THERMOMECHANICAL PROCESSING OF ADVANCED HIGH STRENGTH STEELS IN PRODUCTION HOT STRIP ROLLING

E.I. Poliak, N.S. Pottore, R.M. Skolly, W.P. Umlauf and J.C. Brannbacka

Hot strip rolling of low carbon Advanced High Strength Sheet Steels (AHSS) is challenging due to non-traditional chemical compositions required to attain the unique mechanical properties in AHSS products. In hot strip rolling, TMP implies various types of controlled rolling where temperature, strain rate and rolling reductions are carefully selected to produce the target austenite microstructure, which is either fully recrystallized or fully pancaked austenite before starting cooling. Microalloying of HSLA in combination with suitable TMP provides an efficient tool to control austenite recrystallization prior to the beginning of cooling. However, the existing TMP routes cannot be easily applied to AHSS that have much more sophisticated alloying and lower level of microalloying. TMP of AHSS in the finishing train of hot strip mill should be designed so as to ensure controlled type and extent of transformation on run-out table by precise control of strip temperature and rolling speed with account for mill configuration and capabilities, product dimensions, gauge and shape tolerances. Further complications can be brought about by high sensitivity of AHSS to various aspects of hot strip rolling and cooling parameters. These aspects are discussed in the paper along with various practical implications.

KEYWORDS: advanced high strength steels, hot strip rolling, austenite, recrystallization, transformation

INTRODUCTION

The term advanced high strength steels (AHSS) is generally employed for dual- and multiphase steels, the final microstructure of which is usually a composite of relatively soft ferrite matrix with strengthening phases (martensite, bainite, precipitates) [1, 2]. The production of AHSS has been rapidly expanding in recent years due to their attractiveness for carmakers as these steels allow for considerable reduction in weight and enhancement of automobile's safety. The demand for AHSS continues to grow due to the unique combination of high strength, high toughness and excellent formability. At the same time, the quality requirements for AHSS products are extremely strict and will continue to toughen. Under these circumstances, the contribution of each manufacturing stage to the overall product quality needs to be re-evaluated and new production practices have to be adopted.
One of the feasible tools to enhance the properties and to improve the quality of steel products is the thermomechanical processing (TMP). TMP is the sophisticated combination of well defined deformation operations and well defined heat treatment [3] in a single production stage to control the microstructure of the material. When such combination is realized, the product must satisfy the customer requirements, that is, it must have desired exterior qualities (dimensions, shape and surface quality) and acceptable mechanical properties. From this point of view, TMP is generally considered as the final manufacturing stage [2].
On the other hand, TMP is commonly associated with hot working operations, which for strip manufacturing of low carbon steel grades implies various types of controlled strip rolling in a hot strip mill finishing train with temperature, rolling speed, rolling reductions and run-out cooling pattern being carefully selected to produce the desired mechanical properties of the hot band. Traditionally, the considerations for such TMP have been focusing on metallurgical aspects of producing the microstructure that will provide the desired mechanical properties after hot rolling. The aspects of exterior quality such as shape and flatness, gauge consistency, surface quality, etc., have received much less attention although they are closely related to product metallurgy and processing practices.
The present paper concerns AHSS for cold rolled applications. For such products, hot strip rolling is not the final but rather an intermediate manufacturing stage. However, due to the specific nature of AHSS, it is not a rare occurrence that various effects of hot rolling only manifest themselves in downstream operations and are not readily evident during hot mill proces-

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sing. The objective of the paper is therefore to emphasize the important role of hot strip mill processing of AHSS in delivering their end qualities, along with the necessity to apply the principles of TMP to hot strip rolling of advance high strength steels even if the latter are to be further processed downstream.

THERMOMECHANICAL PROCESSING IN HOT STRIP ROLLING

TMP in the form of controlled rolling was developed to produce hot rolled low carbon HSLA and microalloyed grades with a refined microstructure that allows for simultaneous increase in strength and toughness. This is achieved by implementation of two alternative strategies of hot rolling of austenite in the finishing mill. In the first strategy, the austenite grains are refined through repeated cycles of recrystallization that creates large grain boundary area thus increasing the number of potential nucleation sites for subsequent phase transformation [4]. Steel is rolled at relatively high temperatures with the necessary prerequisite to prevent grain coarsening between the rolling passes and, more importantly, between the finishing mill exit and the cooling section of the run-out table.
The rolling speed is adjusted to attain the aim finishing temperature with account for the final strip thickness and width.
In contrast, the second strategy implies hot rolling of austenite so as to avoid any recrystallization during and between the rolling passes and after the finishing mill exit. This way, a heavily pancaked austenite is produced and the refinement of microstructure is achieved due to significant enhancement of transformation by nucleation at deformation bands, shear bands, etc. [4]. In this case, the rolling schedules are selected in a way that the incubation period for recrystallization is extended beyond the time intervals available in the given mill for the onset of recrystallization. This strategy is commonly applied to steels containing substantial amounts of Nb as a microalloying addition that hinders recrystallization under hot strip rolling conditions. The strip is rolled at relatively low temperatures to further suppress the recrystallization of austenite. Thus, recrystallization behavior of austenite during and after hot deformation is the key factor determining the hot rolling strategy and the final properties of HSLA hot rolled products.
Most of the hot strip mills are presently capable of producing HSLA and microalloyed grades, i.e., the mill has sufficient power to implement both of the hot rolling strategies and can realize basic run-out table cooling patterns to achieve the refinement of microstructure. The mill control models operate as to attain the strip centerline aim finishing and coiling temperatures with reasonable accuracy along the major portion of the length of a coil. By achieving the two aim temperatures it is believed that the required microstructure of austenite and of the products of its transformation, along with the mechanical properties of the hot rolled bands are attained as well.
The need for such TMP (controlled rolling) of AHSS is not yet well realized especially for the products that are further processed after hot rolling. Because of that, the development of hot strip rolling schedules for these grades usually starts with defining the hot band microstructure suitable to attain the final properties of the product after cold rolling and annealing/galvanizing. Then, based on steel chemistry, which is again dictated by the final properties, the aim coiling temperature is determined. The aim hot rolling finishing temperature is then defined based on the length of the run-out table, its cooling capacity, final hot band dimensions (width and thickness) and on the rolling force capability of the particular finishing mill. Several restrictions are taken into account.
First, it is preferable not to have a big difference between finishing and coiling temperatures for the intense cooling of hardenable steels like AHSS can cause significant strip shape distortions on the run-out table. Another restriction, which in combination with roll force capability can give the lower bound for finishing temperature, is the rolling stability requirement as the propensity for the hot mill to encounter various rolling instabilities increases with decreasing finishing temperature.
The rolling speed and acceleration (in zooming mills) are then determined based again on the rolling stability, on the ability to maintain the aim finishing temperature, on the crop shear capacity that often limits the transfer bar thickness especially for hard grades, as well as on slab length restrictions to prevent large temperature differences between head and tail ends.
Obviously, in such hot rolling design for AHSS, the microstructure of austenite is not of primary concern.
It is still not quite clear whether the controlled rolling (TMP) can be beneficial for AHSS processing. In part this stems from the lack of knowledge of high temperature deformation behavior of austenite in AHSS and its effect on the end properties.
Chemical compositions of AHSS differ significantly from those of conventional HSLA and microalloyed steels and often lie outside the chemistry ranges, for which solid experimental data and extensive production experience in controlled rolling have been accumulated. First to mention is that the total alloying content in AHSS can amount up to 5 %, so that these steels can no longer be regarded as low alloy steels. Richer alloying leads to higher hot deformation resistance and hence lead to hot strip mill rolling forces that are higher than those required for HSLA grades [5].
Moreover, for many applications the hot strip mills are required to produce AHSS in gauges lighter than those of HSLA and microalloyed products, which calls for necessity to apply even higher roll forces and hence requires higher hot strip mill capabilities.
Many AHSS are simultaneously alloyed with significant amounts of strong ferrite stabilizers (e.g., Si, Al) and strong austenite stabilizers (e.g., Mn), often in combination with microalloying (Nb, Ti) and other transformation retarding elements (B, Mo, Cr) [4]. Such complicated alloying required for achieving the target properties after final processing, strongly influences the deformation and recrystallization behavior of austenite during its hot strip rolling and subsequent transformation.
Complex alloying can potentially delay the initiation of austenite recrystallization and slow down its kinetics thus contributing to the increase in deformation resistance. Thus, for AHSS it may not be realistic to expect the occurrence of multiple recrystallization cycles in austenite during hot strip rolling. Consequently, the first controlled rolling strategy (the so-called recrystallization controlled rolling [4]) has to be most probably ruled out as a potential TMP tool for AHSS. At the same time it is also unlikely that in these steels the austenite recrystallization can be fully suppressed in hot strip rolling by the means of chemical composition since the microalloying content in AHSS (lower than in traditional microalloyed steels, which is dictated by the requirements for final properties) may not be sufficient to completely cease the recrystallization within

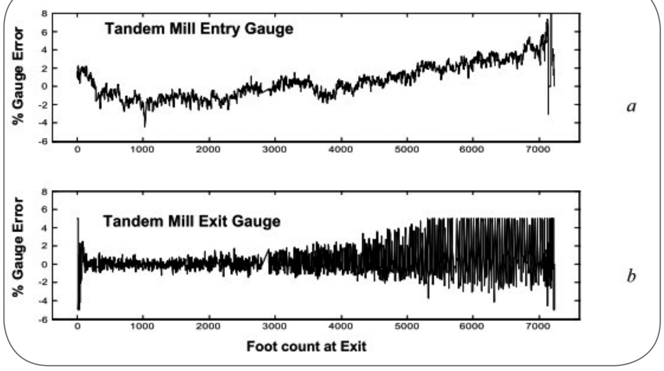


Fig. 1

Strip gauge at the entry (a) and exit (b) of tandem mill.

Calibratura del nastro in ingresso (a) e uscita (b) del laminatoio tandem.

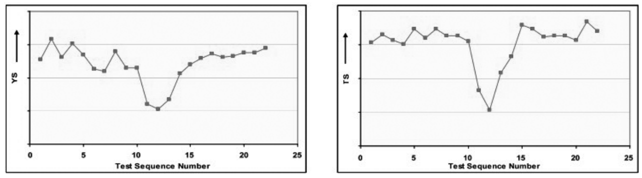


Fig. 2

Variations in yield strength (a, ΔYS ~ 40 MPa) and tensile strength (b, ΔTS ~ 50 MPa) along the length of a complete third outmost lap of hot band.

Variazioni del carico di snervamento (a, ΔYS ~ 40 MPa) e nel carico di rottura (b, ΔTS ~ 50 MPa) per la lunghezza di un terzo giro completo esterno del nastro.

the timing of the given mill. This opens the window for fine control of recrystallization due to its relatively slow kinetics and, as such, for fine control of the rate of subsequent austenite transformation during laminar cooling.
One may still argue that the microstructure of austenite is not of a high importance when hot strip rolling is an intermediate manufacturing operation. However, the unique chemistries of AHSS offer possibilities for utilization of austenite recrystallization and realization of the 'no-recrystallization" hot rolling strategy by the appropriate setup of processing parameters. Minimization of downstream property variability may require a more uniform and defined hot band microstructure from head to tail. These can then provide additional tool to enhance the quality of AHSS products.
The case study exemplified below is intended to emphasize the last statement.

GAUGE PERTURBATIONS IN AHSS AFTER COLD ROLLING

One of the examples for the effects of AHSS hot strip rolling on downstream processing is the phenomenon termed gauge hash. It is observed after cold rolling in tandem mill when the exit gauge exhibits a periodic deviation with the amplitude increasing towards the cold band tail end (Fig. 1), which corresponds to the hot band tail end. The tandem mill entry gauge profile (i.e., hot band gauge) does not exhibit any periodic disturbances (Fig. 1, a) that could be associated with the cold band gauge hash. The outcome of this phenomenon is devastating since it causes unacceptable yield losses as the final product gauge does not meet customer tolerances for a substantial portion of the coil. The pattern shown in Fig. 1, b, can also be seen on cold band head end especially for the part of the coil that was not under tension between the last hot strip mill finishing stand and the coiler (i.e., on the length of the run-out table).
Detailed quantification of the cold band gauge profile in Fig. 1, b, revealed that the periodicity of gauge spikes correlates with circumference of the hot band coil corresponding to once per revolution of the hot coil. Further investigation involving numerous mill trials showed that gauge hash appeared when the transformation of austenite on the hot strip mill run-out table was not complete and continued in the coil. When a coil

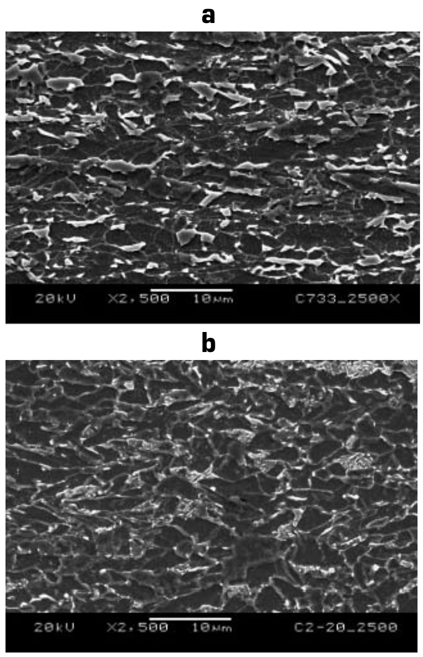
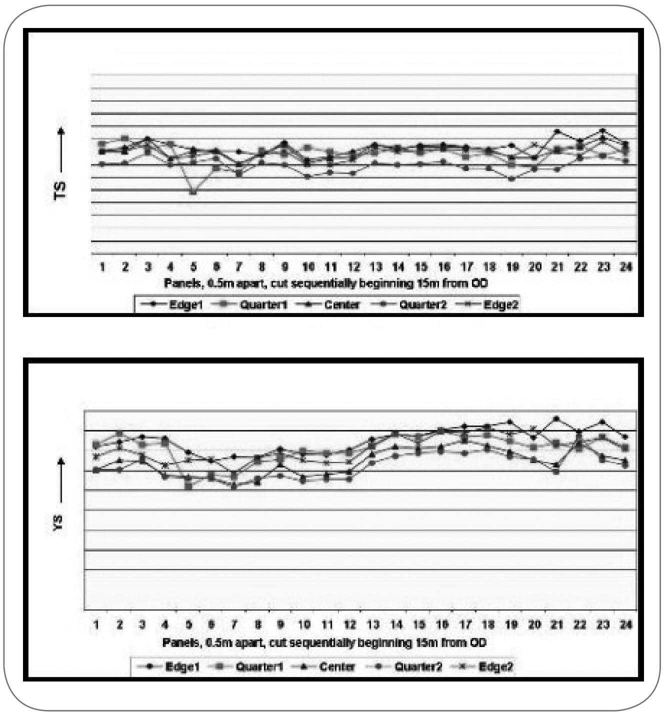


Fig. 3

Micrographs from the same coil lap showing hard spot (a) and soft spot (b) that lead to gauge hashing.

Micrografie dallo stesso giro del nastro che mostrano un punto duro (a) e un punto tenero (b) che portano a un disturbo della calibratura.

is taken off the coiler mandrel and put on a conveyor its top portion cools faster than the bottom portion so that austenite remaining in the material transforms into harder phases (lower bainite, martensite) while less hard phases are formed at the bottom of the coil.
Although this variability in hot band hardness is relatively small, it is seen in mechanical test data (Fig. 2) and variations in microstructure (Fig. 3) and ultimately leads to periodic gauge disturbances in cold rolling. Thermal gradients that induce hardness variations are most pronounced at the outer laps of hot band coil and fade away into the coil similarly as gauge hash amplitude fades away from the tail end into the coil body.



▲ *Fig. 4*

Mechanical properties of the final product are unaffected by gauge hash: ∆ YS ~ 20 MPa, ∆TS ~ 20 MPa.

Proprietà meccaniche del prodotto finale non sono influenzate dall'anomalia di calibratura: ∆ YS ~ 20 MPa, ∆TS ~ 20 MPa.

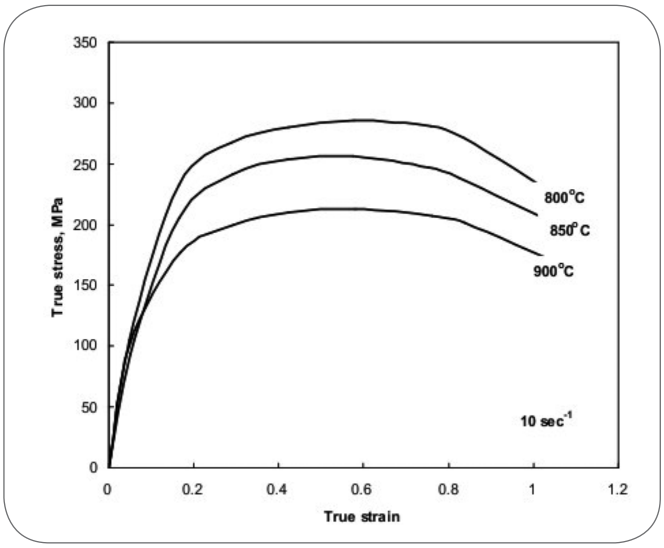
The properties after the final processing, however, are not usually affected by gauge hashing (Fig. 4) so the gauge hash deteriorates only the dimensional quality of the product.
It was also found that the formation of considerable amount of ferrite during run-out table cooling aggravates gauge hash as ferrite induces enrichment of austenite with carbon thus pushing the transformation from the run-out table and increasing the probability for transformation to occur in the coil with formation of harder phases. On the other hand, gauge hash is less pronounced when more bainite is forming at the expense of ferrite.
From these observations it is concluded that the potential cause of gauge hash is the uncontrollable (and non-uniform) transformation of austenite along the strip length on the run out table.

APPLICATION OF TMP TO ELIMINATE GAUGE HASH

To prevent gauge hash it is desirable to avoid the formation of ferrite and to increase the extent of phase transformation of austenite into bainite on the run-out table, which also means a lesser extent of transformation in coil. In the first place, this can be done by lowering the coiling temperature.
There are, however, certain limits to which the coiling temperature can be lowered in a hot strip mill without changing other hot rolling parameters. These are inherent for the particular mill and its run-out table. First, there exist certain minimum finishing and coiling temperatures attainable in the given hot strip mill, which is defined by its design and capabilities. Of course, steel chemistry has a major influence on setting up the minimum finishing and coiling temperatures that can be attained in the particular mill. The maximum difference between the finishing and coiling temperatures is prescribed by the length of the run-out table and by the design of its cooling system. For a relatively short run-out table the difference between the two temperatures cannot be very big as the strip shape can be significantly deteriorated by intense rapid cooling.
Thus, to effectively reduce the coiling temperature to attenuate gauge hash it is necessary to reduce the finishing temperature as well, to adjust the rolling speed and to modify the cooling pattern on the run-out table accordingly. Tuning of finishing temperature and rolling speed literally means implementation of TMP as both of these parameters affect the deformation and recrystallization behavior of austenite in the mill and its microstructure at the exit.
The effect of temperature on austenite recrystallization is well known: the initiation and the progress of recrystallization of any kind is decelerated with decreasing temperature. The effect of the rolling speed on the recrystallization of austenite is worth recalling. It was shown [6] that in a hot strip mill with tandem finishing stands the extent of austenite recrystallization (volume fraction recrystallized X) between the rolling passes and upon the exit from the mill is related to the rolling speed v as

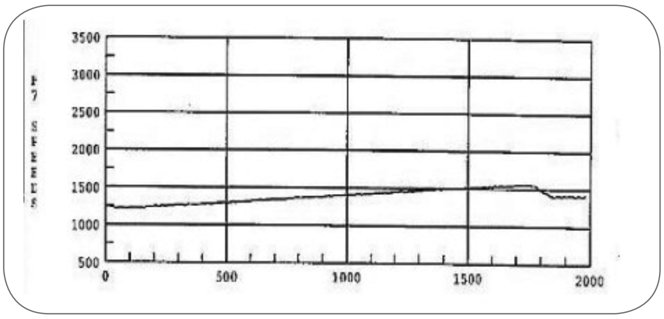
(1) $$X = 1 - \exp\left[-Bv^{n(q-1)}\right]$$

where n is the Avrami exponent, q is the strain rate sensitivity of post-deformation recrystallization and B is the combination of all quantities that do not include v. Although the above expression was obtained for isothermal conditions, it can be also employed for hot strip mill conditions as well where the cooling rate is quite slow, of the order of 0.5°C/sec [7]. Two types of recrystallization can take place after hot deformation: conventional static recrystallization (SRX) and metadynamic recrystallization (MDRX) that can occur if the strain accumulated during preceding deformation has,been sufficient to initiate dynamic recrystallization. The SRX kinetics exhibit fairly weak strain rate dependence (small q→0), while MDRX kinetics are much more strain rate sensitive (high q ≤1) [8, 9]. Consequently, with n □1 ÷ 2 [9], the fractional softening appears to depend substantially on rolling speed as X □1 – exp[-Bv−(1÷2)]. Moreover, an increase in hot strip rolling speed reduces X and hence suppresses SRX, as opposed to constant strain rate laboratory simulations where an increase in strain rate accelerates recrystallization and increases X [9]. SRX is more affected by rolling speed than MDRX because for the latter the value of (q – 1) is small. If recrystallization is to be facilitated, the rolling speed should be reduced provided that other parameters remain unchanged. This can be especially important in zooming mills: recrystallization is suppressed by acceleration.
Steel chemistry has a profound impact on recrystallization. This is illustrated in Fig. 5 that exemplifies the high temperature flow curves obtained in hot compression tests in Gleeble® 3500 thermomechanical simulator. Experimental details of these tests can be found elsewhere [10].
Despite relatively low temperatures and high strain rate used in the tests all the curves in Fig. 5 exhibit visible stress peaks indicative of dynamic recrystallization. Consequently, the occurrence of MDRX can be expected after deformation. Although the hot strip mill exit strain rates are typically higher than that used in the tests and the strain for initiation of dynamic recrystallization should also be higher, the attainment of this

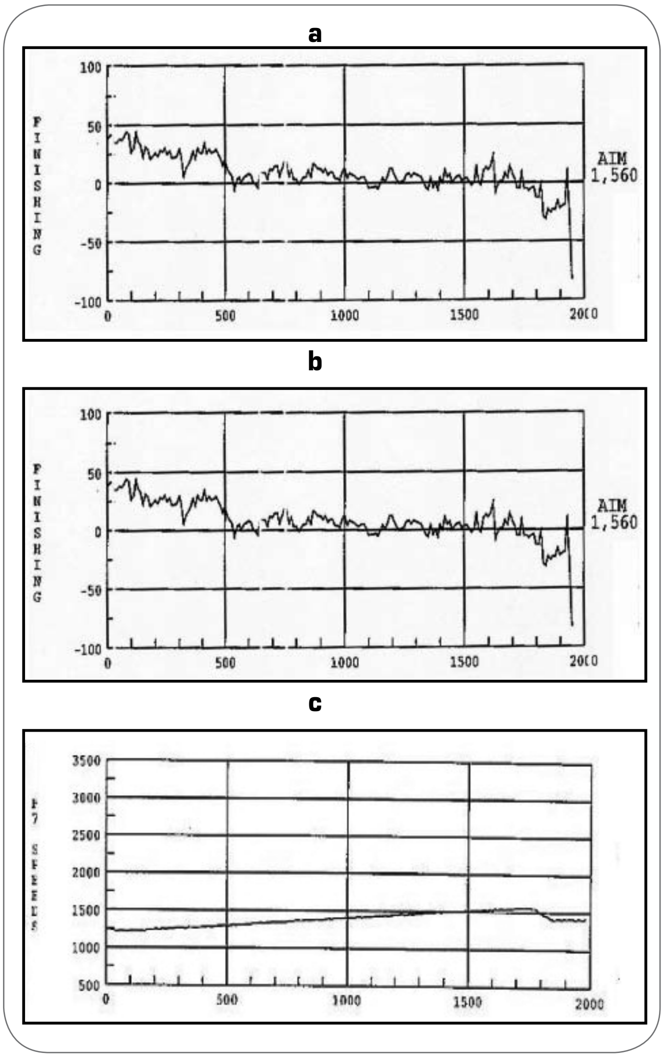


▲ Fig. 5 ***Hot compression curves Mn-Si-Nb AHSS grade showing the occurrence of dynamic recrystallization.***
Curve di compressione a caldo di acciai al AHSS Mn-Si-Nb che mostrano l'insorgere della ricristallizzazione dinamica.

strain in last finishing passes is quite possible if the interpass softening is not rapid, which can be expected for heavily alloyed compositions.
Lowering the rolling speed and acceleration is attractive to attenuate for gauge hash. First, this allows for stable attainment of lower coiling temperature, beneficial for bainitic transformation.
With lower rolling speed more time is available for austenite decomposition on the run-out table. It also facilitates the recrystallization of austenite (in this case most probably MDRX) upon the exit from the finishing mill especially in the presence of alloying additions that slow down the austenite recrystallization (Nb, Mo). This, in turn, eliminates the accelerating effect of austenite straining on ferritic transformation. The cooling efficiency of the run-out table water is higher at lower strip speed and water removal off the strip is more efficient, which prevents its puddling and the related negative impact on the strip shape.
The adverse effect of lowering the rolling speed is the necessity to lower the finishing temperature as well. The main reason for that is the higher heat loss of a bar at slower speed especially towards the tail end. As illustrated in Fig. 6, when low constant rolling speed is employed the finishing temperature runs significantly down because the transfer bar temperature in front of the finishing mill (at crop shear) decreases as the bar is being pushed through the mill. From the mechanical standpoint, a dramatic drop in finishing temperature can bring in rolling stability issues. From a metallurgical point of view, lowering the finishing temperature slows the kinetics of austenite recrystallization but at the same time increases the driving force for both recrystallization and phase transformation. If the former precedes the latter it can enable undesirable transformation of austenite into ferrite on the run-out table and hence aggravate gauge hash.
On the other hand, the absence of recrystallization prior to transformation of austenite can be quite beneficial if the ferrite "nose" can be missed by applying early concentrated cooling. In this case the bainitic transformation of deformed austenite



▲ Fig. 6 ***Variation in crop shear temperature (a) and finishing temperature (b) during hot strip rolling with constant speed (c).***
Variazione della temperatura della spuntatura (a) e della temperatura di finitura (b) durante la laminazione a caldo di nastri con velocità costante (c).



▲ Fig. 7 ***Variation in crop shear temperature (a) and finishing temperature (b) during hot strip rolling with low acceleration in the finishing mill (c).***
Variazione della temperatura della spuntatura (a) e temperatura di finitura (b) durante la laminazione a caldo di nastri con lieve accelerazione nel laminatoio di finitura (c).

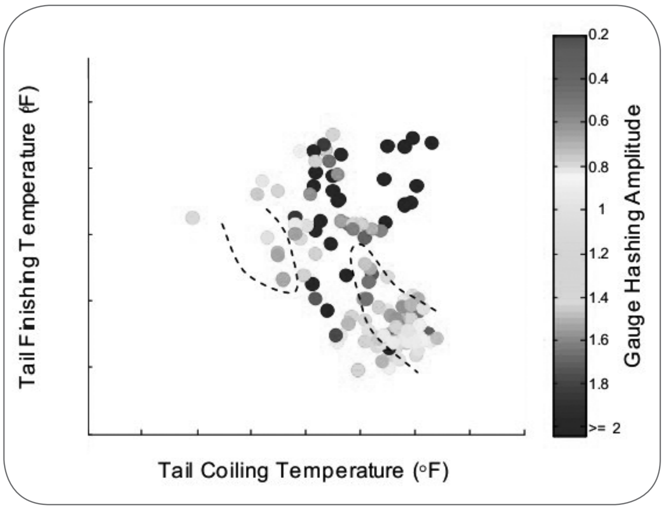


Fig. 8

Processing windows for eliminating gauge hashing. (Hash amplitude in percent of gauge).
Finestre di processo per eliminare disturbi nella calibratura. (Ampiezza del disturbo come percentuale di calibratura).

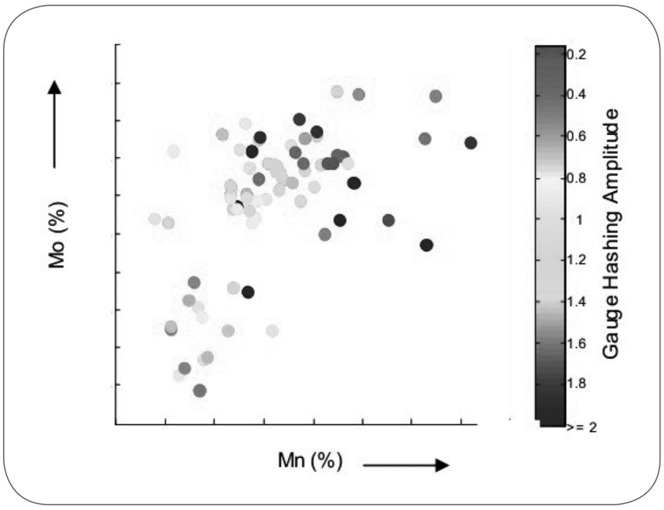


Fig. 9

Alloying effects on gauge hashing.
Effetto dell'alligazione sul disturbo di calibratura.

will start earlier on the run-out table and hence progress for a longer time before coiling. The necessary requirement here is that the deformed microstructure of austenite should be uniform throughout the bar.
As the consequence of beneficial and adverse effects of lowering the hot rolling speed for AHSS grades a delicate balance has to be maintained between mill speed and finishing temperature. This balance can be achieved by employing a very low acceleration in the finishing mill just to compensate for the finishing temperature decrease, as shown in Fig. 7. The processing windows that reflect such a balance are presented in Fig. 8.
An alternative strategy of raising the finishing temperature is also possible. This requires higher speed and acceleration, as well as higher cooling rate on run-out table in the critical temperature range of ferrite transformation. This would shorten the time on the table in ferrite transformation temperature range due to high acceleration of the bar. Similar effects on microstructure can be expected: reduction in carbon enrichment and hardenability of the remaining austenite and hence the formation of uniform ferrite-bainite microstructure without formation of martensite. Austenite should be fully recrystallized before the onset of transformation, otherwise the risk of initiation of ferrite from deformed austenite can be substantial. Recrystallization can be enhanced by higher rolling temperature but at the same it can be slowed down by higher rolling speed and acceleration.
Again, a balance between these two opposite effects should be maintained. In general, the rolling schedule should be tuned with account for correlation between the rates of recrystallization, transformation and the strip speed.
It is worth noting that for any controlled hot strip rolling strategy it is very important to avoid partial recrystallization of austenite prior to the beginning of its transformation: partial recrystallization is very difficult to control considering the normal temperature variability within the bar. Partial recrystallization of austenite leads to sensible variations in austenite transformation start temperature and kinetics. So, it can be expected that in the present case partially recrystallized austenite microstructure would aggravate gauge hash.
Another important factor that affects the relation between rolling speed, finishing and coiling temperatures is the hot band gauge. As the lighter gauges cool more intensely they should be rolled faster to prevent considerable heat losses. Higher rolling speed suppresses recrystallization but, on the other hand, gives less time for the transformation on the run-out table with the necessity to apply more water to reach the aim coiling temperature. Recrystallization and transformation behavior of austenite must be different for different exit thicknesses, which should require different speed practices and cooling patterns. Differences in cooling between strip centerline and edges can lead to differences in microstructure provoking appearance of center buckle during cold rolling. The crosswise cooling non-uniformity is also hot band gauge sensitive.
Steel chemistry has been discovered to have a strong effect on the severity of the gauge hash. This is not surprising since the hot deformation behavior of austenite, its post-deformation recrystallization and transformation are primarily determined by steel composition. Fig. 9 illustrates the effect of manganese and molybdenum on gauge hash severity. It can be seen that with lower concentration of both elements the gauge hash amplitude tends to a minimum. Reducing the molybdenum content makes recrystallization of austenite less sluggish. Also lowering molybdenum decreases the critical cooling rate for ferritic transformation [2] on the run-out table. Higher contents of austenite stabilizers (C, Mn) decrease the Ar3 temperature thus pushing the transformation of austenite from the run-out table into the coil and hence enhancing the propensity for gauge hash.
Evidently, the implementation of controlled rolling strategies strongly depends on configuration and capabilities of the hot strip mill, as well as on the product chemistry. For this reason, the processing route suitable for one hot strip mill to manufacture the AHSS of the given composition may be totally unacceptable for another mill. For exam-

ple, at the 84" Hot Strip Mill of ArcelorMittal USA different hot rolling strategies (with full or zero recrystallization of austenite) and appropriate chemistry adjustments to eliminate gauge hash were employed differently for different cold rolled dual-phase steels. In general, setting the aims and ranges for alloy contents in steel must be closely coupled to the tuning of hot rolling parameters [11] using the principles "right alloy for the available tool" and "right tool for the given alloy".

One of the important conclusions from the presented case of gauge hash is that AHSS grades are characterized by extremely high sensitivity to variations in processing parameters, particularly, in the parameters of hot strip rolling. Typical in-bar and bar-to-bar variations in temperature and speed can induce marked variability in the recrystallized austenite volume fraction and hence in the type and kinetics of austenite transformation during cooling. This can very well induce pronounced variability of the mechanical properties of the hot band. In transverse direction, thermal variation not only can cause transverse variability of hot band properties, but also strip shape can distort as the transverse differences in stress relaxation kinetics in austenite can cause shape distortions prior to cooling and these will be strongly amplified during cooling. Another conclusion is that if TMP in the hot strip mill is performed correctly to prevent gauge hash it eliminates the necessity for taking special measures to control the cooling of coils. Apart from raising the production costs, the controlled cooling of coils by special handling and storage procedures is not repeatable, can be affected by the seasonal variation in ambient temperature and may result in highly variable properties.

ADDITIONAL PRACTICAL CONSIDERATIONS

For the finishing hot rolling TMP strategies to produce expected results, a number of contributing factors determined exclusively by the characteristics of the particular hot strip mill must be accounted for and standardized. These include but are not limited to the following.

- Slab length for given product width as slab length is linearly correlated with finishing temperature rundown.
- Adjustment of mill acceleration practice to simultaneously achieve desired microstructure without overloading the mill and to avoid potential hot shoulder temperature variation (at low speed) or looping and lapping (at high speed) accompanied with run-out table instability and inadequate time for recrystallization before the beginning of cooling.
- Slab reheating profile and reheating homogeneity. Early heating profile should be beneficial as it reduces thermal variability within the bar, which is important when accounting for high sensitivity of AHSS grades to process variability. Also, adequate heating must be assured during operational delays.
- Descaling pattern. Early descaling should be preferable again from the stand point of reducing thermal variability.
- Roughing schedule to assure the transfer bar thickness is compatible with desired speed and temperature strategy.
- Lack of tension can cause non-uniform cooling along the strip length.
- Overall strip shape out of the last finishing stand. Poor strip shape can also cause non-uniform cooling of the strip on the run-out table.
- Finishing mill work roll crowning. High hot deformation resistance of AHSS requires special work roll crowning; otherwise it could be difficult to obtain satisfactory hot band shape out of the hot mill thus negatively impacting the quality and consistency of strip cooling on the run-out table.
- Special attention should be paid to the positioning of AHSS in the rolling campaign.
- Adjustment of laminar curtains to get less water on strip edges.

CONCLUDING REMARKS

The refinement of austenite microstructure is not the primary goal for thermomechanical processing in hot strip rolling of AHSS for cold rolling applications. In this case TMP, which, as shown above, constitutes an especially tuned combination of hot rolling and run-out table cooling parameters, is applied to achieve a desired extent of the transformation of austenite on the run-out table. This is aimed at obtaining the hot band microstructure that is not only optimum for further downstream processing but also permits avoiding the occurrence of adverse effect during that processing, for example, cold band gauge hash.

Presently, many hot strip mills are facing the market driven necessity to make AHSS products with mill configurations, sets of equipment and control models suitable and adapted only for manufacturing of HSLA and microalloyed steels. With growing AHSS production and having no time for full revamp (or revamping on the fly) these mills are facing the necessity to adjust, adapt and fine tune their operations, equipment, models and procedures for AHSS. Most important with this respect is that strict tolerances for the properties, surface quality and dimensions of AHSS products require re-evaluation and multiple tunings of traditional processing routes. For AHSS processing through a hot strip mill, a simple attainment of the aim centerline finishing and coiling temperatures is not sufficient. The time-temperature trajectory in hot strip mill and on run-out table is of the primary importance for such advanced products along with the uniformity of temperature and microstructure both within the bar and within the coil. Close coupling between hot mill finishing temperature control, speed control and coiling temperature control is also imperative for successful manufacturing. The run-out table thermal path, in turn, is to be controlled with respect to phase transformations on the table targeting at aim microstructure, rather than at aim coiling temperature. This is to be done for the given bar chemistry with account for bar-to-bar and in-bar variations in processing parameters (temperature, rolling speed, drafting, etc.) inherent for the particular hot strip mill.

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ABSTRACT

PROCESSI TERMOMECCANICI DEGLI ACCIAI AVANZATI AD ALTA RESISTENZA NELLA PRODUZIONE DI NASTRI LAMINATI A CALDO

Parole chiave: acciaio, laminazione a caldo, ricristallizzazione

La laminazione a caldo di nastri di acciai avanzati a basso carbonio e ad alta resistenza (AHSS) rappresenta una sfida a causa della composizione chimica non tradizionale necessaria per raggiungere le particolari proprietà meccaniche dei prodotti ottenuti con tale acciaio. Nella laminazione a caldo di nastri, i processi termomeccanici implicano diversi tipi di laminazione controlla in cui temperatura, velocità di deformazione e tasso di riduzione vengono accuratamente selezionati per produrre una microstruttura austenitica mirata, che sia o con austenite completamente ricristallizzata o con austenite completamente "pancaked" prima di iniziare il raffreddamento. La microalligazione degli acciai HSLA in combinazione con un appropriato processo termomeccanico fornisce uno strumento efficace per il controllo della ricristallizzazione dell'austenite prima dell'inizio del raffreddamento. Tuttavia, le attuali procedure dei processi termomeccanici non sono facilmente applicabili agli acciai AHSS che sono leghe molto più sofisticate e con un livello inferiore di microalligazione. I processi termomeccanici degli acciai AHSS nel treno di finitura degli impianti di laminazione a caldo per nastri dovrebbero essere studiati in modo da garantire il controllo del tipo e dell'entità della trasformazione sul tavolo di "run-out" mediante un controllo preciso della temperatura del nastro e della velocità di laminazione tenendo conto di parametri come configurazione e capacità del laminatoio, dimensioni del prodotto, tolleranze di forma e calibratura. Ulteriori complicazioni possono essere causate dall' elevata sensibilità degli acciai AHSS ai vari aspetti della laminazione a caldo dei nastri e ai parametri di raffreddamento. Questi problemi sono discussi nel presente documento unitamente a varie implicazioni di tipo pratico.