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# HOT ROLLING OF HSLA STEELS – A REVIEW OF RECENT STUDIES

Although known for many years, HSLA steels are still of considerable interest to researchers. The unique properties offered by the presence of micro-additives Nb, V, Ti in these steels are widely used in a variety of constructions – from the automotive industry, through the transport of media such as oil or gas, to large structures. Unfortunately, much of the research only concerns the theoretical sphere or does not go beyond the area of semi-industrial research. Research on an industrial scale, supported by industrial trials, is relatively scarce. This is certainly due to the very high costs of such research, but also to the rather limited number of places where HSLA steels are mass produced. This paper presents and systematizes research from the last three years into the thermo-mechanical rolling of HSLA steels. The review is divided according to the successive stages of the production process. The work forms the author's basis for further research in this area.

*Keywords:* HSLA steel; thermomechanical rolling; hot rolling; mechanical properties; microstructure

## 1. Introduction

High-strength, low-alloy (HSLA) steels are low-carbon steels based on Nb, V and Ti micro-additives [1]. The low carbon content gives excellent weldability [2] and the presence of micro-additives gives these steels unique properties – high strength (yield strength even above 1000 MPa) combined with very good formability [3].

Thanks to these unique properties, these steels have found a wide range of applications in the automotive [4] and construction industries (especially where structures operate in harsh weather conditions) [5], in the offshore industry, and in oil and gas transportation [6].

Micro-additives, as already mentioned, mainly affect the properties of HSLA steels. These elements form, together with C and N atoms, carbides (MC), nitrides (MN) and carbide nitrides (MC,N), where M is a metal atom – Nb, V or Ti [7]. The presence of these compounds plays a key role in HSLA steels in the formation of the microstructure and the final properties of the material [8]. It also enables the control of the austenite grain size when reheating the steel prior to the rolling process as well as the control of the influence of recrystallisation during finish rolling or the control of the transformation of austenite to ferrite during colling [9].

HSLA-type micro-alloyed steels are produced on an industrial scale by controlled thermomechanical rolling [10] and, although not always, by cold rolling combined with heat treatment [11]. Controlled rolling consists of the rolling process in the austenite range with the final deformation taking place below the recrystallisation stop temperature (RST), i.e. already without recrystallisation, and the subsequent controlled cooling process during which the $\gamma \rightarrow \alpha$ transformation takes place [12].

In Poland, the only place where this type of strip metal can be rolled is ArcelorMittal's Hot Rolling Mill in Krakow. Such rolling process itself, although well-known and widely used, is still often considered as an art rather than a science due to the requirement for extreme precision in the selection and control of thermo-mechanical parameters [13].

This work aims to systematize the research of the last 3 years on the topic of HSLA steels rolling and gives a basis for further research on these steels in industrial scale.

## 2. Slab casting and reheating

The final properties of the steel are strongly influenced by the closely controlled continuous casting of slabs. The proper

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chemical composition (e.g. amount of micro-additives <0.15%) and process parameters can influence the properties of the final product [14, 15]. The authors of work [16] proposed that the steel should not be deoxidized with Al as it is usually performed, but using a compound based on a combination of Ti, Ca and Zr. They proved that, the impact strength of HSLA steel can increase almost three times from 58 J to 188 J. In work [17] was shown that poorly chosen slab cooling parameters can cause edge cracking problems. Based on Tata Steel's production process, they proved that by reducing slab's edge cooling during the casting process and additionally increasing the crush on edgers already during the roughing rolling process, the size of edge cracks can be reduced. It was also noticed, that the amount of cracking increases with an increase in the micro-additive of V, which is an important aspect for HSLA steel.

The thermomechanical rolling process starts with heating the slabs after the continuous casting process to the temperatures of about 1200°C-1250°C [18]. Both heating time and temperature are extremely important in terms of the final properties of HSLA steels. The temperature and austenitizing time affect the solubility of micro-additives but also the final austenite grain size, which directly affects the final ferrite grain size. Work [19] described extensively that up to about 100 μm a ferrite grain of normal size can be expected, and above this the so-called abnormal grain growth starts. Austenitizing temperatures above 1060°C favors such abnormal grain growth (Fig. 1).

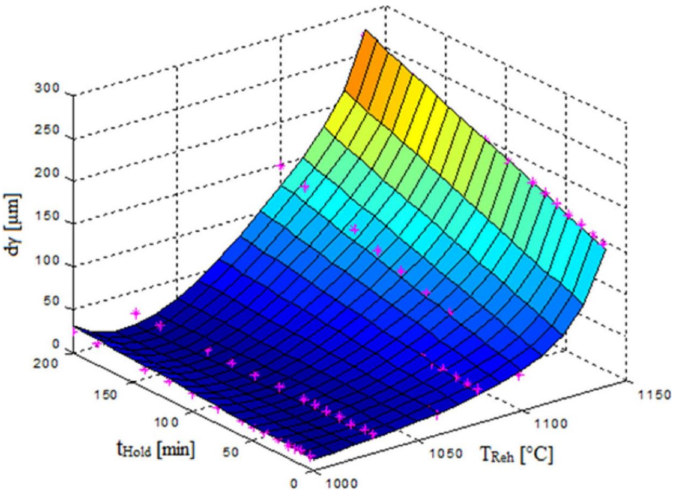


Fig. 1. The relationship between the austenite grain size diameter, temperature and time of slab reheating for HSLA Nb-V steel [19]

Reheating also has a high effect on hot ductility, what was studied in works [20,21]. The authors of [20] showed that as the austenitizing temperature increases, the material becomes more brittle. They pointed to coarse-grained AlN and AlN-MnS precipitates at grain boundaries as the cause of such material behavior. The researchers in work [21], on the other hand, focused on the effect of the Nb micro-additive and its influence on hot ductility during reheating. They showed that an increase in Nb content from 0.025% to 0.5% can almost double hot ductility.

## 3. Roughing and finishing rolling

The next step in the thermomechanical rolling process is the roughing rolling. The whole process is carried out in the austenitic range, usually above 1100°C. Of course, as mentioned above, during heating above 1060°C abnormal grain growth can occur but it is more important to dissolve the alloying micro-additives. After a few passes, finishing rolling takes place. The finishing rolling temperature (FRT) is around 900°C and the process is very often carried out in such a way that the FRT is already below the recrystallization stop temperature (RST). This guarantees the final deformation in the austenitic range, but already without recrystallisation, which strengthens the material considerably [22].

RST or the temperature of non-recrystallization (TNR) can be calculated using equation (1):

$$T_{NR} = 877 + 464\mathrm{C} + 6445\mathrm{Nb} - 644\sqrt{\mathrm{Nb}} + \\ + 732\mathrm{V} - 230\sqrt{\mathrm{V}} + 890\mathrm{Ti} + 363\mathrm{Al} - 357\mathrm{Si} \quad (1)$$

Where C, Nb, V, Ti, Al and Si are mass fractions of the components in % [23]. In work [24] the authors used the same equation but first number was 887. This is so called Boratto equation.

Much of the research works on rolling HSLA steels concern the development of models for calculating force during finishing rolling [25-28]. Models based on machine learning or other algorithms when substituted with data obtained from the process show high data correlations. This shows that we can predict, with a high degree of accuracy, what is happening during the rolling, and thus better design and control the process (Fig. 2).

Equally important to researchers and widely investigated are models describing recrystallization – static (SRX), dynamic (DRX) and metadynamic (MDRX) [27-30]. In [29] there was shown, for example, that stable dynamic recrystallisation during

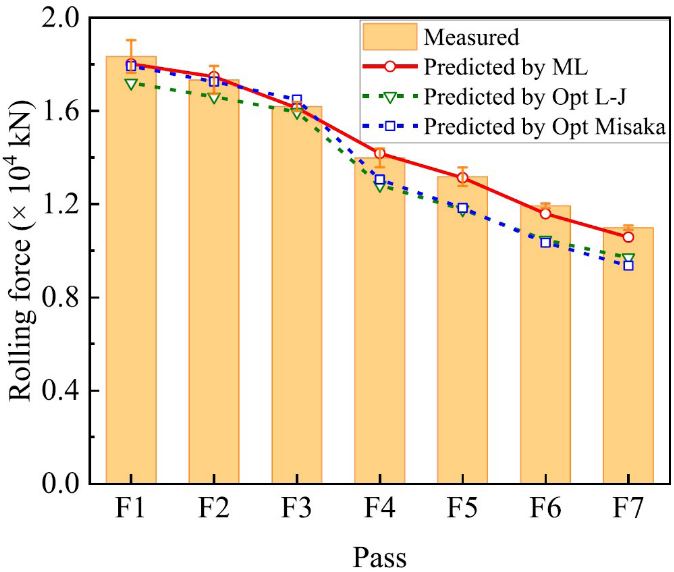


Fig. 2. Comparisons of measured and predicted rolling forces of the investigated steel strip. Steel compositions: 0.07C-0.03Si-0.95Mn-0.004 N-0.07Ti-Fe (wt.%) [27]

thermodynamic rolling, according to their model, occurs under high temperature and low strain rate. The stress increases with increasing strain rate and decreasing temperature. The volume of the recrystallized grains (by DRX) in steel increases with decreasing strain rate and increasing temperature.

## 4. Controlled cooling, coiling and final properties

The rolling process is followed by a controlled cooling stage. It is mainly at this stage, by selecting both the final temperature to which the material is cooled (the so-called coiling temperature – CT) and the cooling rate (CR), the final microstructure and properties of the product can be tailored [31-33]. A significant amount of work is related precisely to the study of the effect of the controlled cooling path on the final properties of the rolled material. The general conclusions coming from many works are quite consistent. As grain size decreases, strength properties (such as YS) increase. In order to obtain a finer grain size, the finishing rolling temperature needs to be lowered to roll well below RST and CR needs to be increased [34]. The grain is clearly finer for high CRs such as 50°C/s or 100°C/s than for 1°C/s. In addition, as YS increases, microhardness increases – in work [35] there was confirmed the correctness of the equation describing the variation in microhardness in HSLA steels:

$$Microhardness\,[HV] = 101.4 + 16.5 \cdot \ln(\mathrm{CR} + 0.41) \quad (2)$$

where CR is cooling rate in °C/s. Furthermore, changes in CR affect changes in the final product microstructure and so with an increase in CR the proportion of bainite or martensite increases at the expense of the basic ferritic-pearlitic structure [24,36].

In several papers, the authors focused on the effect of controlled cooling not only on the overall final properties, but on the individual components of the strengthening. It has been shown that the calculated component values are well correlated with values obtained from physical tests [37,38]. In works [39,40], the researchers suggest that the highest YS values can be achieved with a CT in the range of 600°C-650°C. Moreover, by using a non-stoichiometric Ti to N content (exceeding 3.42), significant grain size reduction (average grain size <3 μm) can be achieved. In work [41], the authors show slightly different results – as the CT decreases, the YS increases, and its highest value is not achieved at 600°C or 650°C, but at 500°C. They also show that, compared to other mechanisms, the effect of precipitation strengthening is small and amounts to about 26-35 MPa (in comparison, the strengthening from dislocation is about 115-150 MPa and from grain refinement about 126-156 MPa – as shown in Fig. 3).

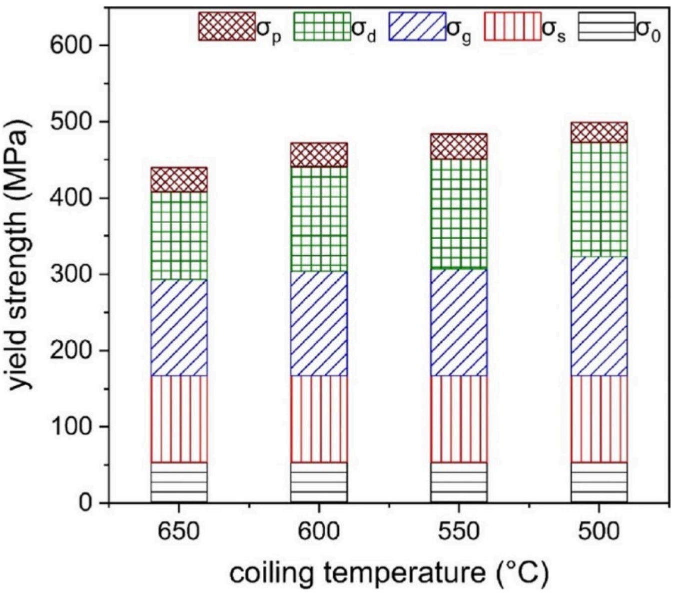


Fig. 3. Calculated results revealing the amount of solid solution strengthening ($\sigma_s$), grain refinement hardening ($\sigma_g$), dislocation hardening ($\sigma_d$) and precipitation hardening ($\sigma_p$) in the investigated HSLA steel, treated at different simulated coiling temperatures [41]

In work [42], the authors focused on investigating the effect of the processing path on the size and distribution of particles affecting the strengthening. They showed that the coiling temperature or cooling rate did not translate well into particle size and distribution (Fig. 4).

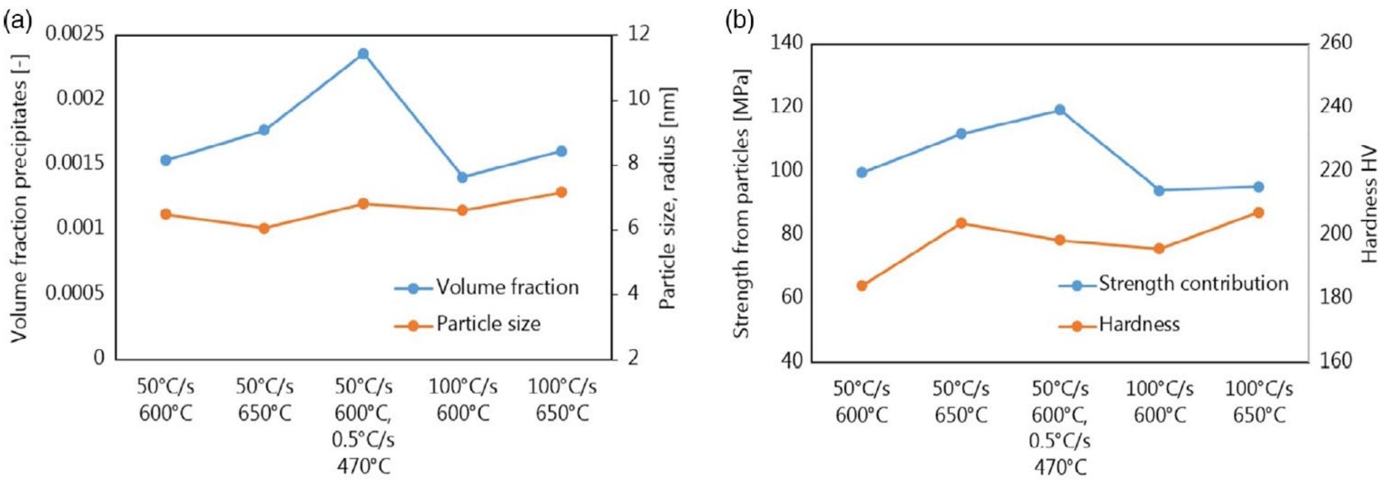


Fig. 4. a) Measured particle size and volume fraction and b) measured hardness and strength contribution according to Orowan-Ashby [42]

The work [43], on the other hand, focused on the study of the transformation of austenite to ferrite during controlled cooling. There was investigated the effect of the cooling rate on the variation of this transformation and reported how, using the various formulae available in the literature, the temperatures of $Ar_1$ and $Ar_3$ can be calculated:

$$Ar_3 = 914 - 6.85CR - 650C - 134Mn + 179Si \quad (3)$$

$$Ar_1 = 814 - 9.08CR - 532C - 121Mn + 165Si \quad (4)$$

$$Ar_3 = 903 - 328C - 102Mn + 116Nb - 0.909CR \quad (5)$$

$$Ar_3 = 902 - 527C - 62Mn + 60Si \quad (6)$$

$$Ar_3 = 879.4 - 516.1C - 65.7Mn + 38.01Si + 274.7P \quad (7)$$

$$Ar_1 = 706.4 - 350.4C - 118.2Mn \quad (8)$$

$$Ar_3 = 910 - 310C - 8Mn - 20Cu - 15Cr - 55Ni - 80Mo + 0.35\,(d - 8) \quad (9)$$

$$Ar_3 = 910 - 273C - 74Mn - 56Ni - 16Cr - 9Mo - 5Cu \quad (10)$$

$$Ar_3 = 910 - 230C - 21Mn - 15Ni + 32Mo + 45Si + 13W + 104V \quad (11)$$

where: CR is cooling rate [°C/s], d is sheet thickness [mm], and C, Mn, Si, Nb, P, Cu, Cr, Ni, Mo are mass fractions of chemical components in %.

## 5. Cold rolling and heat treatment

From an economic point of view, HSLA steels should ideally be produced by a single process – thermomechanical hot rolling. However, it is sometimes necessary to use cold rolling and heat treatment to obtain either different material thicknesses or higher strength properties [44-46]. Cold-rolling is not a necessary operation and a significant proportion of HSLA steels – especially where a simple change in properties is desired – are heat treated immediately after the hot-rolling process [23]. Additional heat treatment not only controls the properties such as YS and ductility, but also influences microstructural changes – depending on the heat treatment path, we can obtain ferritic-pearlitic, bainitic or martensitic microstructures [47-49]. In work [50], the authors showed, that after heat treatment the microstructure of metastable austenite makes it possible to achieve high YS values of 749-772 MPa. In work [51] there was additionally focused on the influence of the V micro-additive. By increasing the V content in the steel together with appropriate heat treatment, YS values above 800 MPa and even 900 MPa can be achieved. Heat treatment operations together with an appropriately selected composition can make it possible to exceed a YS of 1000 MPa in HSLA steel [52] (Fig. 5).

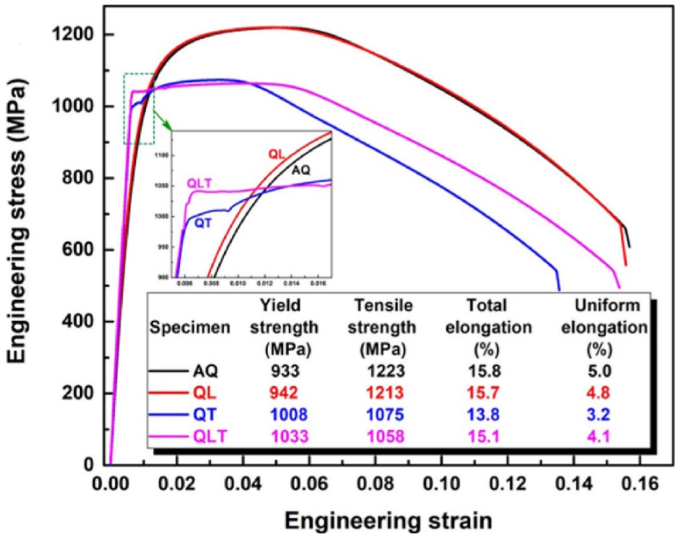


Fig. 5. The engineering stress-strain curves for the AQ, QL, QT and QLT heat-treated HSLA specimens [52]

## 6. Final product

As mentioned in the introduction to this paper, HSLA steels have been widely used in a variety of industries – in the automotive sector, in the transport of media such as oil and gas, and in all kinds of large structures often operating in harsh weather conditions. Due to the high degree of structural responsibility, HSLA steels must be of the highest quality. This is important and interesting also from a scientific point of view, what showed recent works on that subject. In work [53], the authors show how to approach the subject of quality problems in a scientific manner. Through the analysis, edge cracks caused by side guides materials were reduced by 33.16%. Structures made of HSLA steel are often subjected to cyclic loading. In works [54,55] the researchers investigated the fatigue strength of these steels. They showed that the fatigue strength decreased with increasing YS, but also that the pre-stressing of S355MC steel, compared to S460MC steel, worsened these results. S355MC withstood pre-stressing prior to fatigue testing much worse than S460MC. Moreover, in the work [54] was shown that the main determinant of failure was the stress amplitude.

Due to their low carbon content, HSLA steels are well suited for welded structures. The welding process itself, however, is not completely indifferent to the performance of the overall structure. In work [56,57] the so-called heat affected zone (HAZ) was investigated. This zone is created by the welding process through the many temperature fluctuations between $Ac_1$ and $Ac_3$. These fluctuations result in a significant decrease in hardness and fatigue strength. In work [58], the authors showed that up to 714°C ($Ac_1$) the HAZ is stable. When the steel is heated above this temperature, the strength properties in the HAZ region decrease by about 15% (YS). This is mainly due to significant grain growth. In contrast, heat treatment of the structure prior to welding guarantees a stability of the properties to up to approx. 950°C.

## 7. Conclusions

The summary of the above review can be divided into two parts. In general, it can be seen that HSLA steels are enjoying an unflagging popularity among researchers and in just a few years many papers can be found focused on these steels. Unfortunately, most of them are either purely theoretical or the research does not go beyond the laboratory area. Studies conducted under industrial conditions, yielding results on a large population, on an almost mass scale, are rare, which gives great scope for future research in this direction. Testing on an industrial scale will also allow verification of theoretical or laboratory results of other work, which may be of particular interest to those interested in these steels.

However, to sum up the articles themselves in more detail, it can be stated that:

– the process of continuous casting of steels has a significant impact on the end properties of the material, and that the amount of the key micro-additives – Nb, V or Ti – must be properly selected;
– the heating process should be carried out at the temperatures of about 1200°C-1250°C in order to quench the dissolution of the micro-additives, but at the same time without overheating in order to prevent abnormal growth of austenite grains;
– thermomechanical rolling should be carried out close to the material recrystallisation temperature and the final deformation should be carried out below the RST;
– a well-chosen deformation path, defining proper CR and CT, allows for significant and proper development of the microstructure of the final product and its properties;
– according to the literature reviewed, CT should be kept between 500°C and 650°C;
– the application of additional heat treatment after the hot rolling process can significantly change the material properties, and can achieve unprecedented YS values in excess of 1000 MPa for HSLA steels.

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