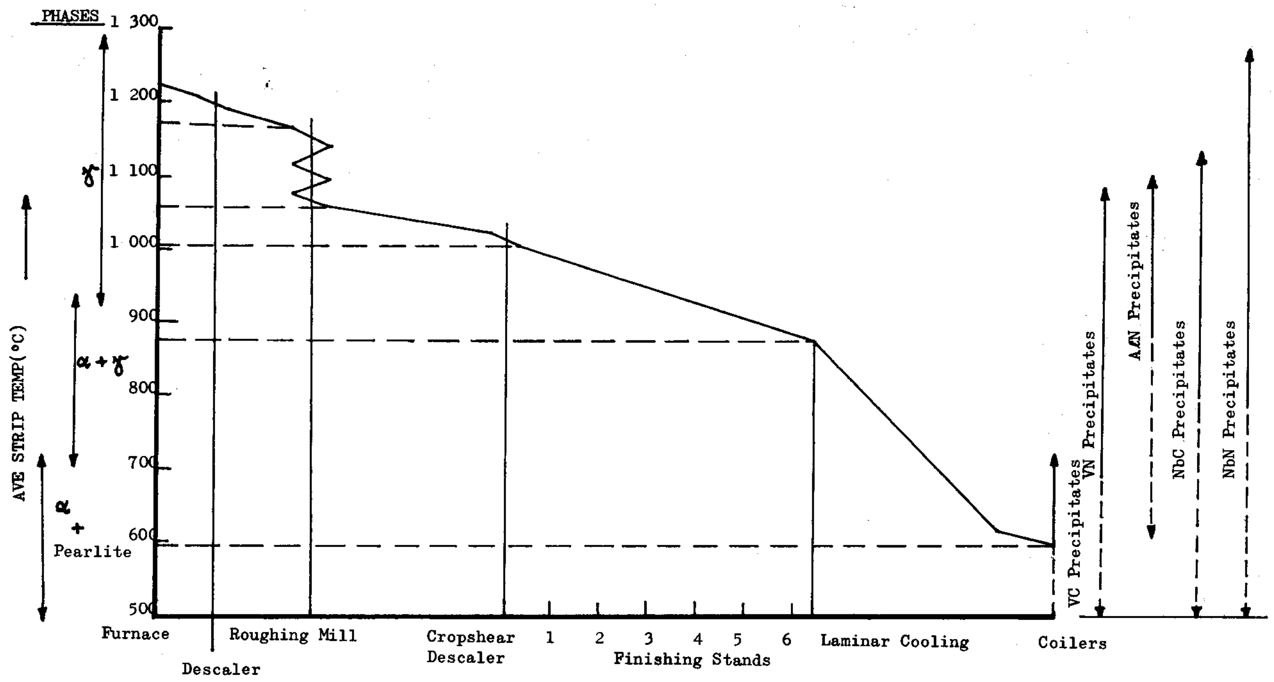

Fig. 2—Typical strip temperatures in the hot-strip mill

elements, means that the mechanical properties can be controlled and so achieve smaller variations.

Anisotropy in mechanical properties, in the rolling direction and perpendicular to the rolling direction, is one of the negative aspects of material produced by this process. New steelmaking technologies greatly assist in minimizing this aspect. Sulphide and oxide inclusions elongated into stringers or tapes are the main causes of this anisotropy. By reduction of the sulphur content and modification of the sulphides and oxides by additions of calcium, zirconium, or cerium, and by limitation of the oxides formed during steelmaking, the ratio of longitudinal to transverse mechanical properties approaches unity. This gives a pronounced improvement in ductility.

Hot Rolling in a Plate Mill

HSLA steels are produced mainly as structural steels in the as-rolled condition on the plate mill. Normal reheating temperatures above 1200°C are used, and the material is not controlled-rolled, which means that the temperature after mechanical deformation depends to a large extent upon the final thickness of the material and can vary between 850 and 1100°C. The thicknesses of the plate normally produced vary from 6,0 to 100 mm. As the finishing temperature is not controlled, and the reductions do not occur in such quick succession as in the case of hot-strip rolling, more grain growth occurs than with material rolled through the hot-strip mill. However, the mechanisms involved in the strengthening of the micro-alloys are still at work, and material with good toughness and strength can be obtained.

The big advantage of plate-mill rolling is that cross rolling can be carried out, thus further preventing to a large extent anisotropy of the material. Certain grades of HSLA steels are normalized following hot rolling, as required by certain specifications, in order to achieve specific mechanical requirements.

Effect of Micro-alloying Elements

The production of micro-alloyed steel covers specifications for pipe steels, structural steels, and low-pressure gas cylinders.

Tables I to III indicate the influence of the various micro-alloying elements on the mechanical properties. As the same mechanical properties can be achieved with different micro-alloying elements, the main considerations include the ease of controlling the properties with the micro-alloying elements and the cost of these elements.

A comparison of heats A and B shows that the only real difference in analysis is the niobium content of 0,021 per cent. An increase in average yield strength of 122 MPa, i.e. from 256 to 378 MPa, and an increase in average tensile strength of 83 MPa, i.e. from 349 to 432 MPa, was achieved. The increase in yield strength is considered to be exceptional, especially when it is compared with heat C, which has an average yield strength of 385 MPa; in addition, an excellent elongation on heat B was achieved. Toughness values in both the *X* direction (perpendicular to the rolling direction) and the *L* direction (in the rolling direction) are extremely good, with a low fracture appearance transition temperature (FATT). The low sulphur and the fine grain size are the main reasons for these excellent toughness values. Toughness values in the *X* direction are higher than in the *L* direction, which often occurs in niobium-bearing steels with a low sulphur content.

Heat C is much higher in carbon and manganese than heats A and B, but still has a very good elongation. A fairly low toughness value is obtained in the *X* direction,

TABLE I
CHEMICAL ANALYSIS (% BY MASS) FOR DIFFERENT HEATS

Heat	Grade	C	Mn	P	S	Si	Al	Nb	V	Total N	Final thickness mm	Coil temp. °C	Remarks
A	AC1	0,044	0,300	0,014	0,013	0,013	0,042	*	*	0,0051	2,50	600	
B	SC3	0,040	0,380	0,010	0,007	0,010	0,050	0,021	*	*	5,50	630	
C	SC1	0,170	0,870	0,015	0,024	0,220	0,076	0,028	*	*	12,00	635	
D	SC1	0,100	0,560	0,009	0,004	0,220	0,055	0,001	0,066	0,013	6,00	605	
E	A12T	0,080	1,010	0,009	0,010	0,180	0,014	0,033	*	*	5,00	625	VAD
F†	A12T	0,124	1,360	0,006	0,005	0,308	0,011	0,033	*	0,009	5,00	575	VAD+TN

* Not determined
† Ti = 0,114%' Zr = 0,025%

TABLE II
AVERAGE MECHANICAL PROPERTIES FOR DIFFERENT HEATS

Heat	Yield point *X*-direction MPa	Tensile strength *X*-direction MPa	Results of Charpy impact test* (V-notch), J										Elongation over 50 mm %
			X rolling direction† at:					*L* rolling drection† at:					
			25°C	0°C	−20°C	−40°C	−60°C	25°C	0°C	− 20°C	−40°C	−60°C	
A	256	349											43,6
B	378	432	151	155	151	61	6	124	136	136	130	9	45,0
C	385	517	35					117					41,3
D	409	524	165	157	103	10	7	112	68	32	13	8	39,1
E	520	592	46	45	44	42		163	165	155	139		30,0
F	640	742	108	110	102	86	80	148	142	124	116	118	27,6

* All Charpy Impact Test results converted to standard size of test specimens (10 by 10 mm)
† *X* direction: perpendicular to rolling direction
L direction: in the rolling direction

TABLE III
AVERAGE MECHANICAL PROPERTIES FOR DIFFERENT HEATS*

Heat	Yield point X-direction MPa	Tensile strength X-direction MPa	Results of Charpy impact test (V-notch), J										Elongation over 50 mm %	Charpy sample size (mm)
			X rolling direction† at;					*L* rolling drection† at:						
			25°C	0°C	−20°C	−40°C	−60°C	25°C	0°C	−20°C	−40°C	−60°C		
A	256	349											43,7	
B	378	432	50	51	50	20	2	41	45	45	43	3	45,0	3,3×10
C	385	517	35					117					41,3	10×10
D	409	524	83	78	52	5	3	56	34	16	6	4	39,1	5,0×10
E	520	592	23	23	22	21		82	83	78	70		30,0	5,0×10
F	640	742	54	55	51	43	40	74	71	62	58	59	27,6	5,0×10

* Subsidiary Charpy test pieces
† *X* direction: perpendicular to rolling direction
L direction: in the rolling direction

mainly owing to the high sulphur and carbon contents.

Heat D, which is micro-alloyed with vanadium, has a very low sulphur content, and its toughness values compare very favourably with those of the other heats. The only heat that is solely VAD treated, i.e. heat E, shows an extremely good toughness value in the *L* direction, with a very low FATT. With TN treatment, the *X* direction toughness improves significantly, especially when the sulphur content is reduced to below 0,008 per cent. Heat F clearly indicates the extremely good toughness values achieved when a low sulphur content and ladle treatment are combined, even though the yield strength of this heat is much higher than that of heat E.

Conclusion

HSLA steels have already firmly established themselves in the market place, and by the use of micro-alloying elements a wider product range can be produced on normal rolling mills, providing that the steelmaking facilities have the capability to produce these steels with a high degree of consistency.

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