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TESI DI LAUREA MAGISTRALE IN INGEGNERIA DEI MATERIALI

Overheating of hot rolled flat steel products: problem analysis and productive process optimization

Sovrariscaldamento di prodotti piani in acciaio laminati a caldo: analisi del problema e ottimizzazione del processo produttivo

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INTRODUCTION

Spartan UK, part of the Metinvest group, is an English factory located in Newcastle upon Tyne. It is the only quarto steel plate re-roller in the United Kingdom, producing about 200000 t of steel plate per year. Plates produced are suitable for applications in numerous industrial fields (building, bridges, yellow goods, industrial machinery, wind turbines, general construction).

Spartan UK

METINVEST®

Together with Ferriera Valsider spa and Metinvest Trametal spa it is part of field commercial Unit Europe of Metinvest Holding.

1 ROLLING

Rolling is a metal forming process by means of which it is possible to reduce the thickness or change the cross-section of a slab. The deformation is obtained through compression forces applied by a series of rolls.

The roll forming process constitutes 90% of all metal forming process, this manufacturing process was developed at the end of sixteenth-century.

In general, the first step in a rolling process starts from an ingot or, always more frequently, from a continuous casting product.

The product obtained from the first step is called slab, billet or bloom depending on shape and dimensions, each one of them semi-finished products is wrought further to get different objects.

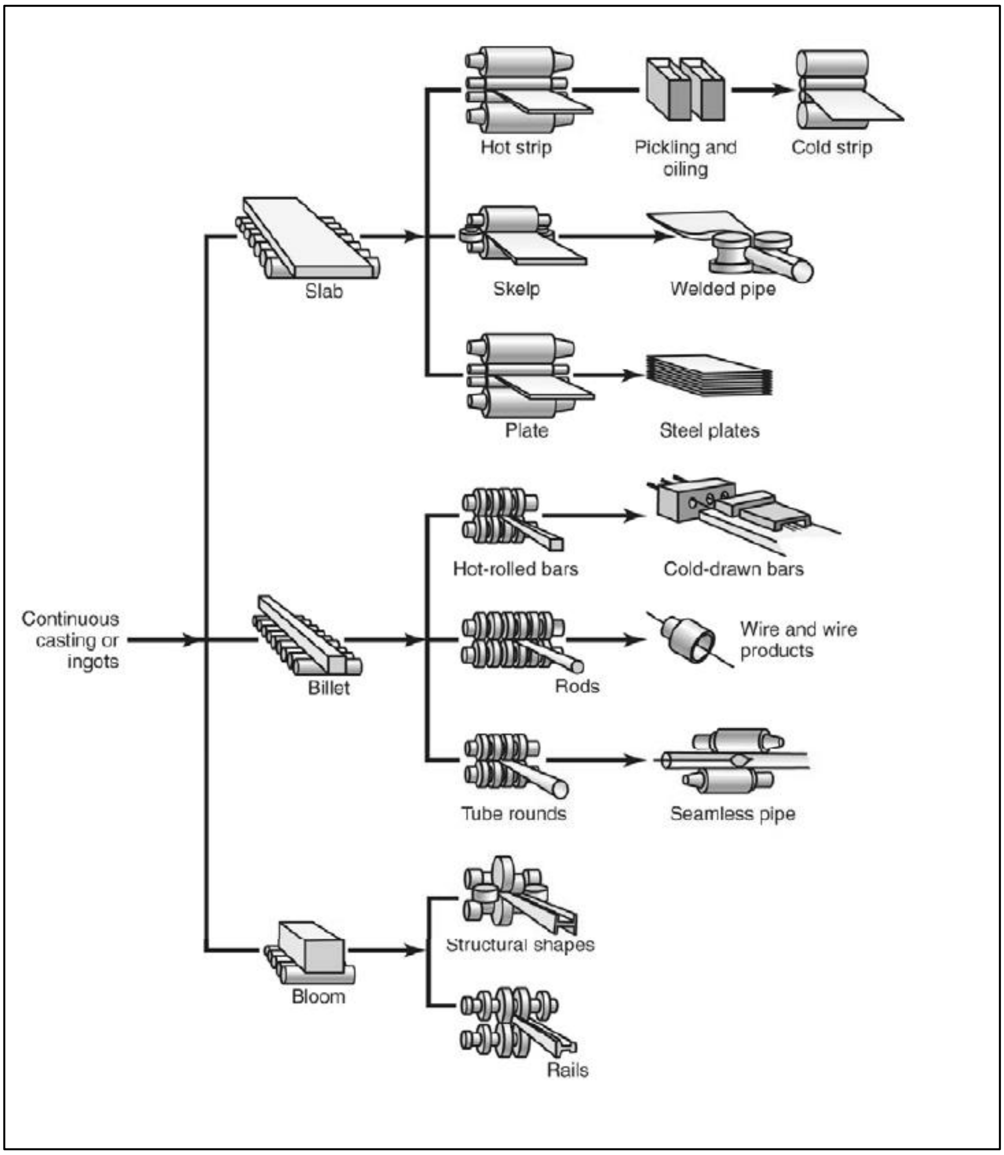


Fig. 1 *Schematic representation of the possible rolling processes*
[from reference 2]

1.1 Flat Rolling Process

The most common and simple rolling process is that to produce of flat products.

The process is schematically presented in figure 2: a strip of material with h_0 thick comes between two rolls and it is reduced to h_f thick.

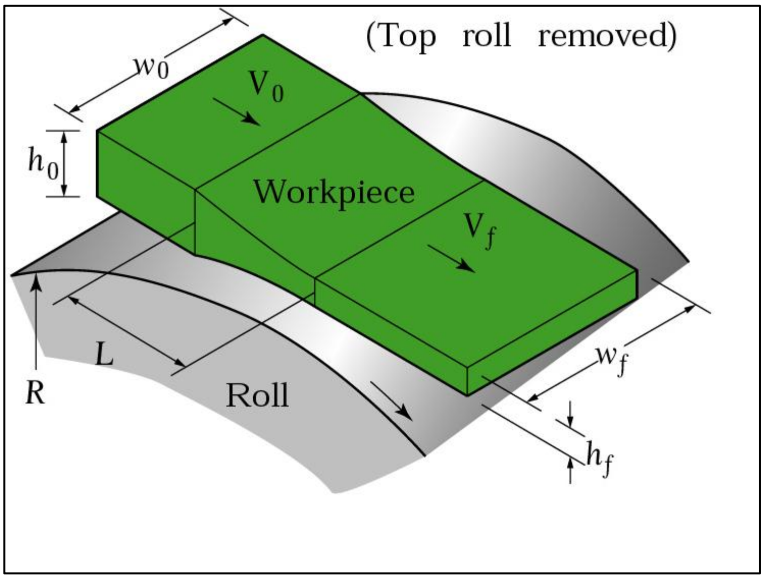


Fig. 2 *Mechanics of flat rolling process*
[from reference 2]

This is accomplished in a rolling mill, in which two work rolls, rotating in opposite directions, draw the strip or plate to be rolled into the roll gap and force it through to the exit, causing the reduction of the thickness.
An explicative diagram of the rolling mill is shown in figure 3.

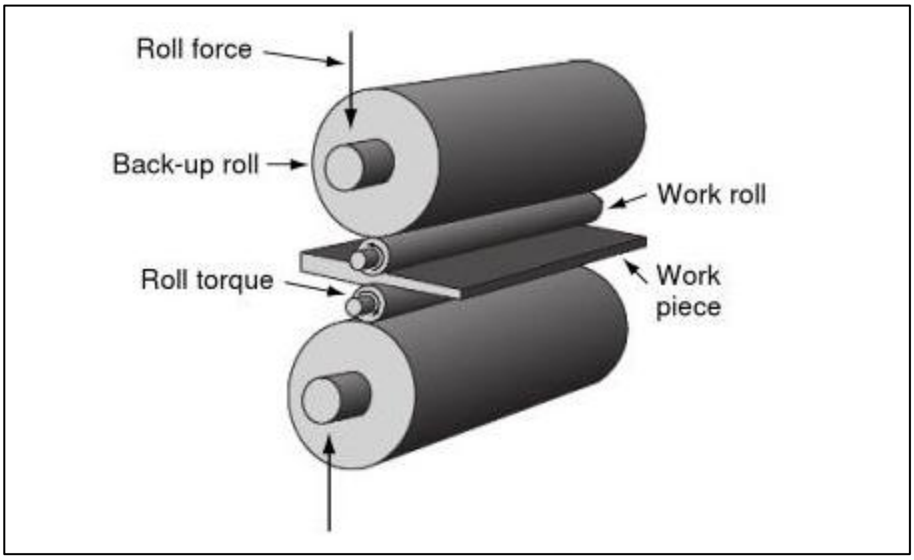


Fig. 3 *Rolling mill diagram*
[from reference 2]

The figure shows the back-up rolls, the work rolls, the strip being rolled, the roll torques and the roll forces acting on the journals of the back-up rolls bearings.

1.2 Hot and Cold Rolling

The rolling process may be divided into hot rolling and cold rolling.

When the process is performed at high temperature above half of the melting point of the metal it is called *hot rolling*; when performed below that temperature it is *cold rolling*.

In addition to those definitions there is the warm rolling process, the temperature range for this phase is not defined very precisely but starts somewhere below half of the melting point and changes to hot rolling at temperature above that.

Each of these processes have their advantages and disadvantages.

At temperatures where hot rolling is performed, the metal becomes more ductile so less power is needed for a determinate reduction, the anisotropy is reduced and the previous microstructure is erased. On the other hand high temperatures cause the development of a layer of scale on the metal surface, increasing the thermal wear and tear of the rolls and requiring a cooling system for the rolls.

The cold rolling process allows a better control of dimensional consistency, a high surface quality and the metal can be strengthened via work hardening. On the other hand major power is needed for small thickness reductions and residual stress may arise in the finished product.

2 SPARTAN UK STEEL

Almost all product produced by Spartan UK is constituted by structural steels.

The main rolled steels are:

- S235
- S275
- S355
- S355W

Whereof S355 steel accounts for 50% of production.

All these steels are Carbon-Manganese steels, are characterized by minimum specified yield point, tensile strength, and notch toughness requirements.

The composition of these steels is showed in table 1, while the mechanical proprieties are reported in table 2.

Range	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%V	%Ti	%Nb	%N
S235											
Min.	0.100	0.200	0.850	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Max.	0.120	0.300	1.000	0.020	0.015	0.050	0.050	0.010	0.005	0.005	0.012
S275											
Min.	0.130	0.200	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Max.	0.150	0.300	1.150	0.015	0.003	0.050	0.050	0.010	0.005	0.005	0.012
S355											
Min.	0.150	0.200	1.400	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000
Max.	0.170	0.300	1.550	0.015	0.003	0.050	0.050	0.010	0.005	0.040	0.012
S355W											
Min.	0.110	0.350	0.950	0.000	0.000	0.450	0.200	0.030	0.000	0.000	0.000
Max.	0.140	0.450	1.150	0.020	0.005	0.550	0.300	0.050	0.005	0.005	0.012

Tab. 1*Chemical composition of Spartan UK steel*

Steel	Yield point [MPa] Thickness 63 -100 mm	Tensile strength [MPa] Thickness 63 -100 mm	Minimal lengthening [%] Thickness 63 -100 mm	Minimal resilience [J] at room temperature
S235	215	340-470	24	27
S275	245	410-560	20	27
S355	325	490-630	20	27

Tab. 2 *Mechanical propriety of Spartan UK steels*

The S235 and S275 are steels for structural basic applications; whereas S355 and S355W steels are designed for more substantial performances.

The proprieties of S355 and S355W steels are due to the presence of micro-additives. The insertion of micro-additives in the composition of steel is a modern practice (developed around the fifties) that led to the establishment of the class of HSLA steels.

3 HSLA STEELS AND TEMPERATURE CONTROL ROLLING

The motivation that led to develop this class of steel was the need to have steels with high yield point, lower transition temperature and weldable.

HSLA (acronym for High-Strength Low-Alloy) is a class of structural Carbon-Manganese steels that contain small amounts, usually under the 0.15%, of Vanadium (V), Niobium (Nb), Zirconium (Zr) or Titanium (Ti). These elements show a marked affinity with Carbon (C) and Nitrogen (N) to form compounds of nano-metric dimension as XC and/or XN.

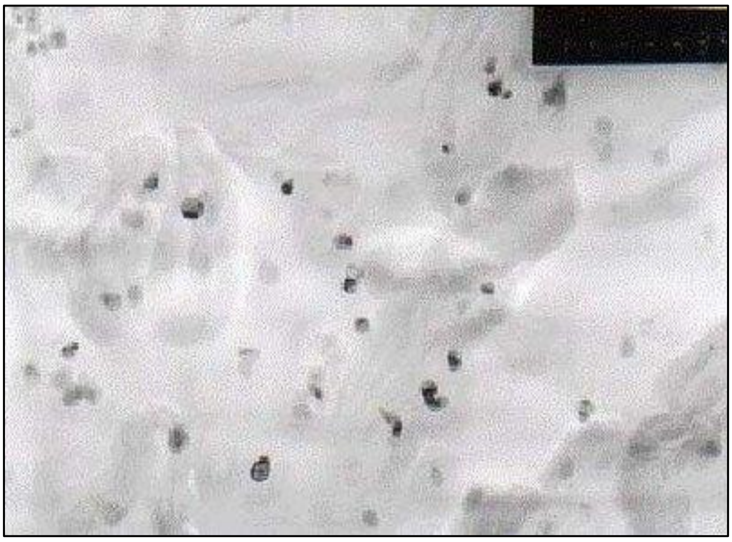


Fig. 4 *Nano metric Vanadium carbide precipitated in the matrix*
[from reference]

Micro-additives, forming fine precipitates at the grain boundaries, limit the mobility of grain boundary and therefore, slow down the austenite grain growth.

This effect is perceptible in two different steps during the rolling process: on one hand, during the re-heating step and on the other hand during the cooling step.

Throughout the heating cycle the presence of fine precipitate inhibits the austenite grain growth, thus structure at high temperature that is not coarse grain.

After rolling the plastically deformed metal recovers and recrystallizes (static or dynamic), leading to a new increase of grain dimensions; in cases of micro-alloy steels, this process can be slowed down by the dispersive particles, as shown in figure 5.

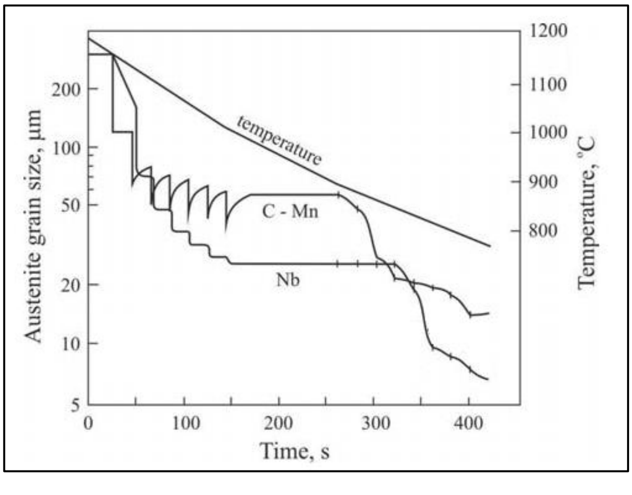


Fig. 5 *Austenite grains size in the course of rolling for a C-Mn steel 0.04% Nb*
[from reference 6]

It must be emphasized that the main purpose of the addition of micro-additives, is not only to obtain the grain refining but also to impede the movement of dislocations; such purposes are achieved by the formation of fine dispersive precipitates.

This creates high values of yield point, strength and hardness and an increase of elastic limit and workability. This is easily observable in figure 6.

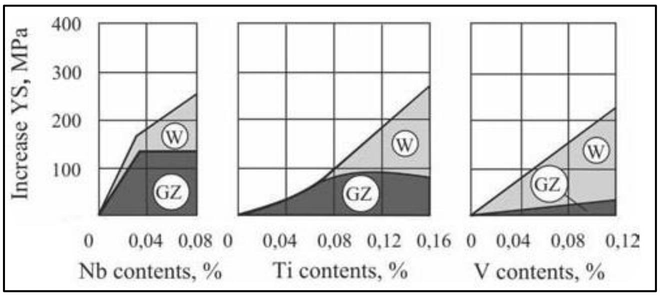


Fig. 6 *Influence of Nb, Ti and V content on the increase of the yield point of low-carbon steel. GZ: Influence of grain refining, W: Influence of precipitation hardening. [from reference 6]*

As a consequence there is the possibility to obtain lighter structures with the same strength. These steels are also weldable.

The main limit of micro-alloy steels is due to the reduction of toughness that can follow the precipitation hardening.

With regards to the S355 and S355W steels worked in Spartan UK, the additives contain in these steels are respectively Niobium and Vanadium.

Vanadium is a chemical element with atomic number 23; it is hard, silver grey and ductile. It is used mainly to produce ferroalloys or alloys used in specific domains, for example Titanium alloys for nuclear applications.

Vanadium contributes to the steel strength increase by forming precipitations in the ferrite structure. The value of the reinforcement varies between 5MPa and 15MPa for each 0.01% of Vanadium introduced.

Niobium is a grey, ductile transition metal with atomic number 41. It is commonly used to produce alloy for high temperature applications and special stainless steels. Also the Niobium increases the steel strength by precipitation, and by reduction in grain size. Its effect is greater compared to that of Vanadium. The value of the reinforcement varies between 30-40MPa for each 0.01% of Niobium introduced and the strengthening effect increases with decreasing size of precipitates.

The mechanical proprieties of these steels are due not only to the chemical composition but also to a particular thermo-mechanical treatment.

In the specific case of Spartan UK rolling process the thermo-mechanical process used is *normalising rolling,* also called *controlled rolling.*

The regulation EN 10025, defines this particular thermo-mechanical treatment as: “Rolling process in which the final deformation is carried out in a certain temperature range leading to a material condition equivalent to that obtained after normalizing so that the specified values of the mechanical properties are retained even after normalizing”

The rolling process is, usually, a multi-pass process; unlike conventional rolling, in which different passes are conducted one after the other in the shortest time as possible.

In thermo-mechanical rolling, the last passes of the process are conducted in a specific gap of temperature.

In the case of normalizing rolling, the last steps are conducted at lower temperatures; this temperatures are above the recrystallization stop temperature but close to the boundary between the recrystallization region and the non-recrystallization region.

In this way, the original equiaxed austenite grains are replaced with a new set of smaller recrystallized grains, but given the proximity to the border, the recrystallization does not allow the formation of coarse austenite grains.

Furthermore, thinking about the HSLA steels, the practice to roll in this temperature gap permits the formation of precipitates small enough to permit recrystallization of austenite but large enough to suppress the grain coarsening; this is shown in the following picture:

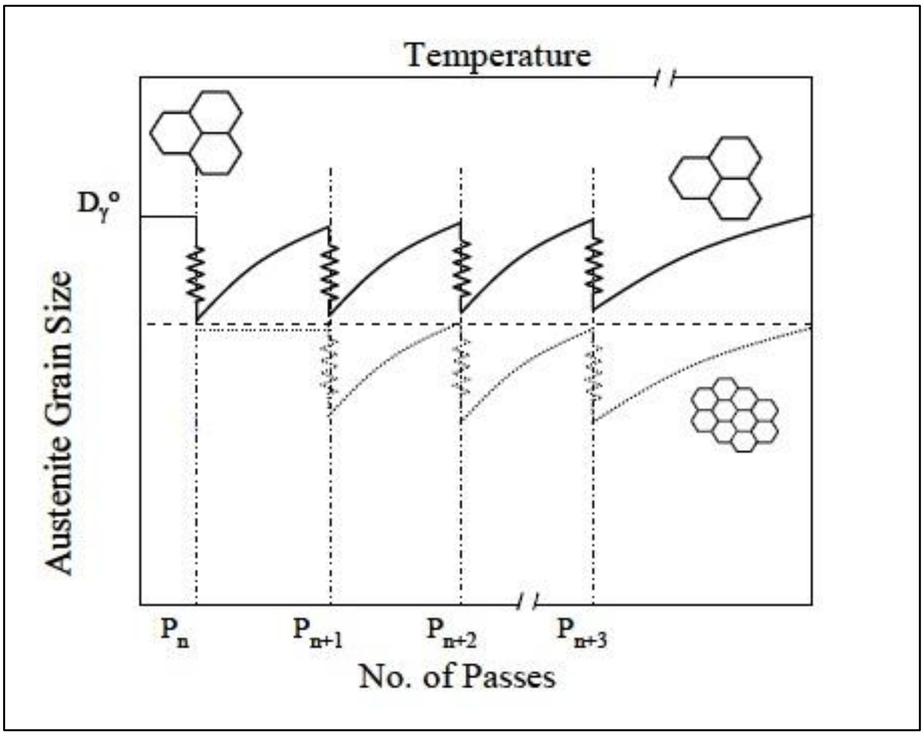


Fig. 7 *Schematic illustration of the differences in the grain size evolution during deformation in both conventional (solid line) and controlled rolling (dashed line)*

After the last step, the plates are cooled down in open air.

The result of this process is a reduction of the ferrite grain dimensions, conventional rolling permits to obtain ferrite grain with average diameter about 20 μm; using normalizing rolling process the average diameter is around 5-10 μm.

The reduction in the grain sizes results in an increase of the mechanical properties in accordance with the law of Hall-Petch.

Besides this process a lot of other thermo-mechanical rolling exists, the other processes and their effect on the grain size are illustrated in figure 8.

These other process are difficult to use on plates with a thickness more than 50mm, (which are commonly used by Spartan UK products) because the thickness can cause variations of rolling temperature and reduction ratio.

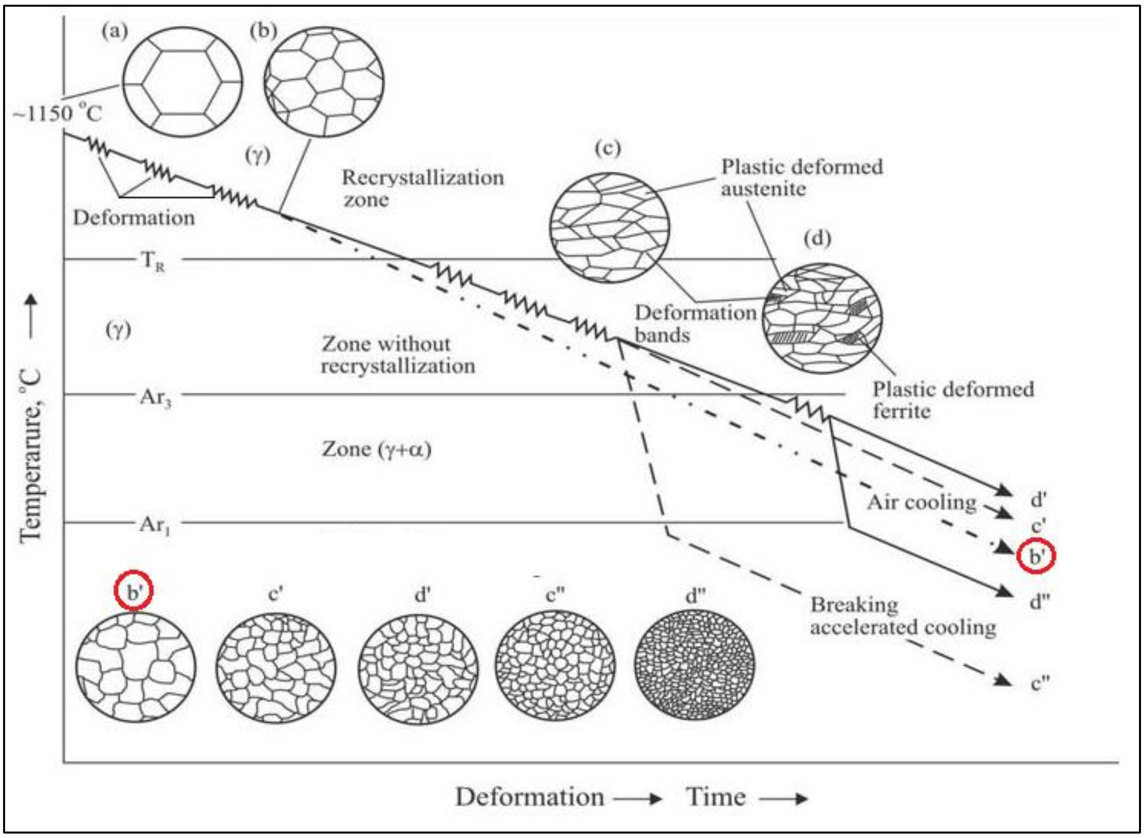


Fig. 8 *b': normalizing rolling; c' and c'': controlled rolling with dynamic recrystallization and two different cooling rates; d' and d'': controlled rolling with last deformation steps in α+γ zone and two different cooling rates.*
[from reference 6]

The temperature of the boundary between the recrystallization region and the non-recrystallization region is easy to determinate for the different steel grades.

For Spartan UK steels this temperature is around 930° - 900° C.

It is important to note that thermo-mechanical processes reduce costs due to reduced lead times and enhanced surface finishes. Indeed these steels can be used in place of quenched and tempered steels, avoiding the heat treatments.

4 SPARTAN UK PRODUCTION PROCESS

As already mentioned the Spartan UK plate mill is a quarto universal reversing mill, with automatic gauge control.

The semi-finished products used to produce steel plates in Spartan UK are from slabs coming from external fully integrated steel mills.

Once purchased, the slabs are stored in a reserved area at the port of Tyne and moved to the plant when it is required to meet a customer's order. Each slab is flame cut on site to the dimensions required for the plate to be produced.

Every slab is marked and imported in a management information system which allows full traceability throughout the production process.

4.1 Reheating

Before being rolled the cut slab is reheated in one of the three furnaces. According to the slab size one of two batch furnaces or a pusher furnace is utilised.

The mill is applied continuously by the pusher furnace and the batch furnaces. The charging and discharging of the furnaces is dependent firstly on their performance and the requirements of the mill.

4.1.1 Pusher Furnace

The "*Gibbons*" pusher furnace is equipped with 20 side burners placed on the side walls and partitioned in 3 independent zones: Preheating zone 8 burners, heating zone 8 burners and homogenization zone 4 burners. Each zone is set to a different temperature. To preheat the combustion air is used a metallic recuperators placed in the chimney stack. The Furnace use natural gas, whose main component is methane CH_4, as fuel and air as comburent.

The furnace is constituted by a pusher system on a single stand the length of the furnace is equal to 21400 mm and the width 2440 mm, the slabs heated in this furnace must not have a diagonal larger than 2500 mm.

The slabs are loaded by magnetic crane and the pusher system drives the slab inside the furnace opening, once the slab has reached the end of the furnace, it comes to the mill via a ramp which connects the bottom of the furnace directly to the rolling mill.

The current Spartan UK standard operate procedure fixes the set point temperatures of the three zones at:

- Preheating zone: 1200°C.
- Heating zone: 1260°C.
- Homogenization zone: 1240°C.

Fig. 9 *Mouth of the "Gibbons" furnace*

4.1.2 Batch Furnaces

The two batch furnaces: "*Hotwork*" and "*Regenerative*"; are built in the same way, with exception of the combustion system.

The Hotwork furnace (in this work also called *HCT*) is equipped with 6 burners and 6 recuperators for combustion air preheating; an air preheater is coupled with each burner.

The burners are inclined of 10° above the horizontal axis and their flame is directed to the furnace floor. Slabs are charged in the furnace heart by positioning on refractory piers.

The Regenerative furnace (in this work also called *Rgen*) has different burners that can preheat the combustion air using a ceramic regenerator. This allows preheating combustion air up to 200-300° C below the furnace temperature.

Burners work in double harness, when one burner burns the fuel the other one suck flue gas from the furnace, heating the ceramic regenerator. When the combustion air passes through the regenerator, it is preheated by the hot mass.

Both furnaces use natural gas, whose main component is methane CH_4, as fuel and air as comburent.

The reheating cycle is performed in the same way in these two furnaces: slabs are loaded in stacks of three, each furnace can contain up to 4 stacks, depending on the size of the slabs.

Slabs are not discharged together but one slab at a time. Slabs are charged and discharged using a lift truck.

Fig. 10 *Unloading of a slab from the batch furnace*

Characteristics of the furnaces are detailed in table 3:

Characteristics	**HCT**	**RGEN**
Length (mm)	9600	9600
Width (mm)	2650	3100
Height (mm)	2950	2950
Maximum temperature °C	1320	1320
Number of control zones	3	6
Maximum load (kg)	90000	90000

Tab. 3 *Batch furnaces technical specifications*

The current Spartan UK standard operate procedure fixes the set point temperature of all the three zones of both furnaces at 1240°C.

4.2 Rolling mill

After the reheating treatment the slabs are moved from one of the furnaces to the rolling mill. Before the rolling process begins, the oxide scale layer, formed in the heating step, is removed by a high-pressure water sprays.

After descaling the slabs are rolled in a *quarto reversing rolling mill*.

The word quarto states that the rolling mill is constituted from 4 rolls: 2 work rolls of smaller diameter in contact with the piece that it is working and 2 back-up rolls of larger diameter that minimize the deflection of the work rolls. The word reversing states that the rolls can rotate in both directions, so the rolled metal may passes back and forth several times through the rolls, as shown in figure 10.

The number of passes through the mill depends on the initial thickness of the slabs and on the dimension of the plate required. The thickness tolerance is guaranteed by a laser gauging machine.

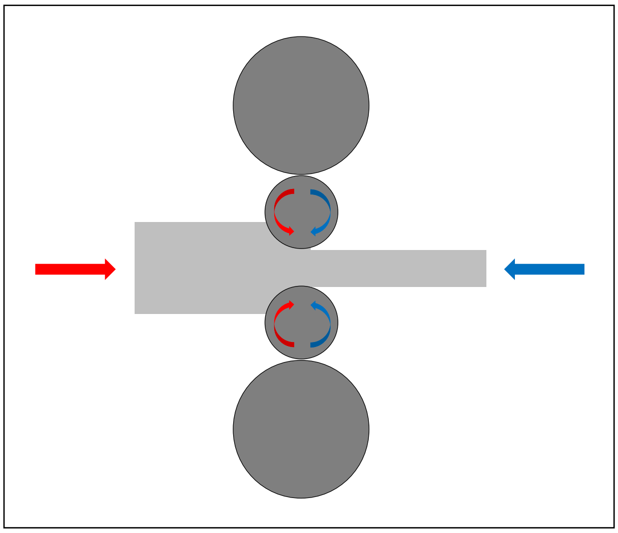


Fig. 11 *Model of a quarto reversing rolling mill*

Two different kinds of supply conditions are carried out in Spartan UK: Normalizing rolling and as-rolled.

The normalizing rolling process as already been described in the previous paragraphs, the as-rolled condition process primarily serves as a shaping process. The term “as-rolled” stems from the fact that the product is not thermo-mechanical-treated; this rolling method is used for materials that are subsequently heat-treated by the customers, or left in the as supplied condition.

4.3 Final treatments and inspection

Depending on the length, on the thickness and on the kind of laminations, the different plates are submitted to different final treatments.

“As rolled” plates, with thickness lower than 100mm, after rolling are re-levelled through a levelling machine while still hot; head and tails are removed from the plates by hot shear. After those operations the plates are cooled down in the work shop until at room temperature.

If the thickness is greater than 100 mm, plates are cooled down in a different work shop and re-levelled when cold through a levelling machine.

“Normalizing rolling” plates follow the same path of “as rolled”, with the same division depending on the thickness.

If costumers require higher mechanical performance, plates can be cooled down in dedicated “slow cool boxes”. These boxes, showed in the figure below, are used to reduce the cooling rate and are particularly suitable for material containing Hydrogen. Indeed, the cooling rate is sufficiently slow to guarantee an effect similar to anti-flaking treatment. Plates cooled down inside slow cool boxes are inspected by ultrasonic testing.

Fig. 12 *Slow cooling box open*

When a normalizing treatment is required, plates follow a different path: after rolling plates are cooled down in a slow cool box, subjected to ultrasonic test and sent to one of two normalizing batch furnaces. After the heat treatment plates are re-levelled through a levelling machine.

All plates are always inspected for surface quality and dimensional accuracy.

On request the plates’ edges can be cut to remove mill edges as rolled.

5 OVERHEATING

The temperatures which the steel slabs are heated before the rolling process fall in the austenite field of iron-carbon diagram.

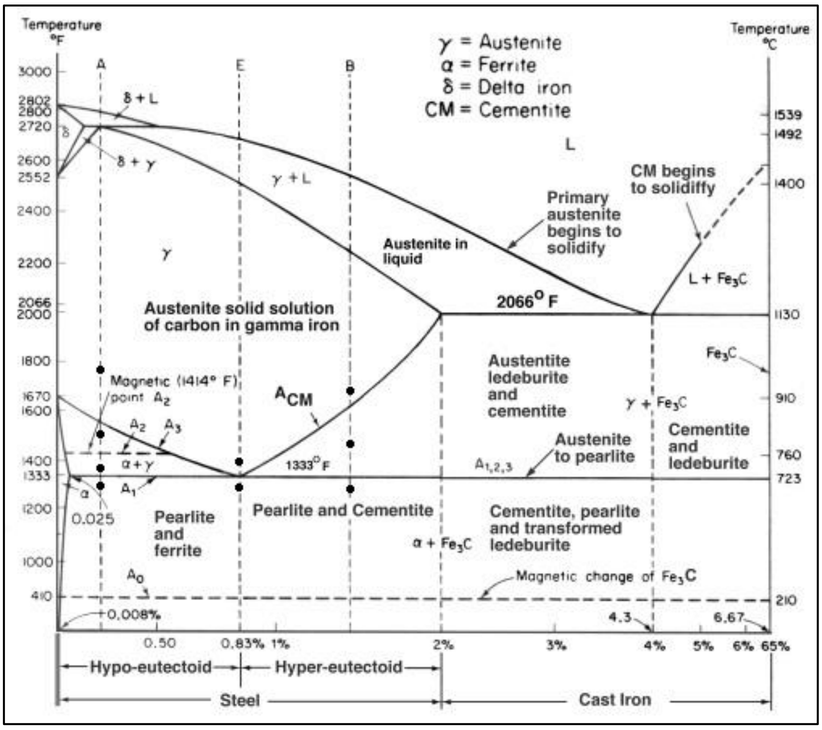


Fig. 13 *Fe-C diagram*

Austenite or gamma-phases iron is an allotrope of iron, usually it is not stable at room temperature.

The fundamental parameters to be taken into consideration during a reheating process that falls within the austenite field are: austenitizing temperature and permanence time in the austenite field.

Increasing the austenitizing temperature it increases the speed of nucleation of the austenite grains and the speed of growth of these; an increase of the permanence time allows austenite grains to increase their size.

When the austenitizing temperature is considerably higher than A_{C3} or A_{CM} and when the soaking time is prolonged overheating can occur.

The term “overheating” refers to the structure associated with coarse austenitic grains which are not uniform in size and with preferential direction of growth; the presence of this kind of structure, after cooling, may cause a course ferrite-cementite structure or a lath structure.

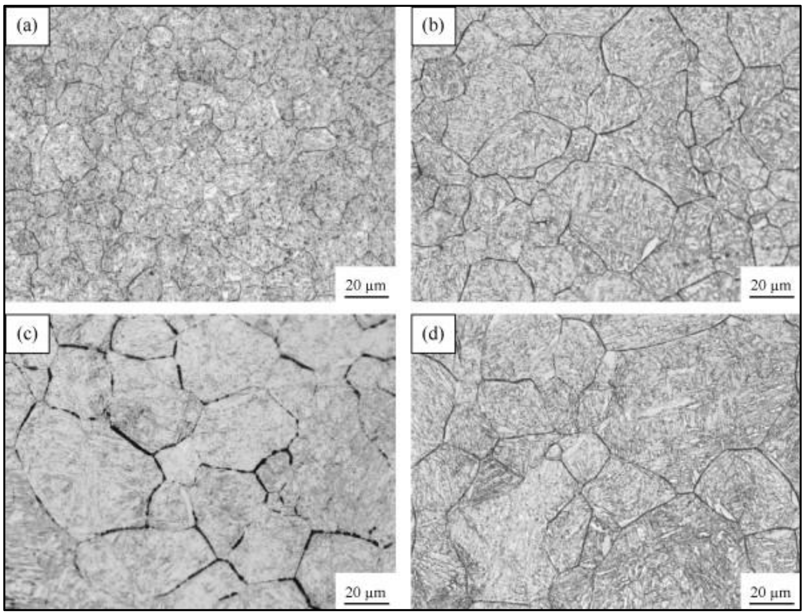


Fig. 14 *Effect of the holding time on the morphology of austenite grain at heating temperature of 900 °C: (a) 5 min, (b) 30 min, (c) 90 min, and (d) 120 min.*

All these faults can result in deterioration of the mechanical proprieties, in which: ductility and impact toughness are reduced and also the fatigue strength is lowered. The tensile strength of a steel is not affected except when it is severely overheated.

The following graphs show the effects of soaking time and soaking temperature on the austenite grains size for a structural steel.

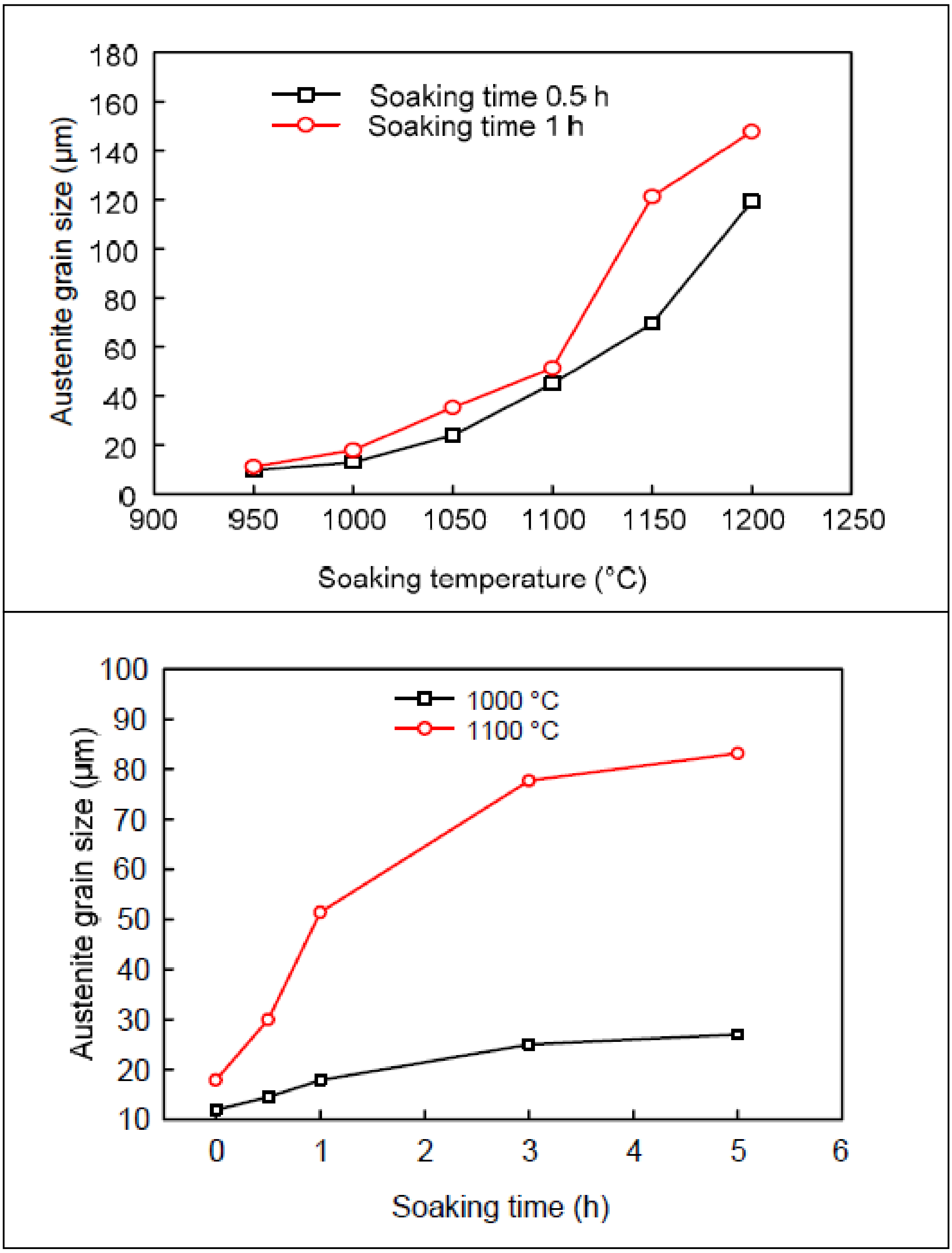


***Fig. 15** Influence of soaking temperature and of soaking time on the austenite grain size [from reference 8]*

Austenite grains with high dimensions increase the hardenability of the steel, this fact explains why the same steel, under the same cooling conditions, may evolve more easily in a lath bainite structure or in martensitic structure, if overheated.

Therefore the cooling rate from heating becomes a parameter of considerable importance, because it can make the difference between developing lath structures or not.

Furthermore austenite grains with large growth result in a smaller grain boundary surfaces; the grain interface is the centre for the nucleation of ferrite grains, and then austenite grains with high dimensions supply a few nucleation centres, resulting in a prevalence of accretion on nucleation with increase of ferrite grain size.

This aspect leads to a microstructure completely different from the microstructure wanted by the thermo-mechanical process.

Each steel is susceptible to the overheating problem differently; a key role is played by the chemical composition of the steel. Some elements like Carbon, Silicon and Manganese promote the growth of the austenite grains; therefore steels containing these elements will be more susceptible to overheating, because the grin growth is fostered not only by the temperature but also by the chemical composition.

Alternatively, steels containing fine precipitates are less susceptible to this problem, indeed fine precipitates inhibit the movement of grain boundaries, impeding the grain growth.

Various studies confirm that steels that contain, at the same time, Manganese and Sulphur show a pronounced tendency to developed overheated structures. The appearance of overheated structures occurs when numerous fine MnS inclusions are dissolved during heating, and subsequently, during cooling to below the high austenitizing temperature, re-precipitate.

These precipitations cause Windmanstatten patterns being frequently observed in overheated specimens.

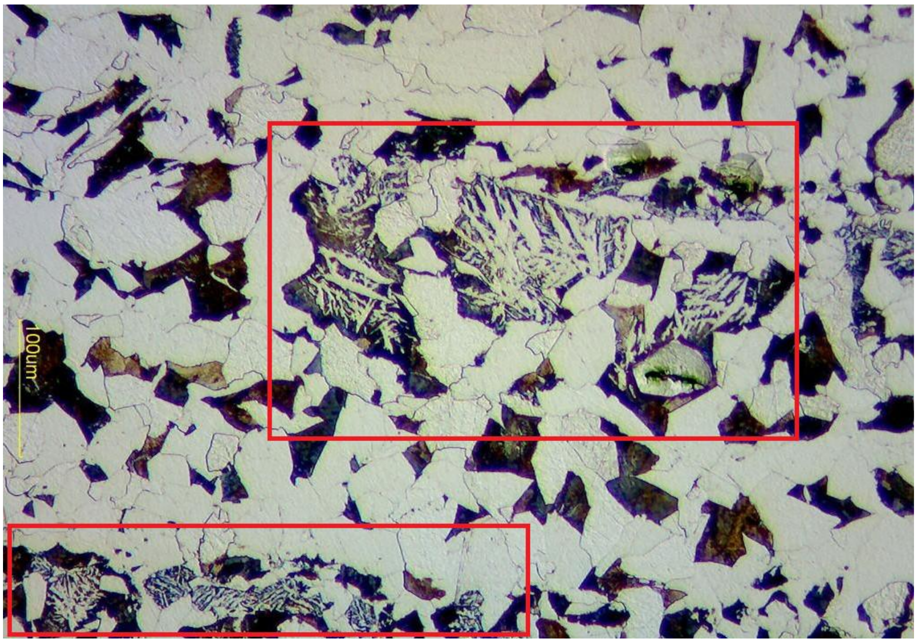


Fig. 16 *Sample of overheating steel with Windmanstatted patterns marked in red*

Beside Manganese`s affinity with sulphur, it also displays a chemical activity with Nitrogen and Carbon.

When the concentration of Manganese is around 1.5% and in the absence of other elements Manganese forms stable interstitial phases with Nitrogen and Carbon and leading to its tendency of coarsening the austenite grains in the course of heat treatment; which is a possible cause of the development of the overheated structure.

In any case it is possible to define, for some steels, a grain coarsening temperature T_{GC}, that is referred to as the temperature that separates two steps of grains growth: the first one, happens at a lower range of temperatures, that consists in a homogeneous and slow growth of the grains and the second one, at a higher range of temperatures, that results in fast growth of the grains with preferential directions.

This temperature varies as a function of heating rate, the faster the heating rate, the higher the grain coarsening temperature, this is due to the fact that with high heating rates, equilibrium conditions are not attained. In figure 16 it is show the parameter T_{GC} for structural Carbon-Manganese steel as a function of heating rate.

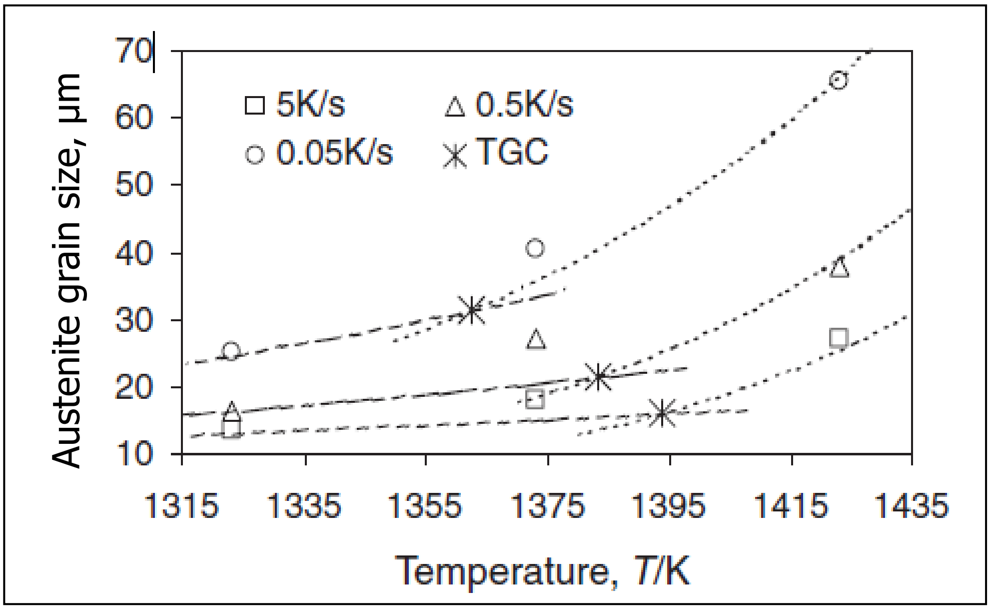


Fig. 17 *Grain coarsening temperature T_{GC} for a C-Mn steel 0.031 Nb*
[from reference 9]

The effects of overheating are difficult to remove; methods of reclaiming overheated steel are:

- Reheating the steel to the original heating temperature, following by slow cooling.
- Repeatedly austenitizing the steel at successively lower temperatures at 100°-150°C intervals.
- If modestly overheated, by a normalising/tempering process.

OBJECTIVES

The purpose of the following research is to solve the problem related to the onset of overheated structures in Spartan UK hot rolled products.

To achieve this objective the equipment and current standard operating practice has been analysed, in order to understand which parameters are linked to the problem.

The attainment of this objective would result in an improvement in quality and a significant cost savings due to the reduction in the number of rejected plates, and energy consumption.

The objective can be considered achieved only after the drafting of a new standard operating procedure able to solve the problem without any reduction in output.

METHOD

The present study started from the examination of a previous research carried out by Spartan UK in February, 2012. This analysed the overheating problem and the influence of operations of the furnace on it. The outcomes of the study showed that all three furnaces have overheated slabs, but with different ratios:

- Gibbons = 14.00% of samples overheated.
- HCT = 62.50% of samples overheated.
- Rgen = 44.50% of samples overheated.

Furthermore, the batch furnace atmospheres were in excess of what they should be and regularly exceeded the set point temperatures.

As a result of this research, the standard Spartan UK procedure was changed, the set point temperature of the batch furnaces was turned down from 1270°C to 1245°C.

Starting from this data and taking into consideration the changes introduced in the standard operating procedure, a new study has been developed.

The new study analysed more factors and its description is given in the following paragraph.

1 RATIONALE AND DESIGN OF THE STUDY

In order to understand which parameters lead to the development of an overheating structure, data was conducted for one month.

The data collection followed three parallel paths; firstly attention was focused on features related to the materials and to the products, secondly on the parameters related to the furnaces, and finally parameters related to the production process.

The means used to verify the presence of overheated structure in the plate is the metallographic analysis, performed by an external laboratory.

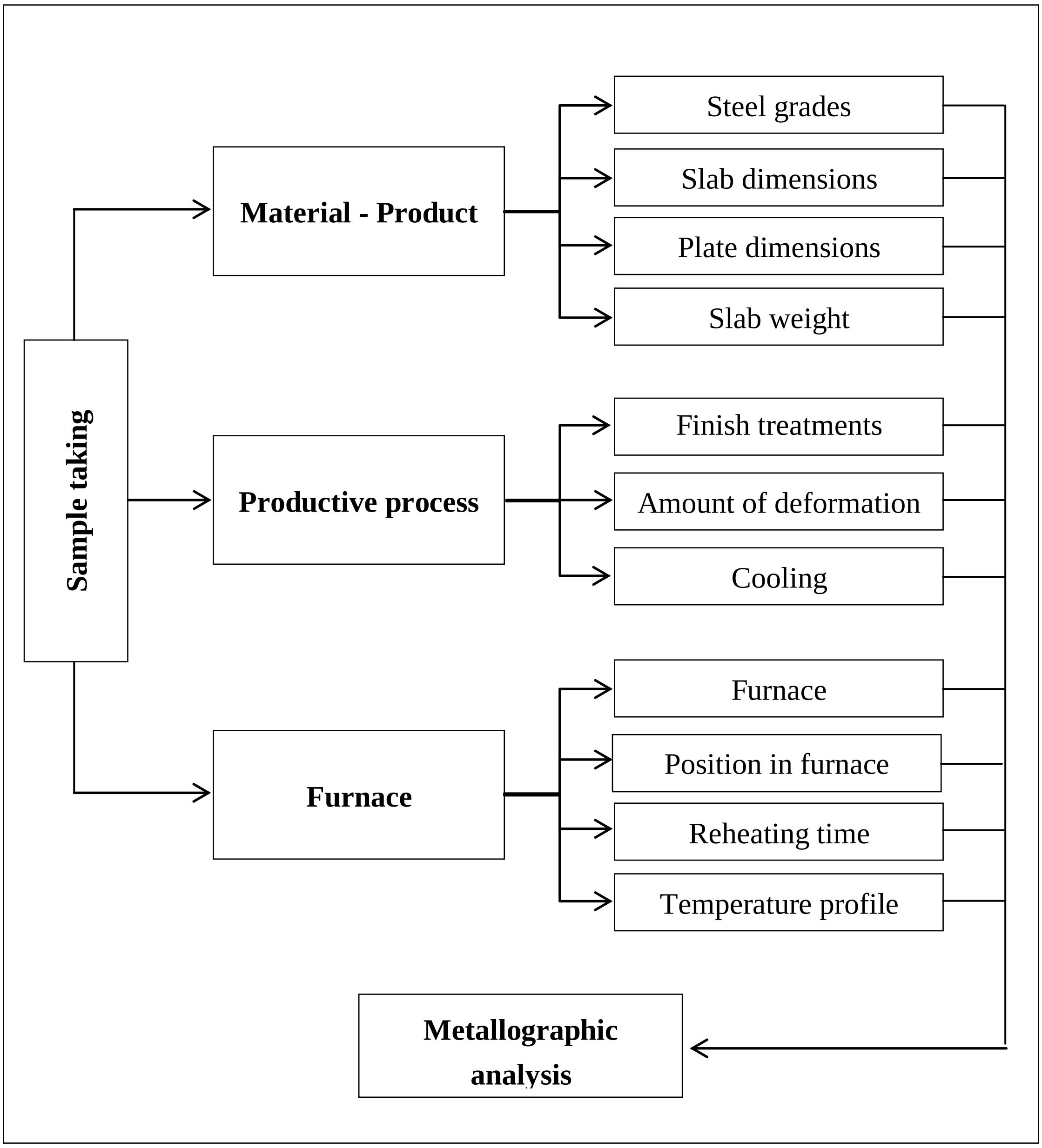


Fig. 18 *Diagram of the rationale of the study*

1.1 Material – Product

The grade of steel is a parameter of importance, indeed, as explained in the previous paragraph, the chemical composition of the steel plays a fundamental role in the development of an overheated structure.

The item “steel grade” also included the analysis of the cast which the slab comes from, this was to determine if the problem can be attributed to the composition or quality of a particular cast.

In the same way, the dimensions of the slab are important if the reheating problem is analysed under the thermodynamic profile. The slab length is large compared with width and thickness.

So the heat transferred the length does not contribute to the temperature uniformity inside the slabs. For this reason the slab's dimensions and especially the slab's thickness were taken into consideration.

The plate's dimensions are significant to know in which zone the plates are stacked for the cooling and to estimate the amount of deformation, as explained in the introduction.

Finally, the weight of the slabs was added in the data collection only to simplify the transfer of data with the furnace managers who usually distinguish the slabs by weight.

1.2 Production process

Spartan UK also provides normalized plates, for this reason any heat treatment after rolling was included in the data collection, in order to understand the effect of this heat treatment on the overheated structure.

The amount of deformation after the rolling process was taken into consideration and sure enough, the amount of deformation is strictly connected to the phenomenon of dynamic recrystallization and recovery; these phenomena may influence the microstructure of the steel after rolling.

The last parameter connected with the productive process was the cooling area. At Spartan UK there are different cooling areas as previously mentioned. By analysing this parameter, it is possible to evaluate possible effects due to the cooling stage and in particular evaluate if there are differences between the cooling rates.

1.3 Furnaces

In the factory, there are three different furnaces, it is important to know from which furnace the slab was heated.

The difference between furnaces was investigated analysing the temperature profile during the production time. Temperature is one of the two most important parameters to be controlled during the study of the overheating problem.

The second most important parameter is the reheating time. For the batch furnaces this factor was recorded according to the weight of the slab:

- Weight < 9000 kg => "*Small slab*"
- Weight > 9000 kg => "*Big slab*"

The Gibbons furnace was recorded without any discrimination of weight or dimension; in effect the slabs heating in the Gibbons furnace have all similar size and weight.

Finally, also the position of slabs in the furnaces was added in the data collection. The position of slabs was collected only for the batch furnaces, because the position of slabs in the pusher furnace are always changing, so this data is not very noteworthy. This parameter was taken into consideration because the proximity between the slabs on top of the stacks and the burners may influence the heating process.

The system used to designate the positions inside the batch furnace is shown in the below figure.

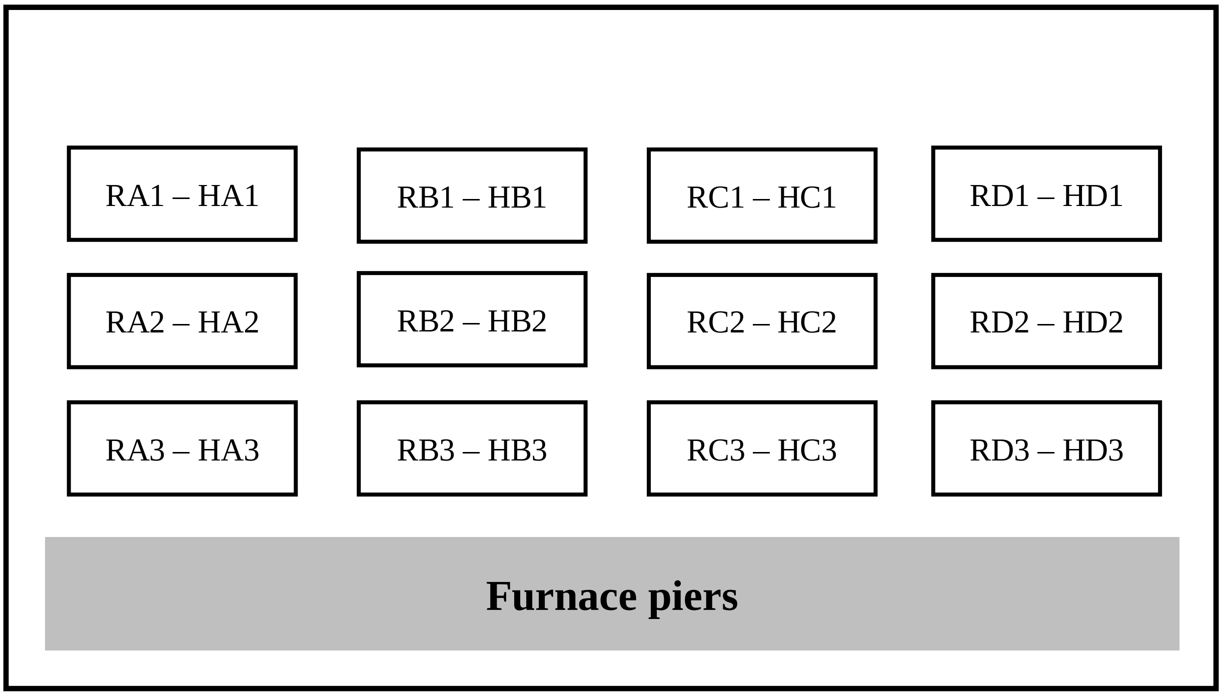


Fig. 19 *Positioning of slabs within batch furnaces, H = Hotworks, R = Rgen; A, B, C, D =Columns left to right; 1, 2, 3 = Top row, middle row, bottom row respectively*

1.4 Metallographic analysis

The European Standard (CR10261) for chemical analysis does not specify the number of specimens and the point at which they are taken from the product, these are left to the manufacturer.

The Spartan UK practice it is to take one specimen from the same steel piece used to acquire the specimens for tensile and impact tests.

These mechanical tests are regulated by the European Standard BS EN 10025 (2004).

Figure 19 shows where the steel piece, from which the specimens for mechanical analysis are taken.

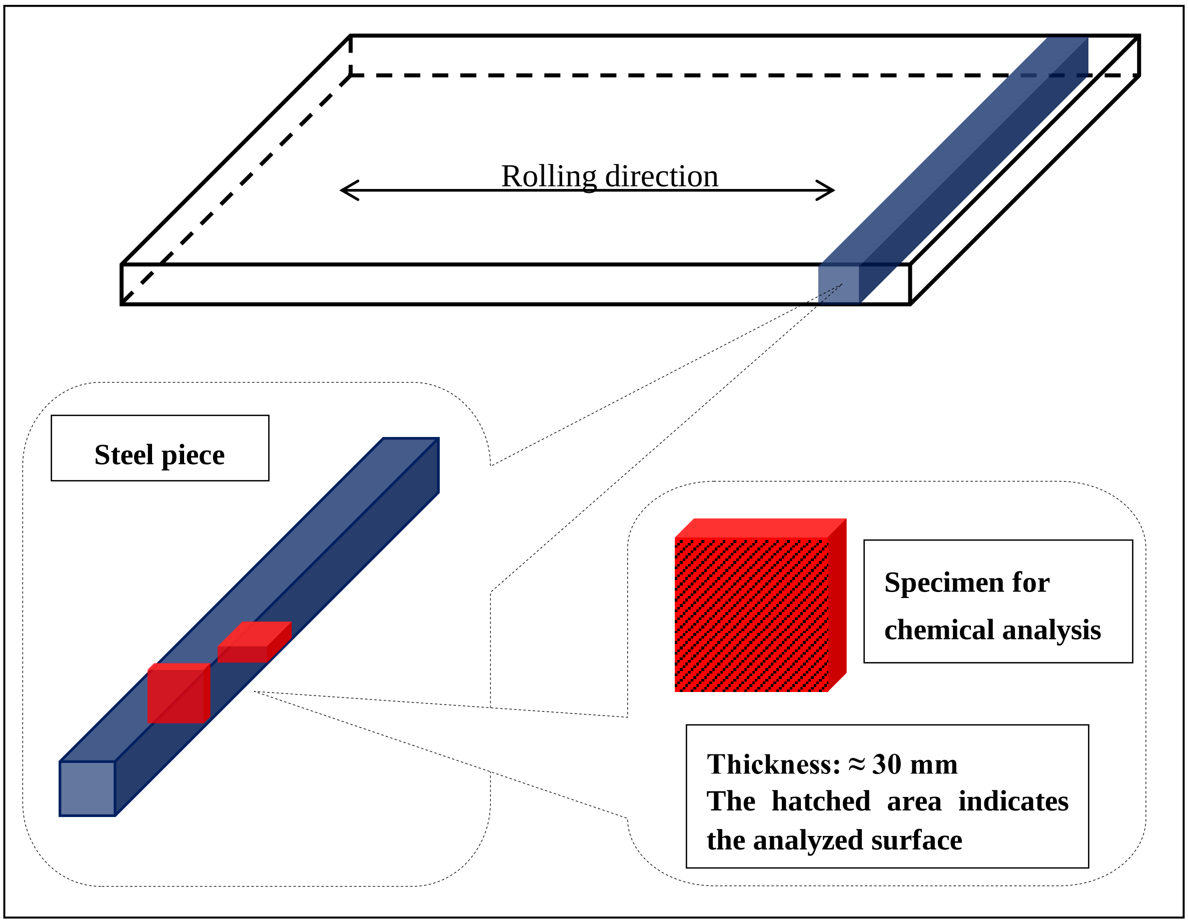


Fig. 20 *Representation of the acquisition zone of the sample*

The steel piece (blue in the picture) is always taken from the plate’s head or tail, and always in the transverse direction to the rolling direction.

The specimen (red in the picture) is taken in a random zone of the steel piece and with a random orientation.

The samples were viewed at a magnification of x200 and etched in 2% Nital solution.

Fig. 21 *Picture of the steel piece (left) and of the chemical sample (right)*

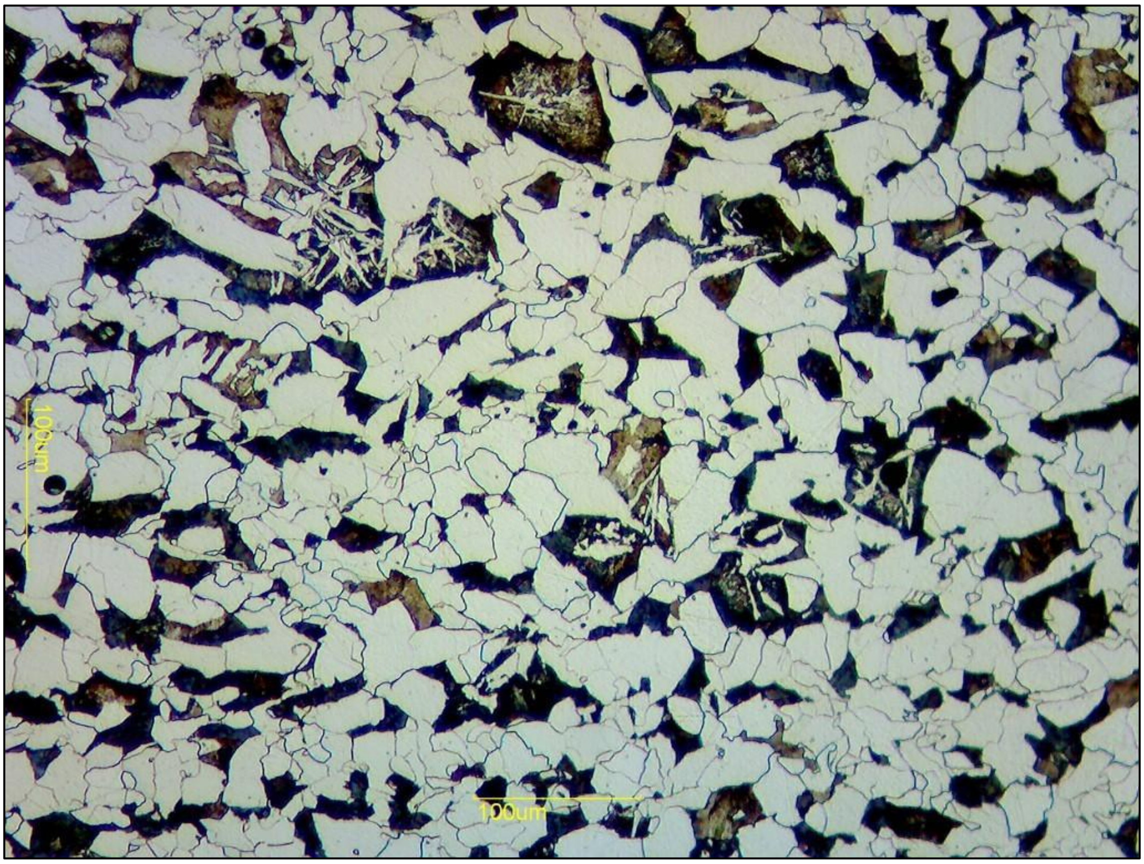


Fig.22 *Example of chemical analysis result*

RESULTS

1 INFLUENCE OF VARIOUS PARAMETERS

1.1 Influence on S355

The first result, from the study, is that S355 steel shows a high tendency to develop overheated structures, significantly higher than the other rolled steels. 24 samples out of 33 have displayed this problem; this means that 72% of this steel grade is overheated after reheating process.

This higher susceptibility is explained by observation of chemical composition of S355: the concentration of Manganese in S355 steel is about 1.5%, this is the concentration at which, as mentioned in the introduction, Manganese forms stable interstitial phase with N and C. This phase is the cause of the tendency to coarsening austenite grains, with consequent development of overheating structure.

The concentration of Manganese in the other steels (S355W, S275 and S235) is lower.

Furthermore, by increasing the equivalent carbon contents it decreases the value of the grain coarsening temperature $T_{GC.}$ The values of C_{eq} for the different steels are shown in the table:

	C_{eq}
S235	0.310
S275	0.365
S355	0.421
S355W	0.398

***Table 4** Value of C_{eq} for Spartan UK steels(long formula used)*

Therefore, S355 has the lower value of T_{GC}; this means that S355 starts to develop grains with a non-uniform size and with preferential directions of growth at lower temperature than the other steels.

All these factors explain why S355 has a higher tendency to develop overheated structures.

The following table shows the connections between the S355 plates analysed and the material-product parameters.

No.	Cast Number	Grade	Thick.	Width	Length	Overheated	Slab Thick.	Slab W.	Slab L.	Peso
			(mm)				(mm)			(kg)
1	AH8449	S355J2G3 + N	55	2000	6000	YES	268	2045	1315	5657
2	AH8441	S355	50	2000	6000	NO	268	2050	1235	5326
3	AH8451	S355J2+N	30	2000	12000	YES	268	2050	1480	6383
4	AF8421	S355J2+N	55	1500	9600	YES	248	1539	2310	6921
5	AF8427	S355J2+N	65	1500	10550	YES	248	1545	2970	8933
6	AF8422	S355J2+N	65	1500	10550	YES	248	1540	2980	8934
7	AF8422	S355J2+N	55	1500	9600	YES	248	1542	2314	6947
8	AF8427	S355J0+AR	50	1510	9480	YES	248	1539	2087	6253
9	EH8461	S355J0+AR	75	1700	15495	NO	223	1758	5721	17606
10	AH8466	S355J2G3	50	2000	6000	YES	268	2040	1233	5292
11	AH8446	S355J2+N	30	2000	12000	NO	268	2040	1508	6472
12	AF8535	S355J0+AR	45	1200	21000	YES	218	1240	4659	9886
13	AF8532	S355J2+N	60	1250	12200	YES	218	1240	3754	7966
14	AF8428	S355J2+N	60	1500	12200	YES	246	1540	3222	9582
15	AH8510	S355J2G3	30	2000	6000	NO	268	2045	750	3227
16	AH8441	S355J2+N	30	2000	120000	NO	266	2040	1510	6432
17	EH8463	S355JR+AR	30	1800	16301	YES	222	1852	2420	7811
18	AF8493	S355J0+AR	60	1250	13000	YES	218	1242	3835	8151
19	EH8459	S355NL	80	1700	10200	YES	222	1757	3960	12125
20	EH8462	S355J0+AR	40	2000	10200	YES	222	1860	2190	7099
21	AF8505	S355J0+AR	60	1250	9732	YES	218	1246	2900	6184
22	AH8441	S355J2+N	45	2050	6100	YES	266	2045	1170	4996
23	HJ8470	S355J2+N	90	2000	4000	NO	249	1547	2164	6544
24	HJ8473	S355J2+N	80	2000	4000	NO	248	1550	1873	5652
25	AH8445	S355J2+N	80	2000	6000	NO	269	2042	1949	8404
26	AH8441	S355J0+AR	100	2000	6000	YES	266	2045	2450	10462
27	AH8455	S355K2+N	40	2000	12000	YES	268	2030	1950	8328
28	HJ8476	S355	20	2000	6000	YES	248	1545	710	2136
29	AH8443	S355J0+AR	75	1800	6500	YES	268	2045	1830	7873
30	AH8451	S355J2+N	40	2000	12000	YES	268	2037	1950	8357
31	AH4530	S355J2+N	60	1975	8000	YES	268	2042	1960	8420
32	AH8453	S355K2+N	50	2000	1000	YES	267	2040	2040	8723
33	AH8454	S355J2+N	40	2000	18000	NO	268	2050	2900	12507

Table 5 *Sample analysed and material-product parameters*

Examining the various parameters suggests that there are no connections between overheating and the cast number or slab and plate dimensions. Except for the sample number 9, indeed, this comes from a slab much larger than the others and far from the standard slab dimensions. The next table shows the parameters connected with the furnaces for the S355 samples.

No.	**Furnace**	**Position**	**Rolling Date**	**Time in**	**Time Out**	**Duration**	**Overheated**
1	GIBBON	-	13/11/2012	23:43	13:44	12:26	YES
2	GIBBON	-	13/11/2012	01:38	15:18	11:56	NO
3	HCT	HC1	14/11/2012	05:36	12:33	07:01	YES
4	HCT	HA2	02/11/2012	12:18	21:17	08:59	YES
5	HCT	HA1	02/11/2012	12:18	21:05	08:47	YES
6	RGEN	RA2	02/11/2012	12:50	19:48	06:58	YES
7	HCT	HC3	02/11/2012	10:52	17:55	07:03	YES
8	HCT	HC2	02/11/2012	10:52	17:46	06:54	YES
9	RGEN	RA3	03/11/2012	19:59	05:39	09:40	NO
10	RGEN	RA2	15/11/2012	13:22	21:30	08:08	YES
11	HCT	HC3	15/11/2012	04:39	15:18	10:39	NO
12	RGEN	RD2	11/11/2012	11:02	19:09	08:07	YES
13	HCT	HD1	16/11/2012	07:46	16:19	08:33	YES
14	RGEN	RD2	16/11/2012	12:38	19:38	07:01	YES
15	GIBBON	-	19/11/2012			62:00:00	NO
16	RGEN	RA2	21/11/2012	09:36	17:38	08:02	NO
17	HCT	HC2	21/11/2012	11:19	19:37	08:18	YES
18	HCT	HD2	22/11/2012	05:24	12:53	07:29	YES
19	RGEN	RA3	22/11/2012	12:06	20:34	08:28	YES
20	RGEN	RD1	22/11/2012	12:07	20:06	07:59	YES
21	RGEN	RB3	23/11/2012	05:19	14:34	09:15	YES
22	HCT	HC2	23/11/2012	07:08	16:26	09:18	YES
23	HTC	HA2	06/11/2012	11:53	19:42	07:49	NO
24	HCT	HD2	08/11/2012	02:00	11:13	09:13	NO
25	HCT	HD1	19/11/2012			23:06	NO
26	HCT	HD3	21/11/2012	01:52	11:19	09:27	YES
27	HCT	HC1	27/11/2012	09:44	20:03	10:19	YES
28	GIBBON	-	28/11/2012	10:15	21:29	10:39	YES
29	RGEN	RA3	30/11/2012	05:36	16:08	10:32	YES
30	RGEN	RB3	03/12/2012	12:02	23:17	11:15	YES
31	RGEN	RA3	04/12/2012	04:22	17:57	13:35	YES
32	HCT	HB3	07/12/2012	02:07	10:55	08:48	YES
33	RGEN	RC3	05/12/2012	04:56	15:30	10:34	NO

Table 6 *Sample analyzed and furnace parameters*

The first observation is that, slabs heated in batch furnaces, show overheated structures regardless of the position in which they are in the furnace. In the same way there is not a clear connection between reheating time and overheated development.

A few words should be said about the samples number 1, 2, 15 and 28. These came from the Gibbons furnace during a period of non-standard conditions; in effect these samples were taken during two different prolonged (more than two hours) downtime situations, caused by mill malfunctioning.

In the first case (samples 1, 2 and 28) nothing was changed in the Gibbons furnace settings; therefore samples 1 and 28 were for a longer period (than average) in the homogenization zone of the pusher furnace, i.e. 1240°C, while sample 2 was for a longer period (than average) in the preheating zone of the pusher furnace, i.e. 1200°C.

In the second case, the Gibbons setting were changed, and the three zones have been set respectively to 1000°C, 1000°C and 1125°C; therefore sample 15 was for a longer period (than average) ~20 hours, in the homogenization zone of the pusher furnace, i.e. 1125°C.

It is important to note that samples 1 and 28 developed overheated structures whereas the other two samples did not.

The analysis of these situations is of primary importance to understand the meaning and the role of the grain coarsening temperature (paragraph 5 of the introduction); is it assumed that the grain coarsening temperature T_{GC} for S355 steel is above 1200°C, indeed, prolonged soaking time at temperature of 1200°C or 1125°C did not result in the development of overheated structures. This result is in accordance with what is show in the figure 16 that concerns a steel very similar to S355.

The following table shows connection between overheating and productive process.

No.	Grade	Thick.	Width	Length	Overheated	Slab Thick	Slab W.	Slab L.	Treatment	Deformation	Cooling
		(mm)				(mm)					
1	S355J2G3 + N	55	2000	6000	YES	268	2045	1315		80%	Inside
2	S355	50	2000	6000	NO	268	2050	1235		82%	Inside
3	S355J2+N	30	2000	12000	YES	268	2050	1480		89%	Inside
4	S355J2+N	55	1500	9600	YES	248	1539	2310		78%	Box
5	S355J2+N	65	1500	10550	YES	248	1545	2970		75%	Box
6	S355J2+N	65	1500	10550	YES	248	1540	2980		74%	Box
7	S355J2+N	55	1500	9600	YES	248	1542	2314		78%	Box
8	S355J0+AR	50	1510	9480	YES	248	1539	2087		80%	Box
9	S355J0+AR	75	1700	15495	NO	223	1758	5721		67%	Inside
10	S355J2G3	50	2000	6000	YES	268	2040	1233		82%	Inside
11	S355J2+N	30	2000	12000	NO	268	2040	1508		89%	Inside
12	S355J0+AR	45	1200	21000	YES	218	1240	4659		80%	Inside
13	S355J2+N	60	1250	12200	YES	218	1240	3754		72%	Inside
14	S355J2+N	60	1500	12200	YES	246	1540	3222		76%	Inside
15	S355J2G3	30	2000	6000	NO	268	2045	750		89%	Inside
16	S355J2+N	30	2000	120000	NO	266	2040	1510		89%	Inside
17	S355JR+AR	30	1800	16301	YES	222	1852	2420		87%	Inside
18	S355J0+AR	60	1250	13000	YES	218	1242	3835		72%	Inside
19	S355NL	80	1700	10200	YES	222	1757	3960		65%	Box
20	S355J0+AR	40	2000	10200	YES	222	1860	2190		81%	Inside
21	S355J0+AR	60	1250	9732	YES	218	1246	2900		72%	Box
22	S355J2+N	45	2050	6100	YES	266	2045	1170		83%	Inside
23	S355J2+N	90	2000	4000	NO	249	1547	2164	Normalised	53%	Box
24	S355J2+N	80	2000	4000	NO	248	1550	1873	Normalised	58%	Box
25	S355J2+N	80	2000	6000	NO	269	2042	1949	Normalised	71%	Box
26	S355J0+AR	100	2000	6000	YES	266	2045	2450		63%	Box
27	S355K2+N	40	2000	12000	YES	268	2030	1950		85%	Inside
28	S355	20	2000	6000	YES	248	1545	710		90%	Inside
29	S355J0+AR	75	1800	6500	YES	268	2045	1830		75%	Inside
30	S355J2+N	40	2000	12000	YES	268	2037	1950		85%	Inside
31	S355J2+N	60	1975	8000	YES	268	2042	1960		78%	Box
32	S355K2+N	50	2000	1000	YES	267	2040	2040		82%	Box
33	S355J2+N	40	2000	18000	NO	268	2050	2900		85%	Inside

Table 7 *Sample analyzed and productive parameters*

Ignoring samples 1, 2, 15 and 28, of which have already been discussed, it is easy to note that specimens that have undergone a normalization treatment (23, 24, and 25) do not show an overheated structure. This is in accordance with what is mentioned in the introduction.

Observing specimens 3, 11 and 16, it will be noted that these have the highest amount of deformation, around 89%, and that two of these do not show overheated problems. The correlation between these aspects has already been cited in the introduction chapter. During and following the hot rolling process, or any hot deformation process, two phenomena happen generally: dynamic recrystallization and recovery.

The evolution of these is shown in the following picture.

The driving force of these events is the reduction of internal energy of the system. This reduction is obtained reducing the grains boundary surface and rearranging or eliminating the areas full of dislocations.

The recrystallization phenomenon is directly proportional to the amount of deformation; plates that have undergone a strong reduction of thickness have a high tendency to recrystallize, especially considering that the deformation process ends when the plate is still hot.

It is possible to assume that the amount of recrystallized material is such as to eliminate the coarse structure due to overheating.

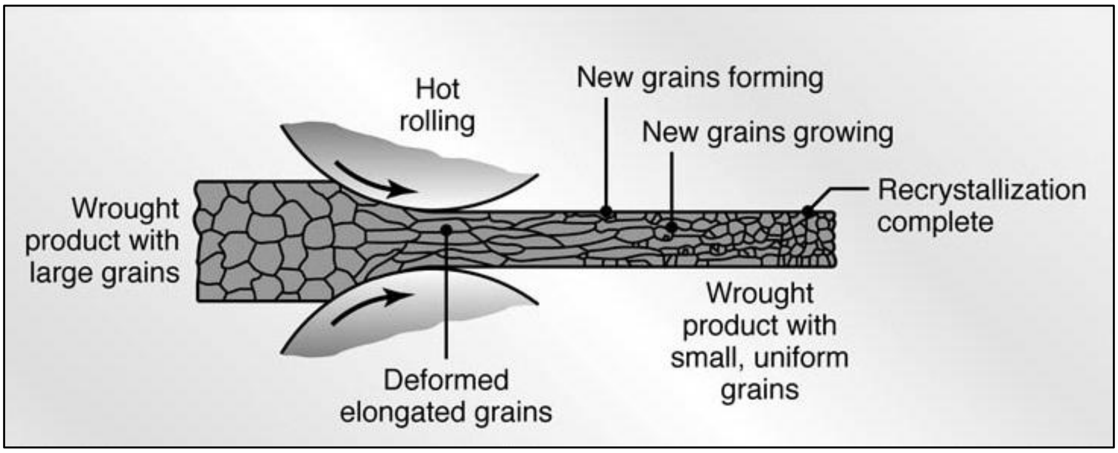


Fig. 23 *Schematic diagram of structure changes of deformed metal in the course of rolling and after its completion*
[from reference 6]

Lastly, slabs cooled down in different places, slow cooling box (*Box*) or shop floor (*Inside*), show overheated structures regardless of the area in which they are.

So the end of the S355 analysis it is important to note that, of 9 samples not overheated:

- 3 are not overheated due to normalization treatment.
- 2 are not overheated probably due to high amount of deformation.
- 2 were taken in particular conditions.

This means that 92% of the S355 heated with the standard Spartan UK procedure are overheated.

1.2 Influence on S235, S275 and S355W

Results on these steel grades are extremely clear; of all samples analyzed only one has developed a overheated structure. But, this sample comes from a prolonged downtime of the rolling mill and was heated in the Gibbons furnace for more than twelve hours at 1260°C (that is about 8 hours more than normal).

None of these samples have undergone a normalization treatment and the amount of deformation was always below 85%.

In conclusion, these steel grades are less sensitive to the overheating problem.

The explanation of the minor susceptibility of these is the same already described in the previous paragraph: lower concentration of Manganese and lower value of equivalent carbon then S355 steel.

2 FURNACES TEMPERATURE PROFILE AND REHEATING PROCEDURE

Not mentioned until now is been the temperature profile of the furnaces and the reheating time, indeed, this subject deserves a separate discussion, especially in the light of what has been discussed in the previous paragraphs about S355 steel.

Temperatures were recorded daily for the data collection and are shown below.

The Gibbons furnace shows a very constant temperature profile as show in the graphs.

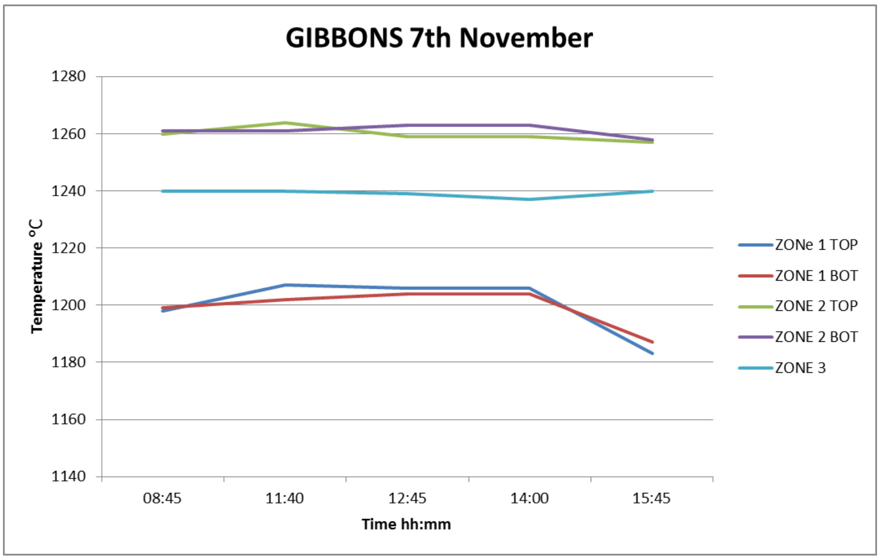


Fig. 24 *Example of temperature profile data for the Gibbons furnace*

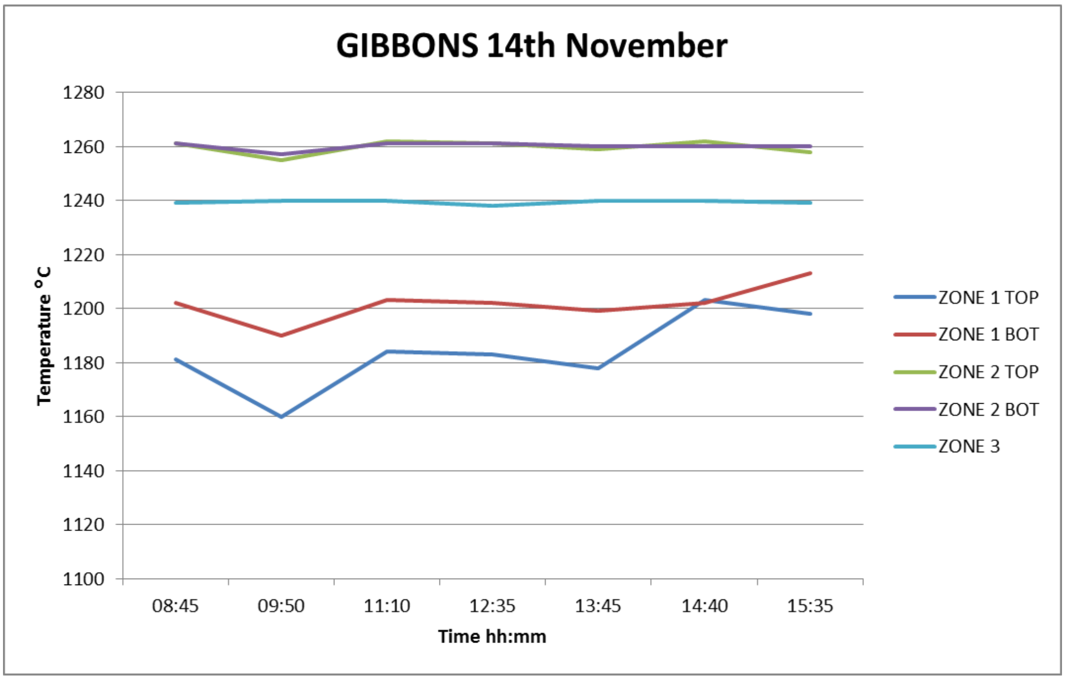


Fig. 25 *Example of temperature profile data for the Gibbons furnace*

Findings showed that temperature fluctuations never exceed 100°C.

Reheating time in Gibbons furnace varies between 3 and 5.5 hours depending on thickness, and usually it is constant, without significant variations.

Remembering that the Gibbons furnace is divided into three zones, each of which is at a different temperature, 1200°C, 1260°C and 1240°C; it is easy to note in the following graphs that the soaking time at a high temperature (zone 2 and zone 3) never exceeds 4 hours.

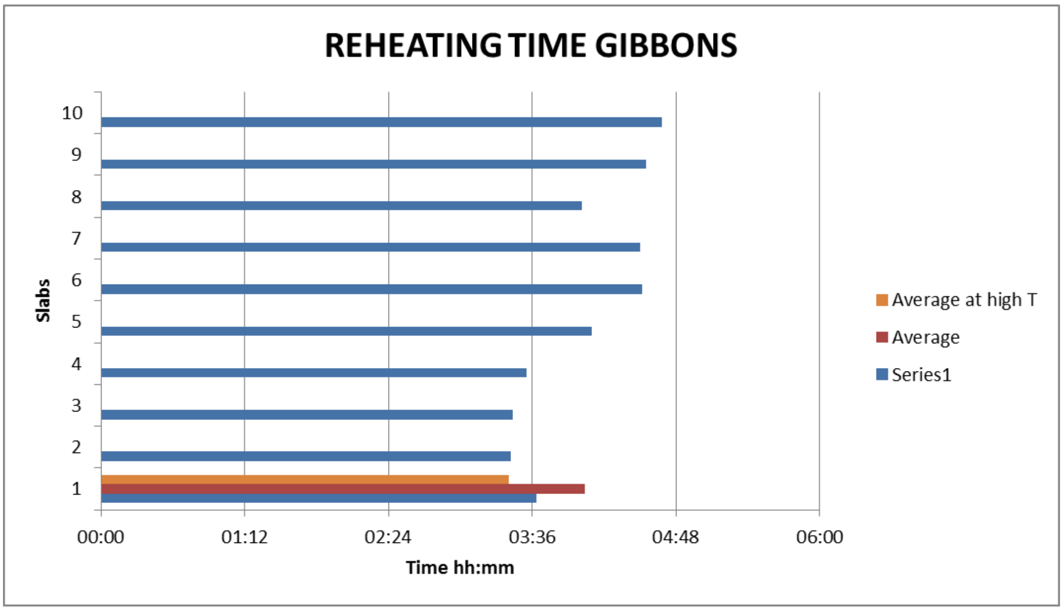


Fig. 26 *Example of reheating time data for the Gibbons furnace*

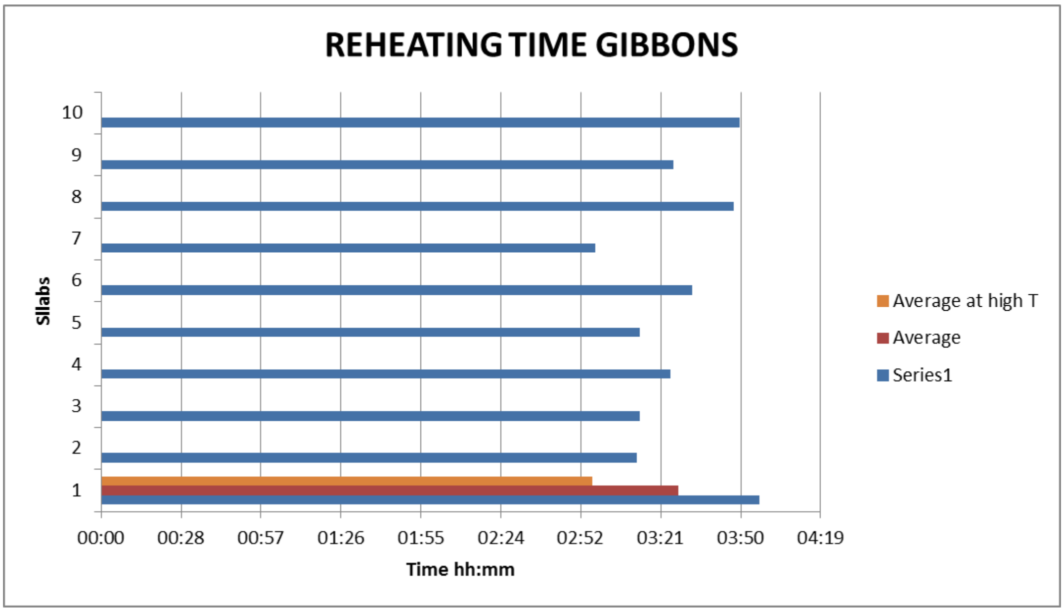


Fig. 27 Example of reheating time data for the Gibbons furnace

In the previous figures the blue lines show the reheating time for random slabs, the red line shows the average of reheating time and the orange line indicates the average of time at high temperature, that is the soaking time in zone 2 and 3.

On the other hand, batch furnaces show the opposite trend: temperature profile is not constant with high variations of the temperature during the operations, variations that exceed 300°C. These considerations are shown in the pictures below.

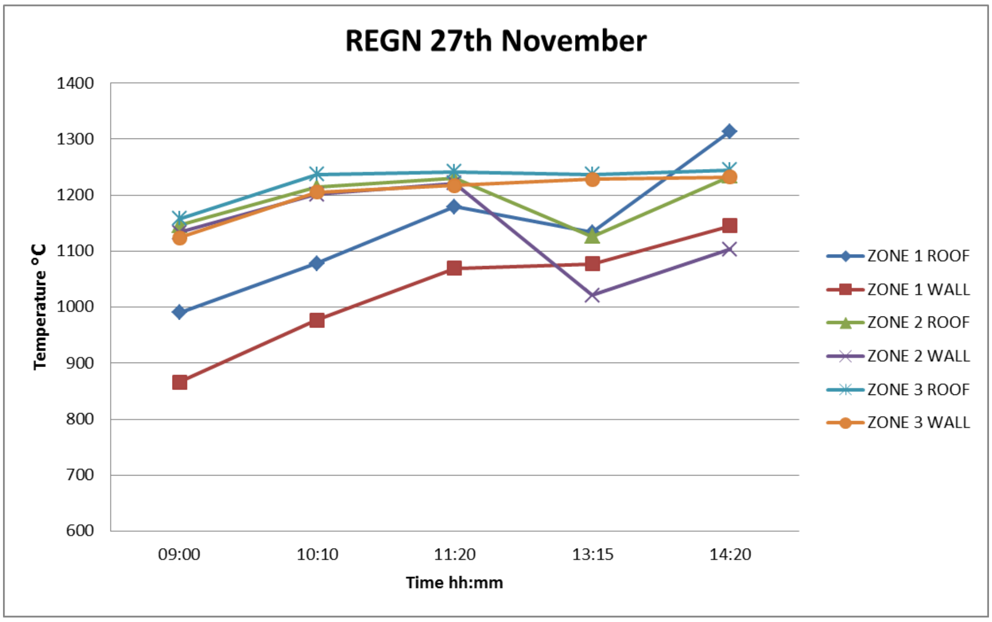


Fig. 28 Example of temperature profile data for the RGEN furnace

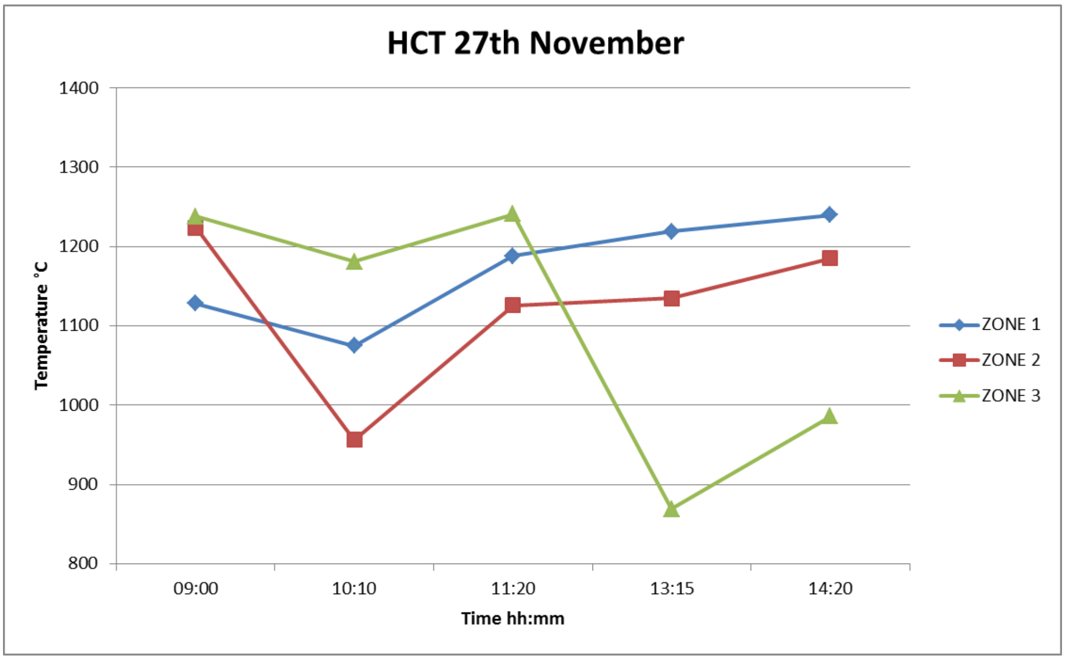


Fig. 29 Example of temperature profile data for the HCT furnace

The reheating time in the batch furnaces is not consistent and varies between 6 and 12 hours.

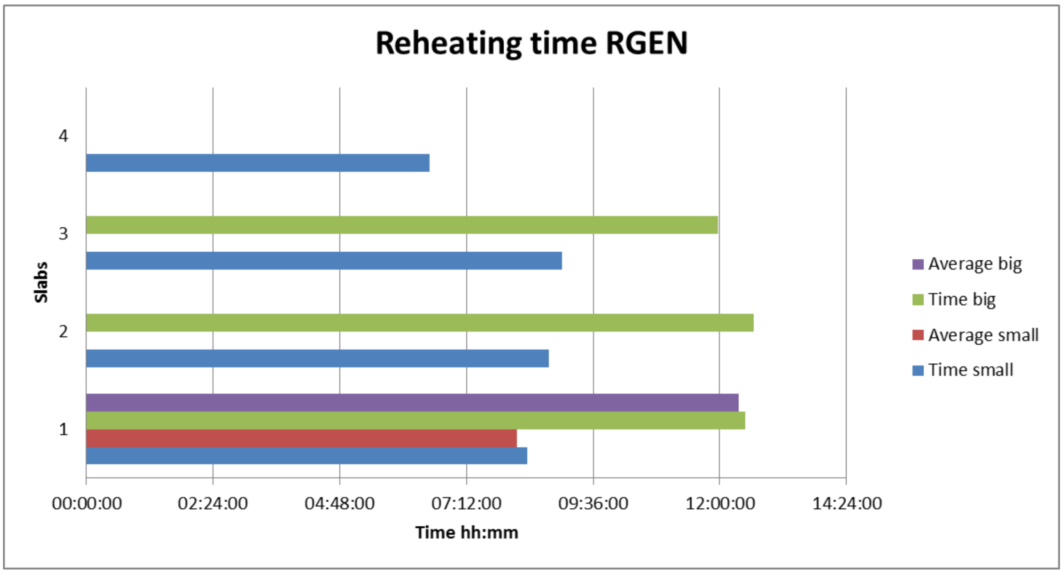


Fig. 30 Example of reheating time data for the RGEN furnace

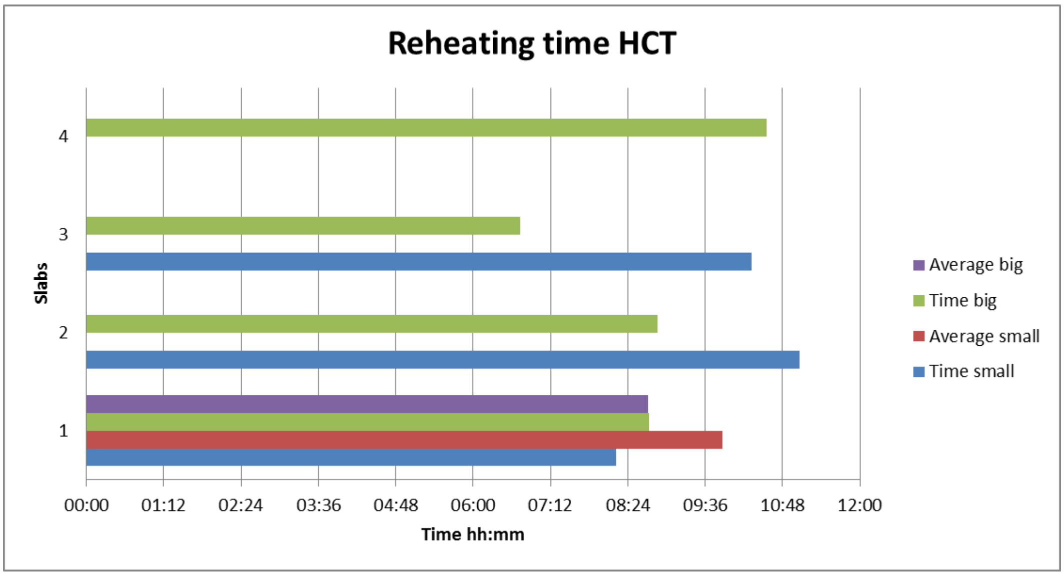


Fig. 31 *Example of reheating time data for the HCT furnace*

It is important to note that, as shown in the graph, the reheating time is not related to the slab weight, the smaller slab (blue lines), indeed, are heated longer then the big slabs (green lines).

In the light of this evidence, it is easy to notice the absence of a standard operating procedure for the batch furnaces and that the reheating time in these furnaces seem illogical.

In order to understand the practices behind these data, an interviews were conducted with the furnaces operators.

The results of these interviews were that the each work-shift estimated the reheating time for the batch furnaces in different ways:

- First shift estimated the reheating time based on the stack (group of three slabs) weight.
- Second shift estimated the reheating time based on the slabs thickness.
- Third shift estimated the reheating time based on value of pressure inside the burners of the furnace.

This is the reason why the reheating time for batch furnaces seems illogical.

Already in the previous study carried out by Spartan UK it was clear that the overheating problem is mainly linked to the batch furnaces. In the light of this study, the uniform temperature profile, the reduced reheating time, the reduced soak at high temperature and the use of a more standardize practice are the reason why slabs heated in Gibbons furnace show a very small percentage of overheated slabs; less than 14%.

Batch furnaces, instead, miss a standardize procedure.

The missing of this and the absence of a constant reheating time and the chemical composition of steel are the evident causes that involving the onset of overheated structures in S355 steel heated in these furnaces.

3 PROCEDURE ORDINARY

From the analysis of these results raises the need to adopt a standard and unequivocal procedure able to solve the overheating problem for the batch furnaces.
In this study two possible strategies were taken into consideration to achieve the objective:

- Reduce the reheating time
- Reduce the soaking temperature

It could also be possible to work on the steel composition, but this possibility was not take into account because it was not one of the company's objectives.
Although temperature reduction may on the face of it be the most appropriate action it is deemed as inappropriate as reducing the temperature further could result in a reduction of steel plasticity, with obvious effects on the rolling process.
The strategy adopted in this study is to reduce the reheating time, especially as a first attempt to solve the problem; in this way the time allowed to austenite grains to increase their dimensions is reduced.
This in accordance with various studies in which have shown that, reduction of 30 minutes of the soaking time, had substantial effects on the grains dimensions. As illustrated in the following pictures:

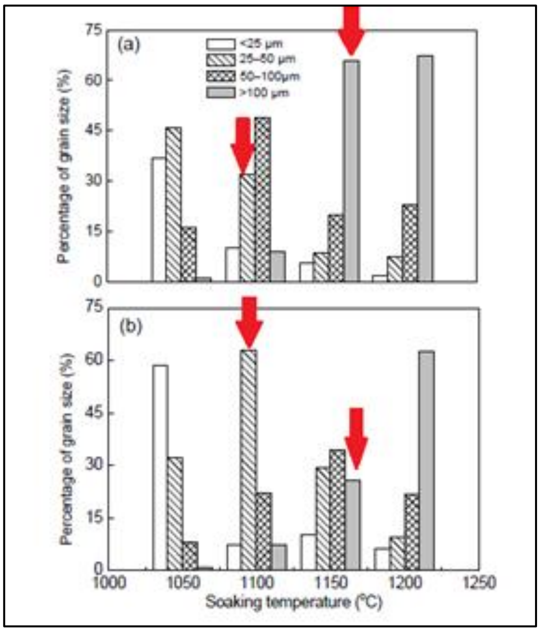


Fig. 32 *Relationship between soaking temperature and percentages of grain sizes for different holding times [from reference 8]*

To estimate the soaking time reduction an empirical method has been used. It estimates the time to heat a slab with known dimension, starting from a smaller slab with known dimension that is not overheated.

To estimate the new reheating time the method steps are:

- Calculate the difference of weight between the two slabs.
- Calculate the extra volume.
- Redistribute the extra volume on the slab surface.
- Increase the heating time for 1 minute every thickness millimeters extra.
- Adding this extra time to the heating time for the starting slab.

The starting slab chosen was a slab heated in the Gibbons furnace, this is because some evidences, already mentioned in the previous paragraph, suggest that the slabs heated in this furnace usually do not present overheating problems.

The outcomes achieved from this method are lower than the Spartan UK registered average.

The outcomes obtained from this method have been compared with past reheating times used by Spartan UK and with an earlier study carry out in the company on the HCT furnace.

From the first comparison it was found that the outcomes correspond with some of the lower reheating times used by Spartan UK. This indicates that it is possible to roll slabs with reheating times below the usual average, without reduction in workability.

From the comparison between the outcomes and past study it was found that the reheating times are comparable.

Supported by these facts, an easy program has been produced to show the reheating time starting from the slab dimension.

This program uses the method already mentioned, but the outcomes are built on the results obtained using five starting slabs heated in the Gibbons furnace.

The starting slabs and the respective reheating times are shown in the following table.

Thickness (mm)	**Width (mm)**	**Length (mm)**	**Weight (kg)**	**Reheating time (min)**
268	2055	971	4198	266
268	2060	783	3393	264
268	2050	870	3752	251
247	1540	1477	4410	244
218	1232	1860	3921	280

Tab. 8 *Starting slabs and reheating time used to build the program*

Thinking about how the method is built up, it is easy to understand that for slabs weighing less than 4410 kg the reheating time cannot be calculated; for these slabs the reheating time has been set arbitrarily at 4 h and 30 min. This is because, usually, slabs so small are heated in the Gibbons furnace and because a previous Spartan UK study shows that this kind of slabs is heated after 250 – 300 min.

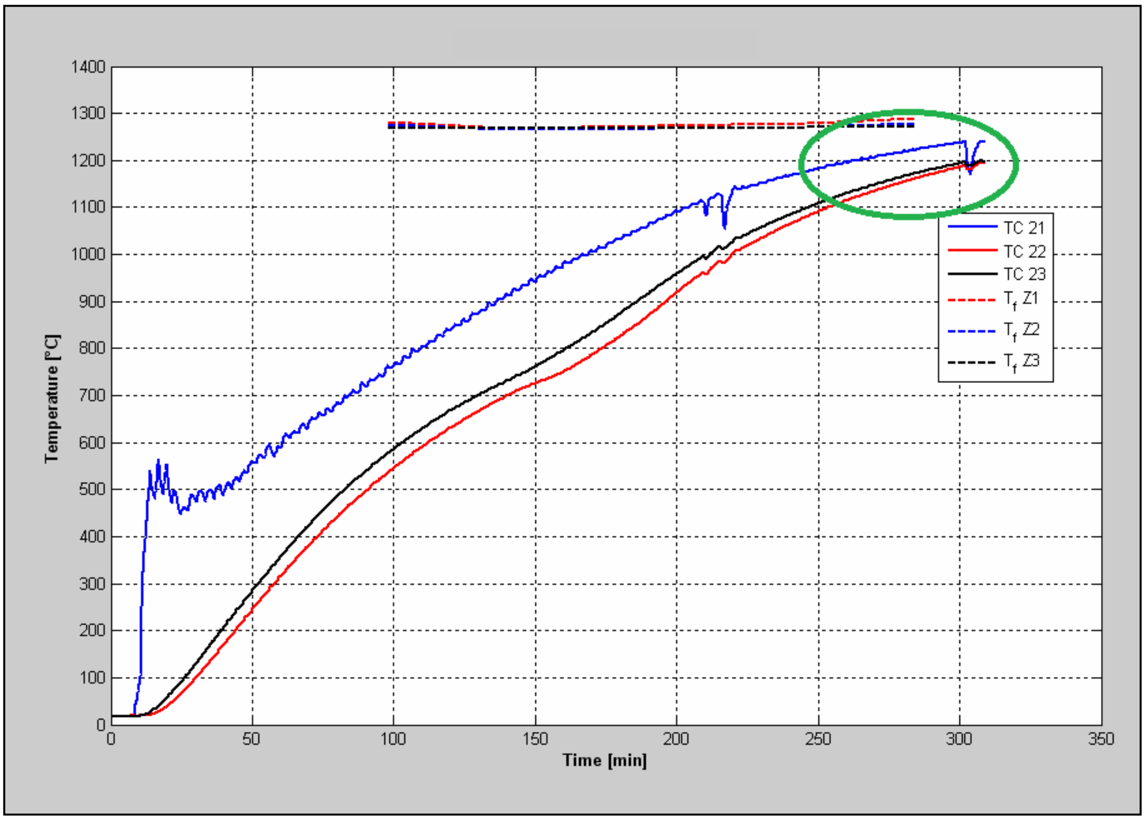
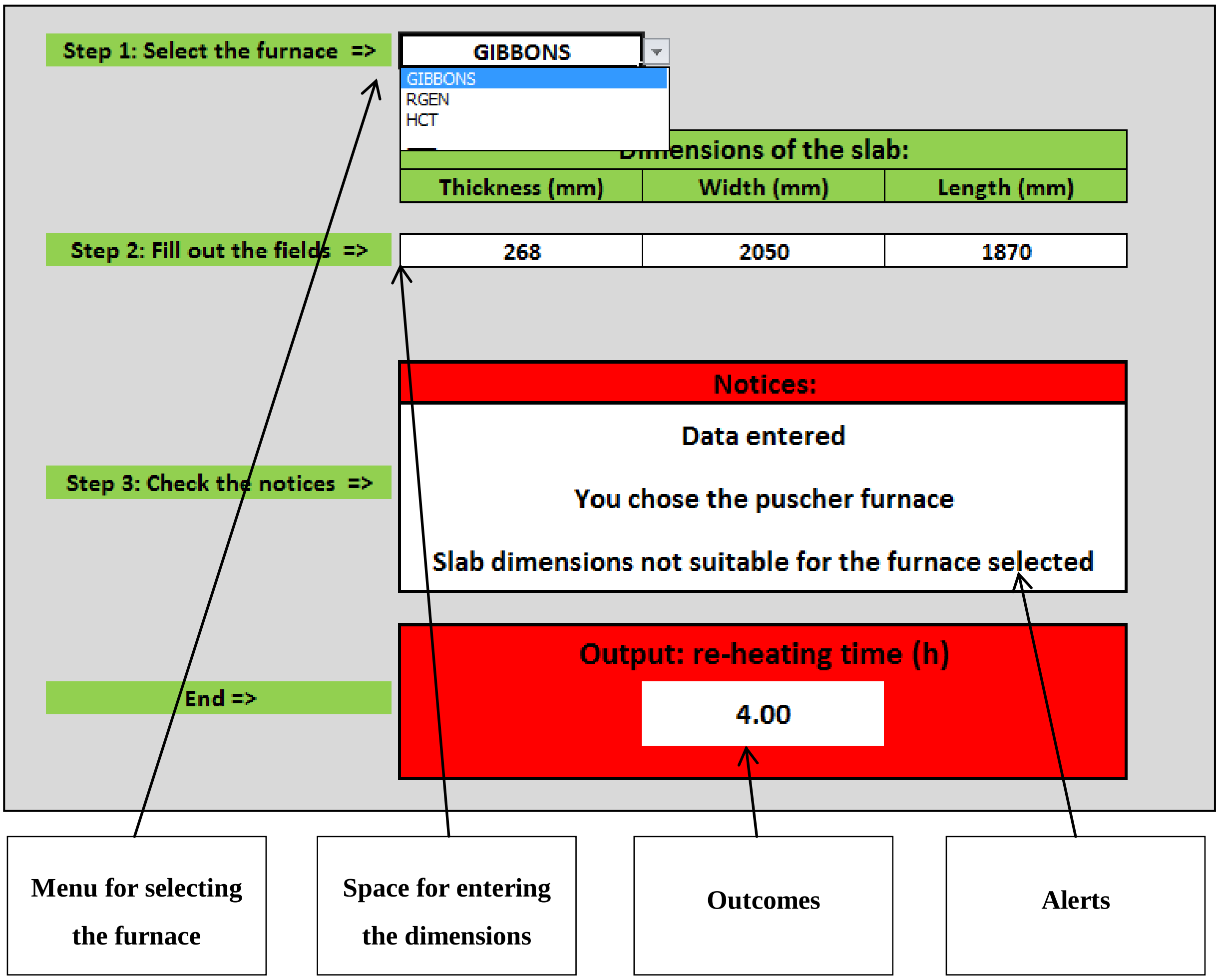


Fig. 33 *Thermal profile of a stack of three slabs heated in HCT furnace*
[from reference 16]

The program also supplies the reheating times for the pusher furnace, these times are the same currently used in the factory for this furnace.

Lastly to make the use of the program easier the system provides alerts in the event that the slab is too large to be heated in the Gibbons furnace or in the case in which the information provided is not sufficient to provide a response.



Step 1: Select the furnace => GIBBONS

Dimensions of the slab:

Thickness (mm)	Width (mm)	Length (mm)
268	2050	1870

Step 2: Fill out the fields =>

Step 3: Check the notices =>

Notices:

Data entered

You chose the puscher furnace

Slab dimensions not suitable for the furnace selected

End =>

Output: re-heating time (h)

4.00

Fig. 34 Screen of the excel program

In conclusion, for the batch furnaces a new standard procedure has been proposed. This consists of reducing the reheating times, using the times calculated by the empirical method and supplied by the program.

In addition, the order of slab weight and thickness in the stack has to be descending.

This kind of organization of the loading procedure was developed in order to ensure that the first slab of the stack drawn from the furnace is the slab that required less time to be in temperature.

Adopting this procedure, also, avoids the possibility that each work shift utilizes a different way to estimate the reheating time.

This is a fundamental aspect to ensure control on the process and uniformity in the products.

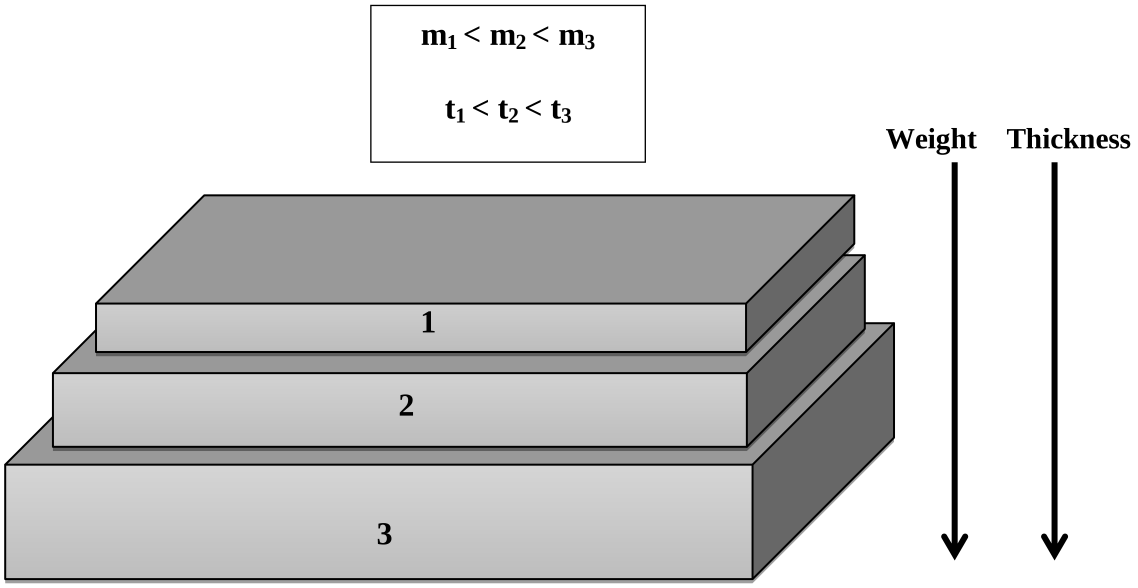


Fig. 35 *Schematic diagram of the loading procedure of the stack*

4 PROCEDURES EXTRAORDINARY

During the development of this study and during data capture time, the rolling mill stopped functioning twice for a period of over an hour, each time.

During this period, also, the Gibbons furnace stopped functioning.

Always with reference to the overheating problem, two procedures, to be applied, were drawn up.

4.1 Rolling mill stop

In the case of prolonged downtime, as for example the malfunctioning of the rolling mill, Spartan UK's past practice is to change the Gibbons temperature setting and not to change the batch furnaces temperature setting.

The changes in Gibbons were:

- Preheating zone from 1200°C to 1000°C
- Heating zone from 1260°C to 1000°C
- Homogenization zone from 1240°C to 1125°C

Only one sample was taken to analyse this situation and, as already sated, after around 20 hours at 1125°C the steel did not have evidence of overheating.

So, the procedure adopted for the Gibbons furnace, is suitable to avoid the overheating of steel.

On the other hand, the maintenance of the usual temperature setting in the batch furnaces leads to an opposite result. Just one sample coming from the batch furnaces was analysed and found to be overheated; so we can suppose that additional hours at 1240°C have made the slabs overheated.

Indeed, typical reheating times are already sufficient to make the slabs overheated.

In the light of this a new procedure for the batch furnaces, in order to avoid the problem.

The procedure if the mill stops for a period longer than two hours is to turn down the temperature from 1240°C to 1000°C in zone 1 and 2 and turn down the temperature from 1240°C to 1125°C in zone 3. If the mill stops for an hour but not more than 2 hours the procedure is to turn down the temperature from 1240°C to 1100°C in zone 1 and 2 and turn down the temperature from 1240°C to 1125°C in zone 3. Lastly, if the mill stops for less than 1 hour the ordinary procedure is to be maintained.

Using this procedure guarantees on the one hand the absence of overheating and on the other hand the possibility to restart the production process as soon as possible.

4.2 Gibbons off

In the case of the Gibbons malfunctioning, the furnace practice was to increase the temperature of the batch furnaces, bringing it from 1240°C to 1260°C.

In the light of this study it is easy to understand that this procedure results in overheating problems for the S355 steel and, furthermore, an increase of the temperature could cause the development of the problem in other steel grades too.

In this case, also the loading of slabs inside the furnaces logic was analysed.

The standard Spartan UK procedure, in this situation, is to fill up three stacks for each furnace, wait until the slabs are ready and after roll 12 slabs: (4 stacks) 6 slabs from RGEN and 6 slabs from HCT. Re-fill up the furnaces with 12 slabs, wait, and roll 6 slabs: 3 from RGEN and 3 from HCT.

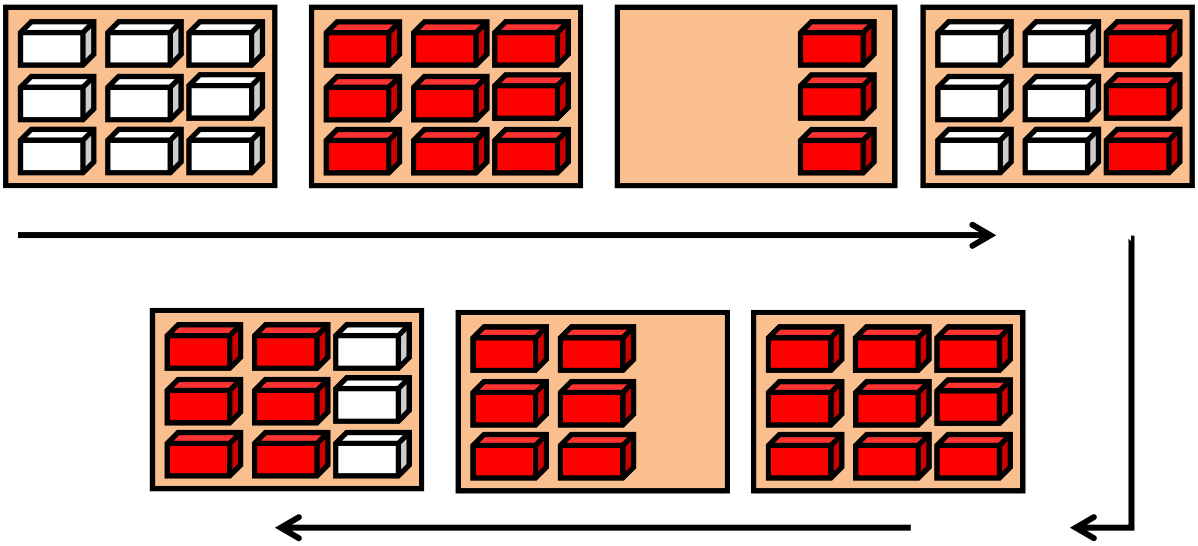


__Fig. 36__ Standard loading procedure

This procedure results in large temperature fluctuations inside the furnaces, with loss of control of slab temperature. Furthermore, it is necessary to wait a long time before the temperature in the furnaces reach equilibrium.

In the following figure, is shown the effects on the RGEN furnace, the same effects can be find in the HTC furnace.

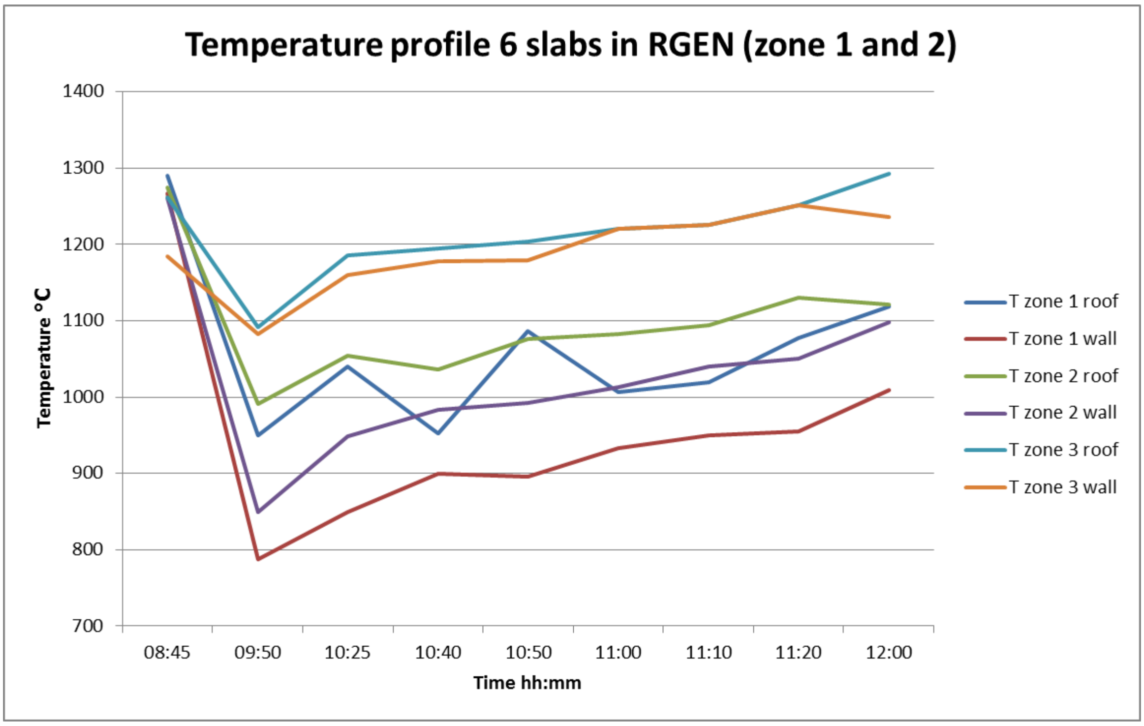


__Fig. 37__ Temperature profile of the RGEN furnace after the addition of six slabs (two stacks)

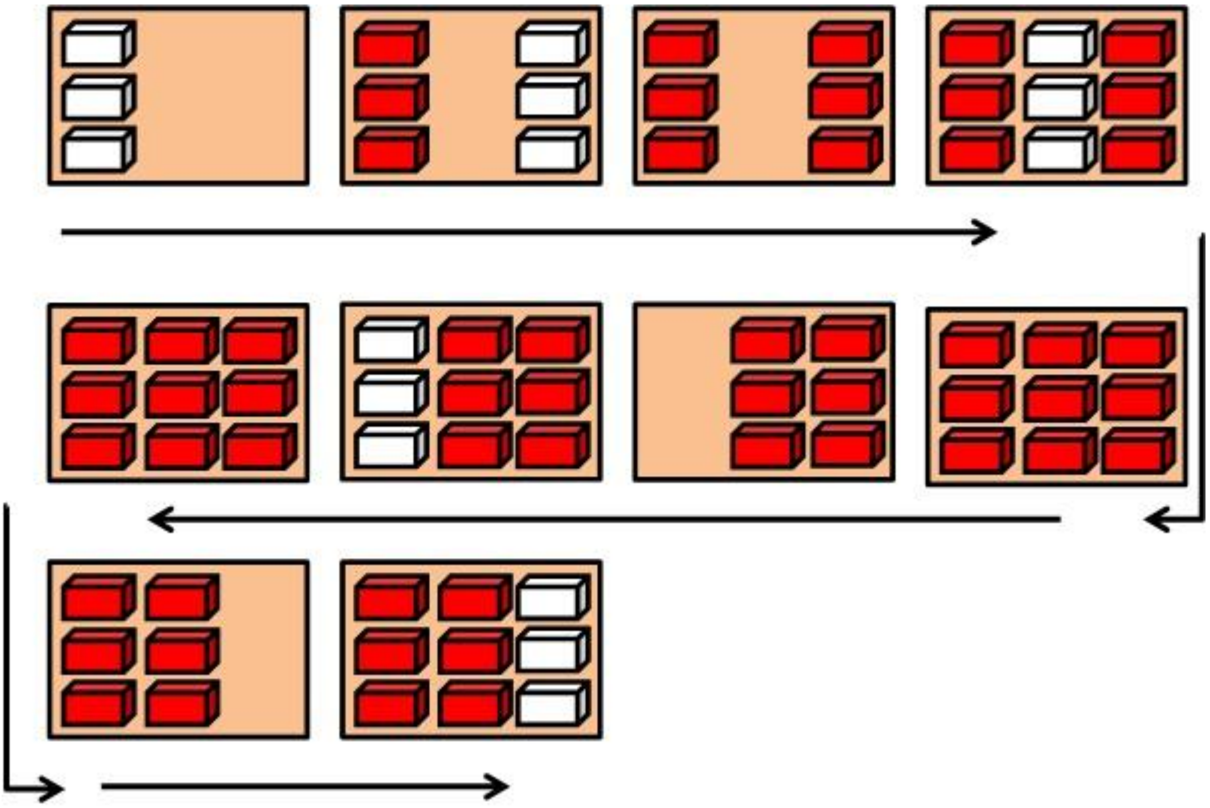


__Fig. 38__ Suggested loading procedure

The fluctuations are given by the introduction of a big volume of “cold” metal inside the furnace.

By hanging the loading and unloading procedure, as shown in the following picture, it is possible to minimize these fluctuations, and it is also possible to reduce the time required to reach the set point temperature.

Also by waiting for a short time between the insertions of two different stacks the fluctuations are notably reduced.

This unloading and loading procedure is the procedure that generally is used in Spartan UK for standard working conditions; therefore, when the Gibbons furnace is malfunctioning the suggestion is to continue to use the procedure generally used.

What has just been said is confirmed by the chart below:

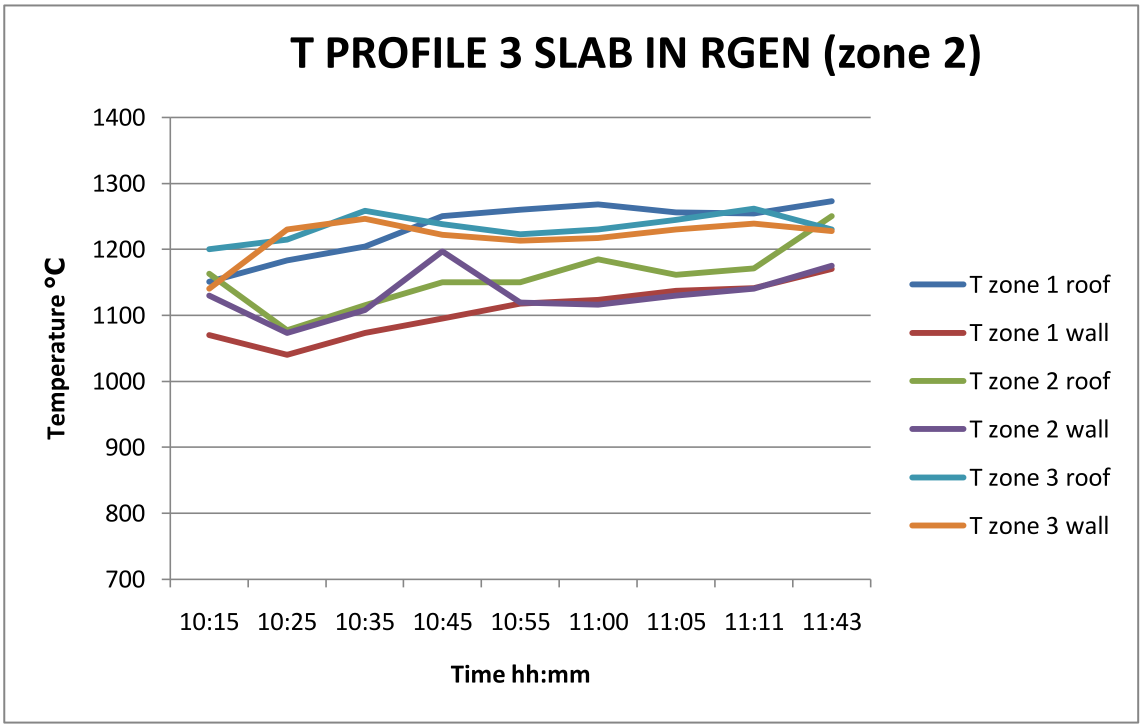


Fig 39 *Temperature profile of the RGEN furnace after the addition of three slabs (one stack)*

The differences between the insertions of three or six slabs is evident.

Six slabs cause a drop in temperature to 800°C and more than 2 hours are required to rebalance the temperature inside the furnace.

These facts indicate that this procedure results a loss of control of slab temperature.

On the other hand, three slabs cause a drop in temperature to only 1050°C and in 1 hour the furnace reaches again the set temperature.

In conclusion, the suggested procedure is to not change the temperature of the batch furnace, reducing the reheating time using the time calculated with the empirical method and change the loading-unloading procedure in order to maintain a strict control of the temperature inside the furnaces.

5 CONCLUSIVE TESTS

After analysing these results a new data collection was carried out, in order to understand if the suggested procedure can solve the overheating problem.

The new data collection has followed the same method described in the previous paragraphs, but as already stated the reheating time used are the times calculated by the empirical method.

The following table shows the samples tested, the connected parameters and the results of the data collection.

The new data collection concerns only S355 steel grade and only the batch furnaces; this is because, as already mentioned, the overheating problem concerns only S355 steel and mostly slabs coming from the batch furnaces.

All the samples analysed have not undergone normalization treatment, since as already seen in the results, such treatment solves the problem of overheating.

Furthermore this data collection affects only plates that have been cooling down in the same work shop.

In the table it is clearly visible that the suggested procedure has resulted in a reduction of the number of slabs overheated.

No.	Cast Number	Plate number	Grade	Thick.	Width	Length	Overheated	Slab Thick.	Slab W.	Slab L.	Weight	Furnace	Position	Duration	Deformation
					(mm)				(mm)		(kg)			(hh:mm)	
1	AH883410	319458	S355+N	40	2000	6000	YES low	268	2050	1000	4313	HCT	HD1	05:11	85%
2	AH883410	319459	S355+N	55	2000	4000	NO	268	2050	920	3968	HCT	HD2	05:40	80%
3	AH885901	319460	S355+N	25	2000	12000	YES low	268	2050	1230	5305	HCT	HD3	05:50	91%
4	EH880710	319571	S355+N	30	1800	18400	NO	223	1844	2700	8716	RGEN	RA1	07:11	87%
5	AH867501	320772	S355+AR	45	1350	8400	YES low	260	2047	1110	4637	HCT	HB1	08:30	89%
6	AH867501	320773	S355+N	40	2000	6000	NO	260	2047	1018	4253	HCT	HB2	08:36	85%
7	AH887803	320774	S355+N	25	2000	6000	NO	268	2047	1266	5452	HCT	HB3	08:46	91%
8	AH887607	320901	S355+N	60	2000	6000	NO	268	2050	1480	6383	HCT	HD2	06:42	78%
9	AH887606	320903	S355+N	40	2000	8000	YES low	268	2050	1310	5650	RGEN	RD1	07:00	85%
10	AH886805	320904	S355+N	60	2000	6000	NO	268	2042	1480	6358	RGEN	RD2	07:11	78%
11	AH887607	320905	S355+N	45	2000	8825	NO	268	2050	1620	6987	RGEN	RD3	07:24	84%
12	AH885706	321039	S355+N	50	2000	14150	NO	268	2050	2850	12291	HCT	HA1	07:46	82%
13	AH885707	321165	S355+N	35	2000	12000	YES low	267	2045	1750	7501	RGEN	RD2	07:27	87%
14	AH885707	321166	S355+N	35	2000	12000	YES low	267	2045	1750	7501	RGEN	RD3	07:38	87%
15	AH885204	321450	S355	30	2000	19825	NO	268	2049	2456	10587	HCT	HA3	06:20	89%
16	AH879910	321474	S355+N	40	1375	8400	YES	217	1245	1920	4072	HCT	HA1	05:07	80%
17	AF879910	321475	S355+N	40	1375	8400	YES low	217	1245	1920	4072	HCT	HA2	05:15	80%
18	AF879910	321476	S355+N	25	1200	19000	NO	217	1245	2416	5124	HCT	HA3	05:23	89%

Table 9 *Samples analyzed with new suggested procedure*

CONCLUSIONS

The first result of this data collection is that the reheating time calculated with the empirical method is enough to guarantee the workability of the slabs. Then, the reduced reheating time enables a uniform temperature profile along the slab thickness. The reached temperature makes it possible to complete the rolling process without a significant cooling of the plate during the rolling operations and without a significant increase of the force applying by the working rolls.

The second result is that is easy to see that comparing these outcomes with the outcomes coming from the first data collection there is a substantial reduction of overheated slabs.

The number of slabs overheated is less than 50% against the 92% that was previously found. Furthermore the samples overheated show a small amount of lath structures, considerably less than the amount of overheating previously found; this is easy to see in the following pictures.

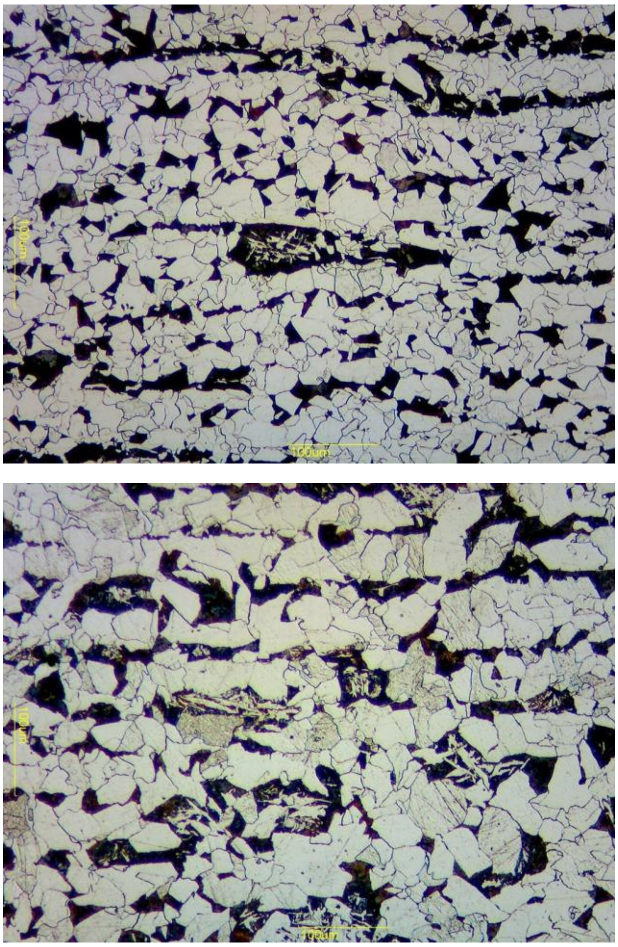


Fig. 40 *On top slab reheated with the suggested procedure, on the bottom slab reheated with the standard procedure*

The two samples compared in the picture come from two S355 slabs with similar size, heated in the same furnace and in the same position of the furnace; both of these samples have not undergone secondary heat treatments and each have undergone an amount of deformation around 80%.

The lowest number of samples overheated is due to the reduction of the soaking times, this in line with studies concerning the phenomenon. A lower soaking time prevents the growing of the austenite grains, because the overheating problem is controlled by time and temperature.

Small reductions of the soaking time, on the order of 30 min at 1200°C, have a notable influence on the growth rate; considering that the suggested procedure reduces the average of the reheating time from 8 h and 40 min to 6 h 40 min (as show in the graph below) the reduction of the overheating phenomena is easy understandable.

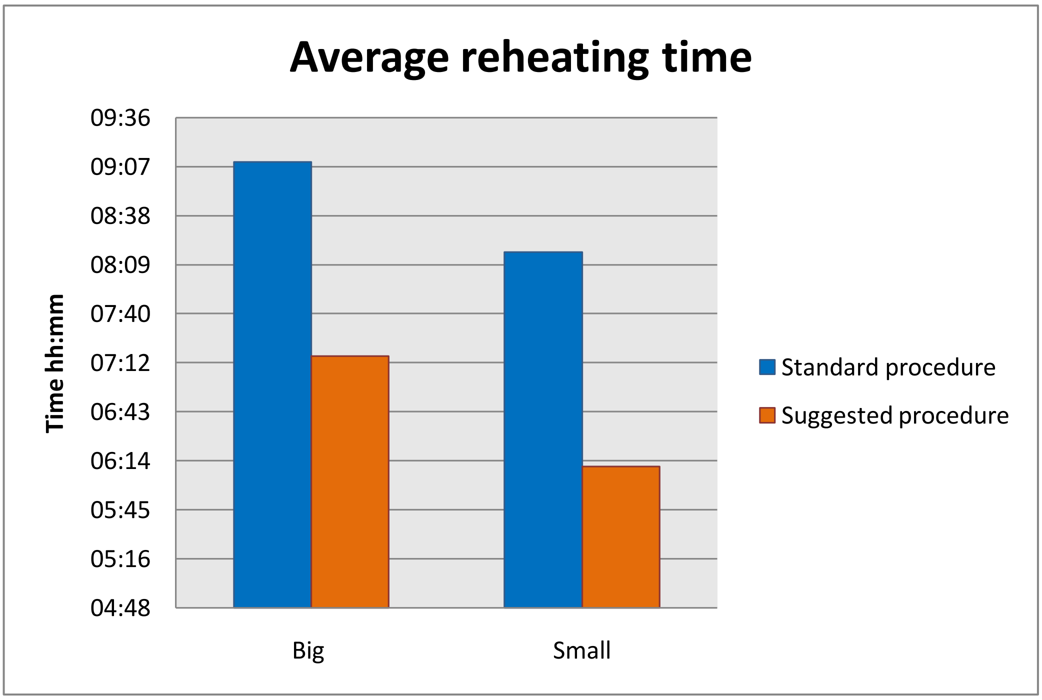


Fig. 41 *Average of reheating time with standard and suggested procedure*

From the microstructure picture it is clear that the shorter reheating time not only reduces the amount of overheating but also has an effect on the grain size, indeed the grain size of the sample on the top is smaller than the grain size of the samples on the bottom.

A fine grain structure means highest mechanical proprieties.

Regarding the position of slabs inside the furnace it was identified as practical problem; the suggested procedure states that the order of slab weight and thickness in the stack has to be descending.

Regrettably, is not always possible to organize the slab stacks as suggested, due to customer requirements and mixed slabs.
Therefore, the suggested procedure is only used when possible; in other cases the position of the slabs follow the standard Spartan UK procedure.

An overheated plate is a plate with low mechanical properties; when a plate does not meet the standard it is sold as scrap with the consequent loss of money and with the need to plan a new production cycle in order to complete the demands of customer. This means loss of material, more gas consumption for the furnaces and higher staff costs.
It is easy to understand that the reduction of the number of overheated plates result in cost savings for Spartan UK.

The results of this work can be a starting point for new research in the context of overheating of Spartan UK steel.
The next step, should be to investigated the effect of a reduction of the furnaces temperature on the overheating problem and its influence on the machinability of the steel. Many of the studies reviewed indicate that heating temperature suitable to avoid the phenomenon of overheating is 1000 - 1100°C, about 100 - 150°C lower than the Spartan UK standard temperature.
Another aspect to be studied in more detail is the relationship between overheating and position inside the furnace.
This aspect should be analysed by the use of thermocouples inserted into the slabs; a more in-depth study of the heating rate and of the heating time as a function of slab position in the furnace could be the starting point for the drafting of a procedure able to solve the problem of overheating entirely and able to increase the products quality and cost savings in Spartan UK.

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