Challenges, innovation and designs in galvanising technologies for AHSS

Steel grades requiring galvanising have changed dramatically in the last 20 years, going from simple carbon grades for construction to ultra-high tensile strength dual phase grades and extra soft and deep drawing qualities for automotive applications. These new steels have required key modifications and improvements in galvanising lines. For instance, furnaces must accommodate new heat cycles, some with annealing temperatures over 900°C, fast cooling to various temperatures is sometimes followed by ageing sections in the line, and surface oxidation must be controlled to achieve good zinc wettability. Plant operating constraints, design changes, areas of investigation and thoughts about even newer steels are discussed.

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Driven by the wish for sustainable development and minimising greenhouse gases, the automotive industry has pushed for increased use of thinner, higher strength, yet ductile steels to reduce the weight of the body-in-white and improve crash resistance. The development and increased use of advanced high strength steels (AHSS) has required the development and implementation of new technologies for galvanising lines in two main areas:

- Strip heat cycles with higher temperatures and faster cooling rates
- Surface control to ensure a good zinc wettability.

Additionally, some process steps had to be improved and upgraded with more powerful devices such as shears, bridle power, skin pass mills and recoilers.

HEAT CYCLES AND TECHNOLOGY DEVELOPMENT

For traditional carbon grades (CQ), simple heat cycles consisted of heating up to 720°C, minimal soaking and then forced cooling down to the zinc pot temperature. For AHSS grades, however, the cycles are much more complex and varied, as illustrated below:

- Peak strip temperatures have dramatically increased up to 920°C to ensure full austenitisation as required by fully martensitic grades
- After an initial slow cool, fast cooling sometimes reaches around 100°C/sec using gas cooling or 500°C/sec using a non-oxidising liquid hydrocarbons to reach temperatures between 450 and 250°C (both for 1mm strip)
- A reheating process under a H_2 atmosphere before the Zn pot may be required
- Overaging for up to 120sec may be required for bainitic transformations

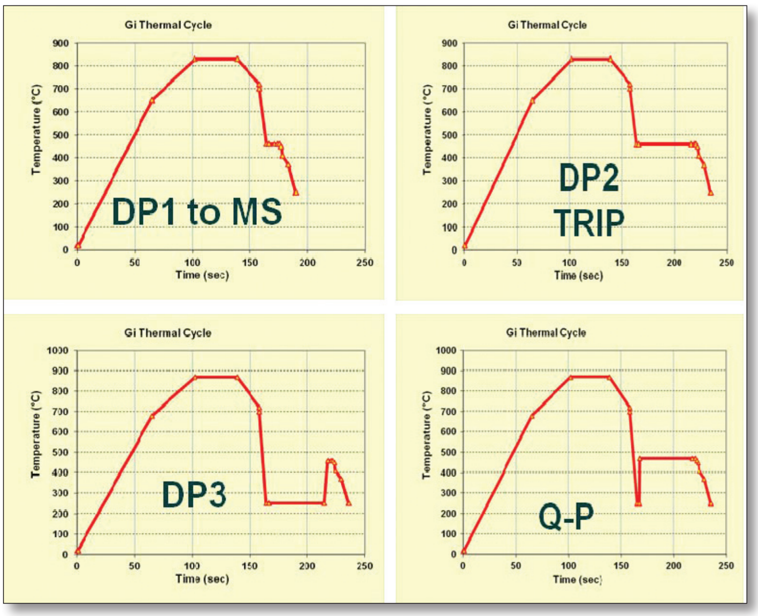

Fig 1 **Heat cycles one for dual phase (DP3), martensitic (DP1 to MS), twinning induced plasticity (DP2 TRIP) and quench & partitioning (Q-P) steels**

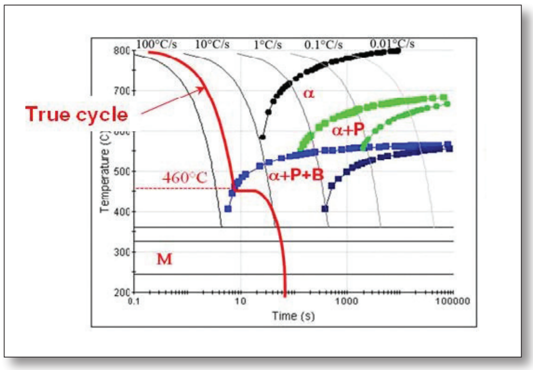

Fig 2 **CGL cooling curve through a CCT diagram, austenitisation 800°C**

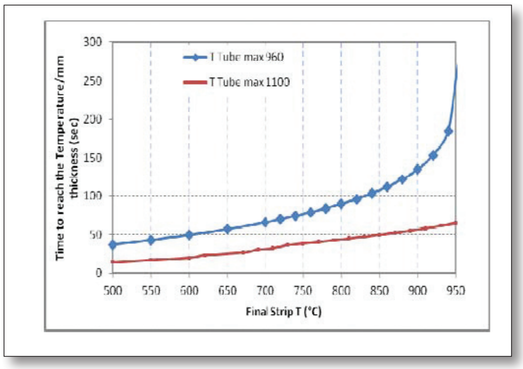

Fig 3 **Time to reach annealing temperature for 1mm thickness with two tube temperatures**

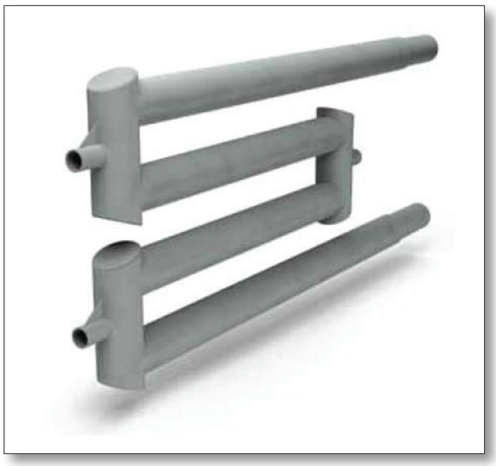

Fig 4 **Example of double P radiant tubes with high Ni-Cr alloy for 1,100°C**

- A rapid cool after coating may be added to limit either the time before martensite transformation and/or ageing.

Figure 1 shows four typical heat cycles that are used today. Because of the different cycles, a single furnace is not capable of producing all of them without significant changes in the strip pass line, an operation that requires a long stoppage time, and is unlikely to be acceptable.

The galvanising heat cycle is, unfortunately, far from ideal as regards quenchability. After fast cooling, there is an unavoidable soaking time of 10-20sec at ~450°C, depending on line speed. This is the location of the bainitic nose in CCT diagrams and the soaking time corresponds to the strip length through the hot bridle, snout, Zn pot, strip wiping and cooling areas down to about 400°C in the tower. This means that the use of the classical CCT diagram is not valid and it is important that metallurgical designers allow for this fact in their steel composition/process design calculations. For example, *Figure 2* shows the cooling profile computed by dedicated software for a dual phase (DP) grade superimposed on the CCT diagram.

TECHNOLOGIES FOR HEATING

To reach the full austenitisation temperature, classical radiant tube technology has reached its limits, as the classical refractory metal heating elements such as Inconel 601 and refractory stainless steels are limited to about 950-980°C. *Figure 3* indicates the time required to reach a defined peak temperature for two different zone temperatures. It is evident that when the target is 920°C the use of classical radiant tubes significantly reduces line productivity, as the line speed has to be reduced compared to the use of modern high Cr alloys used up to 1,100°C.

Some technological innovations have been developed to circumvent this problem, for instance, double P radiant tubes (*see Figure 4*) enable higher average operating temperatures, thanks to the high internal circulation rate of the gases.

For horizontal furnaces that are less sensitive to strip breakages, ceramic tubes (typically made of SiC; *see Figure 5*) are proposed and can operate at 1,100°C and above, but they are only available as straight tubes. Finally, the technology used in stainless bright annealing plants (Cr-Mo resistance elements operating at 1,200°C) can also be used (*see Figure 6*), however this can increase problems of strip breakage and short circuits, electrical insulation and furnace lining materials. An option could be to have a dedicated section for their implementation, located after a classical radiant tube heating.

Instead of radiative heating, induction with transverse flux technology can be used to overcome the reduction in steel permeability above 700°C – the Curie point. Various patents and technical solutions including dedicated software are proposed by suppliers to avoid the differential heating between edges and centre.

TECHNOLOGIES FOR COOLING

Some steel grades require rapid cooling through quenching to achieve the desired properties. However, for hot-dip coating lines, in order to maintain good wettability and coating adhesion, the steel surface should not be significantly oxidised. Water cooling, the most rapid method is, therefore, not applicable, and this impacts on the maximum tensile strength that can be obtained with a defined steel composition.

Technological development has been focused on the optimisation of classical gas cooling, working on the nozzle shape, gas flow, H_2 content and nozzle to strip distance. Cooling rates of 100-140°C/sec between 700 and 450°C for 1mm strip thickness are possible with high H_2 content cooling gas.

High cooling rates using gas do have consequences, however. The electrical consumption of the blower is very large with required motor power reaching 1MW. This is due to the fact that the electrical power required varies with the 4th power of the heat transfer coefficient, so doubling the cooling rate requires 16 times more power. Another issue is the possible H_2 pickup by steel that may induce hydrogen embrittlement after forming. If the risk of H_2 pickup is high, then residence time in the cooling section should be minimised. Also furnace partitioning is recommended to keep H_2 content after cooling to a minimum.

In order to address the above, an innovative solution using a non-oxidising liquid hydrocarbon called 'Ultra Dry Cooling' has been developed by CMI. Cooling rates of ~400°C/sec on 1mm strip can be reached as well as final temperatures as low as 250-280°C, such values being required for some stop-quench processes.

Some plants use a reheating inductor situated before the pot to enable the strip to reach the pot temperature after a low overaging (typically 250-400°C) treatment. Classical longitudinal induction furnaces are being used but the technological improvement has been limited to the use of HNX atmospheres. Gas tightness and thermal expansion in operation are critical.

Finally, a cooler operating on the liquid coating with variable blowing rates can be added after the pot, and before the classical APC cooling tower, to minimise the time before Ms temperature (or ageing if martensite is formed before the pot) while avoiding damage of the liquid layer which is very sensitive to gas impingement (*see Figure 8*).

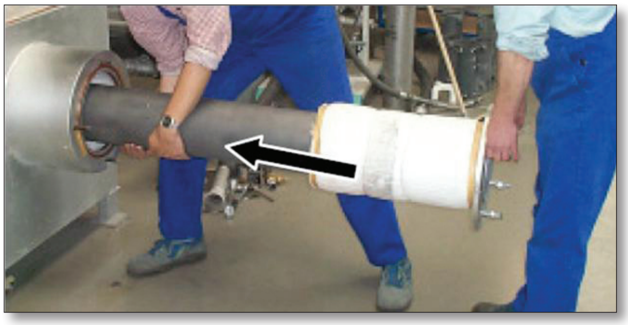

Fig 5 **Silicon carbide tube introduced in a furnace**

Fig 6 **Cr-Mo resistance heating elements**

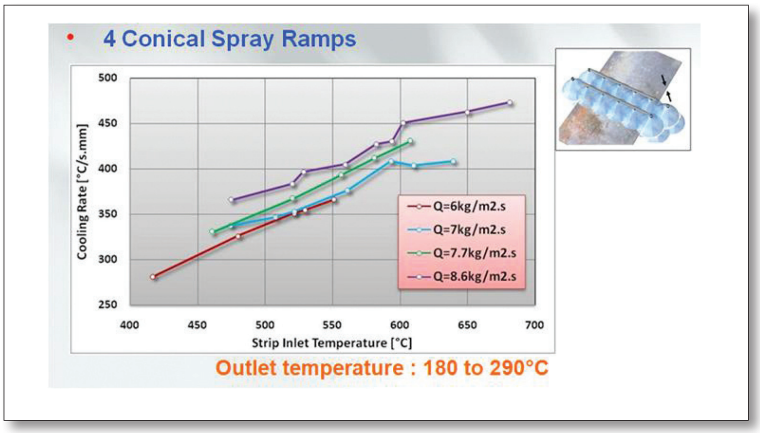

Fig 7 **Performance obtained with CMI's Ultra Dry cooling**

HEAT CYCLE CHALLENGES

The need for consistency and reproducibility of mechanical properties is paramount in an industrial plant. The example of steel grades requiring an accurate stop quench process such as quench and partitioning (Q&P) is especially of concern, given that steel composition and upstream processing may vary slightly between batches, and that Ac1 and Ac3 temperatures depend on heating rate and composition. Intelligent metallurgical models are expected to help define the set points and targets for each production batch.

Additionally, there is a need to control the temperature uniformity along and across the strip at +/-5°C, not an easy task considering the variations in steel surface emissivity that are known to be affected by surface cleanliness and oxidation. Systems including measurement and actuators to control the transverse uniformity are quite rare and/or difficult to operate industrially.

A key question is: "What will be the most economic way to produce the grades that require very different heat cycles?" Dedicated lines, multiple pass line selection with or without twisting towers are some options. The examples of DP and Q&P grades emphasise the point: one requires overaging, the other not. The situation is much more critical in continuous galvanising lines than in continuous annealing lines due to the constraint on the entry strip temperature: 450°C, for example, leads to fast ageing of martensite. Other areas of concern are the possible need for better flatness control at the wiping nozzle for those grades that have the phase transformation before the pot, and the question of crossbow correction with the existing pot roll design.

The use of Zn-Al+Mg bath composition offers the chance to reduce the pot temperature by typically 40°C. This may provide some benefits since the soaking temperature before the pot will be significantly below the bainitic nose.

MANAGING SURFACE WETTABILITY

It is well known that during annealing in industrial furnace atmospheres, Cr, Si and Mn will oxidise, leading to a surface oxide layer that inhibits reactive wetting between Fe and Zn. Three key ways have been proposed to circumvent this:

- Precoating of steel before annealing: Ni or Cu plating was proposed some years ago but is not yet used industrially due to the cost and the fact that those elements can diffuse into the steel, impacting the Fe-Zn reaction. The question of optimum deposit thickness is also still to be clarified.
- Internal oxidation during annealing: as the dew point increases, the oxide-forming potential for the alloying elements that can be oxidised underneath the surface also rises, particularly for B, Al, Mn and Si. The Wagner ▷

Fig 8 **Example of pre-cooler for galvanising**

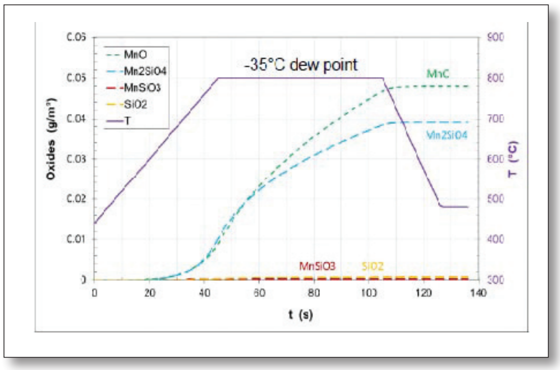

Fig 9a **Prediction by AESOP with 0°C Dew point**

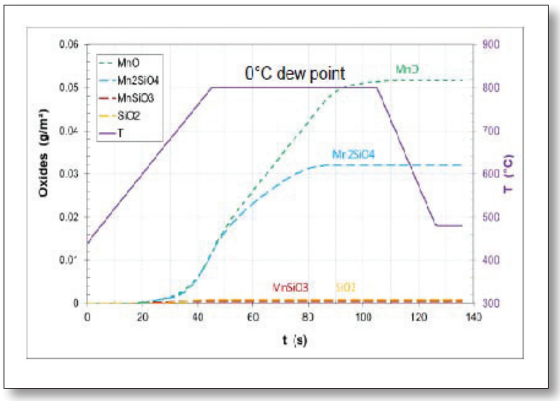

Fig 9b **Prediction by AESOP with -35°C Dew point**

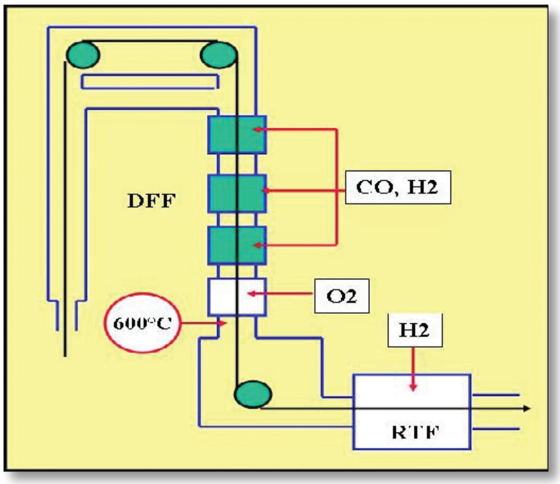

Fig 10 **Strip oxidation principle**

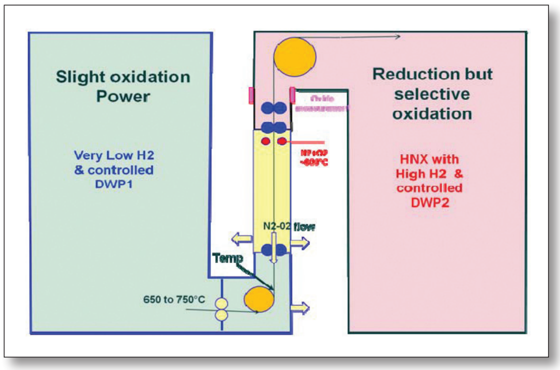

Fig 11 **Oxidation control in radiant tube furnace patented by CMI**

theory explains the phenomena. It has limitations, however, because it is based on the competition of the oxidant diffusion to the strip core and the alloying elements towards the surface. Si, for example, when present at a concentration higher than about 75% that of Mn, cannot be oxidised internally and will make a covering SiO_2 layer.

Figure 9 shows the predictions obtained by AESOP, a computer model, for two different dew points for a CP1180 grade. CO is being generated from carbon in the furnace and a significant amount of water is consumed. The surface becomes carbon-depleted so it is less easily transformed into austenite during annealing below 910°C, and also loses its hardenability. Furthermore, a high CO content in the furnace can lead to carbon deposits and to safety issues close to the entry seal areas due to the toxicity of that gas. The question of possible carburisation of the radiant tubes with its potential detrimental effect is under debate.

- Full Fe oxidation: this method is well known and was the way followed by the old Sendzimir process. However, due to the increase in concentration of the alloying elements, the Fe oxide thickness must reach 50-200nm before entering a fully reducing atmosphere. This requires full oxidation between 650 and 750°C. The next step of the process reduces that oxide with H_2 while avoiding the migration of the alloying elements to the surface during the residence time at high temperature.

TECHNOLOGIES FOR CONTROL OF SURFACE WETTABILITY

CMI has developed two main technologies: one dedicated to direct fired furnaces (DFF) in which a slight air excess in the last zones oxidises the strip surface. *Figure 10* shows the principle. It requires good control of the gas quality to ensure the right air excess and efficient operation. A concept upgrade, also dedicated to DFFs, consists of the implementation of an additional zone dedicated to accurately control the oxidation all across the strip width. The DFF is then always running in its classical gas excess mode, oxidation being controlled only at the end in a dedicated section.

Alternatives are available for full radiant tube furnaces that are known to be more energy efficient and less sensitive to the gas calorific value. Two main proposals exist: one consists of a full oxidation zone inside a full radiant tube furnace operating with a full reducing atmosphere; the second, developed and patented by CMI, offers a three-section furnace, the first is close to neutral for Fe, the second generates the oxide with dedicated control for each side, the third changes the reduction of the Fe oxide while keeping some oxidant potential for the alloying elements (*see Figure 11 from left to right*).

CHALLENGES ON SURFACE WETTABILITY

Numerous laboratories have investigated the question of wettability, and the need for high dew point and/or full surface oxidation is recognised. However, customers require good coating adhesion and it is known that good wetting and poor adhesion are not always linked. In addition, oxidation at grain boundaries is not recommended since it may initiate cracks during deformation. Some laboratories have also investigated the possibility of operating at very low dew point with a H_2O/H_2 ratio so low that the oxidation of Mn, Si, etc. does not occur. If this were possible, it means that SiO_2-based furnace linings need to be replaced by Al_2O_3, thanks to its higher resistance to reducing agents. Unfortunately, operating at -100°C dew point seems not possible industrially since experiments have shown that there is no efficient means to reduce the dew point to that value.

Alternatively, running with high H_2, as in stainless steel practice, is not a solution due to the problem of H_2 pickup during annealing and the impermeability of a Zn layer to the H_2 diffusion.

Another issue is grade transition in industrial schedules. It is known, for example, that the oxide thickness increases much faster on CQ grades than on AHSS, therefore, the furnace atmosphere requires adjustment at grade changes. This may impact line scheduling, as with annealing cycles. The question of Zn reactivity in terms of its dissolution, dross formation and the galvannealing reaction with reduced Fe oxide in a 'fresh and pure' state is presently not clear. Finally, there is the potential for oxides to stick on furnace rolls, resulting in dents on the strip. It is known that high Mn grades require specific roll coatings, but extensive experience is lacking.

NEW COATINGS AND ZN POT AREA

The last decade has seen the appearance of numerous Al-Zn+Mg coatings dedicated to construction and automotive products, the later usually containing less Mg. There has also been a rebirth of aluminising in connection with the hot stamping process to make high strength safety components (up to 2,000MPa). The question of the benefits of AlZnMg coatings for AHSS is, however, still open in relation to the expected lower pot temperature that may impact the heat cycle. Technology development has been in two main areas:

- Specific wiping devices to minimise the oxidation of high Al-Mg content. The Arcelor patent WO 2010130895 describes the device and is industrially implemented.

Fig 12 **316L sink roll after 6 runs of 4 days in AlSi**

Fig 13 **Spring effect on recoiler leading to poor grip**

- Due to the aggressiveness of liquid AlSi, pot rollers are particularly vulnerable, as illustrated in *Figure 12*. Various solutions are proposed by different suppliers. Some have proposed specific ceramic bearings and/or coatings for pot rolls. Replacing the classical 316L materials with high carbon cast steels can provide longer roll life, however, even with those innovations, the pot roll life time is only three to four days. One solution might be a full ceramic sink roll but experience including cost efficiency is limited.

It is worth noting that it has not been necessary to innovate in induction heating technology for galvannealing AHSS even though its magnetic permeability is lower than ferrite, since the longitudinal flux technology can operate with up to 50-60% of austenite at the pot. A special design of the induction heater is, however, necessary to heat high austenite steel strip and for steels with higher amounts of non-magnetic phase, the question may need to be addressed also, despite a mature technology.

If not, there may be concerns at the pot equipment in relation to crossbow correction. It is known that the corrector roll penetration increases with strip thickness and hardness and the corrector roll shaft design may need to be reconsidered due to the higher level of stress that it will encounter especially at high tower tensions with thick and wide sheet.

STRIP CONVEYING FOR AHSS

The robustness of the strip conveying process is a key issue of any continuous lines. Handling high strength steels does not require specific technologies excepting the entry welder – either a laser type or conventional one but with post annealing. However, some improvements may be required to be able to manage the higher material strength. For instance:

- Shears and side trimmer including compactors and scrap chopper must be powerful enough
- Bridles must be verified due to loss of wrapping angle
- Skin pass rolling force and tension must be increased: a load of 1,200-1,500t is recommended, including 450mm work roll diameter
- Tension leveller requires tensions that are usually much higher than the initial design. Considering a minimum specific tension of 20% of the yield strength (YS), a DP1000 grade will require a value close to 40t for a 1,500mm wide, 2mm thick strip for only 0.2% elongation. This implies a significant increase in cassette stiffness as well as the number of rolls in the entry and exit bridles. For instance a 1,000MPa grade would require 5 or 6 rolls compared to 3 or 4 for a 300MPa grade.
- Recoiler with belt wrapper must be designed to ensure that the very stiffness strip will wrap properly and grip the mandrel.

Figure 13 shows the case of a stiff sheet that does not wrap due to spring back.

WHAT IS NEXT?

The market has always been driven by overall cost reduction, environmental issues and product use by the final customer. Three product areas at laboratory development stage are:

- Austenitic-martensite microstructures, the target being improved formability without reduction of strength
- Medium Mn steels with up to 6-8% Mn, and possibly with other additions
- Fully bainitic structures known for their excellent elongation-stress performance

CONCLUSIONS

Steel grades requiring galvanising have dramatically changed in the last 20 years, going from simple carbon grades for construction to ultra-high tensile strength (1,100-1,220MPa) strength complex DP grades. As a result innovations and improvements were required on the process. Some are related to the heat cycle which requires a certain level of austenitisation, followed by a quenching and eventual ageing to let the microstructure develop. Others are related to the control of the strip surface to have a good zinc wettability and coating adhesion.

Challenges however still exist, especially related to mass production. Product consistency and reproducibility are essential for success and profitability. Campaign management including transitions and line schedule are also key issues

The future will probably be just as challenging as it has been in the past, and developments will always find their roots in total cost reduction. The position of AHSS must also be included in the Industry 4.0 concept which consists in intelligent factories with computer models to control processes, maintenance and quality, allowing steel manufacturers to respond quickly to a changing demand and/or environment.

However, innovation and solutions will be in from people, thanks to their passion in technology, creativity, knowledge and experience. MS

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