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Thermomechanical processing of HSLA steels: Overview

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Abstract. Thermomechanical processing of steels is an advanced process for producing high-strength steels. Low-alloy high-strength steel grades have a wide range of applications in the production of large-diameter pipes for transporting oil and gas. The application of API grades like X70 steels in pipe rolling production has led to a reduction in metal consumption and energy expenses for their production. Warm rolling or controlled rolling is one of the advanced technological modes of steel processing, which is described in this article. Therefore, it needs to be emphasized that high-strength low-alloy (HSLA) steels have gained significant attention due to their superior mechanical properties and cost-effectiveness in various industrial applications. Thermomechanical processing (TMP) plays a crucial role in optimizing the microstructure and mechanical performance of these steels. This paper explores the fundamental principles of TMP, including controlled rolling, accelerated cooling, and precipitation strengthening. The impact of processing parameters on grain refinement, phase transformations, and mechanical properties is discussed. Advances in TMP techniques, such as direct quenching and ultra-fast cooling, are also highlighted. Understanding these processes enables the development of HSLA steels with enhanced strength, toughness, and weldability. The paper also contains experimental part regarding to plane strain compression test results, which is modelling thermomechanical processing of HSLA steels.

Keywords: *HSLA steels, thermomechanical processing, microstructure, controlled rolling, accelerated cooling, phase transformation, precipitation strengthening.*

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1. Introduction

The rapid development of the oil and gas industry has led to an increase in hydrocarbon consumption and, accordingly, to the construction of main oil and gas pipelines. Accordingly, there was a need to produce large diameter pipes. The development of steel grades from the X50 to X100 series has led to a decrease in metal consumption and an increase in strength characteristics.

High-strength low-alloy (HSLA) steels are a class of steel designed to provide improved mechanical properties compared to conventional carbon steels while maintaining cost efficiency. These steels achieve their superior strength and toughness through microalloying and TMP. The key to optimizing HSLA steel properties lies in carefully controlling deformation and thermal cycles during processing [1].

This paper provides an in-depth analysis of TMP, including its effects on grain refinement, precipitation strengthening, and phase transformations. The latest advancements in processing techniques are also discussed.

TMP combines mechanical deformation with controlled thermal treatments to manipulate the microstructure of HSLA steels. It includes grain refinement to enhance strength and toughness, controlled phase transformations for microstructural optimization and precipitation strengthening through microalloy additions such as Nb, Ti, and V etc. [2-7].

TMP typically involves the following key stages [8]:

1. Controlled rolling, where deformation is applied at specific temperature ranges to control recrystallization and grain size.
2. Accelerated cooling, when rapid cooling rates adjust phase transformations, refining microstructure and enhancing strength.
3. Precipitation hardening, the controlled formation of fine precipitates to improve yield strength.

1.1 Effects of TMP on microstructure and properties

One of the primary benefits of TMP is its ability to refine grain structure. Fine-grained microstructures enhance yield strength, toughness, and resistance to brittle fracture. The application of controlled rolling below the recrystallization temperature suppresses grain growth, resulting in finer structures [8-10].

The microstructural evolution during TMP significantly affects the final properties of HSLA steels. The key phase transformations include ferrite formation at high temperatures, improving ductility; bainitic or martensitic transformation in accelerated cooling, enhancing strength; retained austenite stabilization for improved toughness.

Microalloyed HSLA steels contain Nb, Ti, or V, which form fine precipitates during processing (Figures 1, 2). These precipitates hinder dislocation movement, improving yield strength without compromising ductility. The precise control of precipitation kinetics is essential for achieving the desired mechanical performance.

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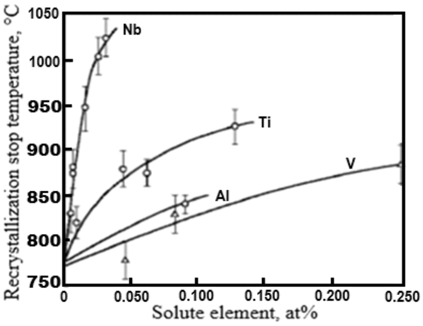

Figure 1. Influence of microalloying elements on recrystallization stop temperature in steel 0.07C-0.225Si-1.40Mn [2]

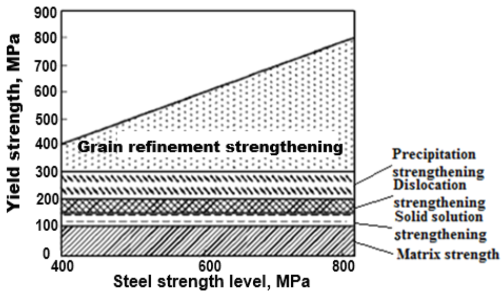

Figure 2. Effects of different strengthening mechanisms [2]

Grain refinement is a strengthening mechanism that provides the advantage of high strength combined with a low impact transition temperature (ITT). Unlike other strengthening methods, grain refinement improves or maintains toughness without compromising it.

In ferritic steels, grain refinement is typically achieved through thermomechanical processing. This involves precise control over austenite grain growth, which is suppressed using microalloying elements such as titanium (Ti) and niobium (Nb) during the reheating and rough rolling stages. These elements form stable precipitates that pin the grain boundaries of austenite, preventing excessive grain growth.

As a result, the austenite grains become pancaked-flattened due to deformation – by the end of the rolling process. Upon cooling, the transformation from austenite (γ) to ferrite (α) leads to the formation of fine ferrite grains, thereby achieving the desired grain refinement.

Another key parameter associated with grain refinement is the interfacial boundary area (S_v) of ferrite grains. It is necessary to highlight that a higher S_v, resulting from austenite pre-transformation, contributes significantly to ferrite grain refinement. For this reason, the steel is reheated above the austenite recrystallization temperature (T_{RXN}) and then subjected to rolling, promoting the formation of fine, equiaxed grains compared to the basic coarser structure. Consequently, the decrease in grain size leads to rise significantly of grain boundary area, thereby enhancing the S_v value simultaneously.

1.2. Advanced thermomechanical processing techniques

Recent advancements in TMP have led to novel techniques designed to further enhance HSLA steel properties. Some notable developments include Direct quenching (DQ), rapid quenching immediately after controlled rolling improves hardness and strength; Ultra-fast cooling (UFC), extreme cooling rates enhance the formation of bainitic and martensitic microstructures; Thermal-mechanical control processing (TMCP) (Figure 3), an optimized combination of rolling and controlled cooling enhances strength-toughness balance [3].

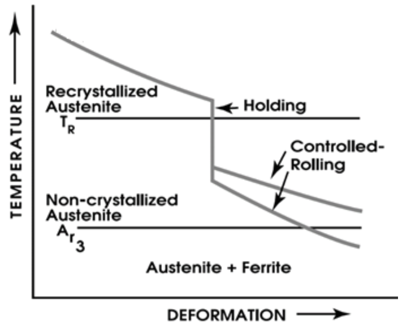

Figure 3. Schematic diagram of controlled rolling [5]

A major difference between thermomechanical processing (TMP) and conventional hot rolling (CHR) lies in the reheating, rough rolling, and final rolling temperatures, which are generally higher in CHR than in TMP. Moreover, TMP employs a faster cooling rate following the finishing rolling stage compared to CHR, contributing to significant differences in microstructural evolution.

Further development in this field led to the improvements of recrystallization-controlled rolling (RCR) – a variant of CR. In RCR, both rough and finishing rolling passes are carried out above the austenite recrystallization temperature (T_{RXN}), ensuring the formation of fine, equiaxed austenite grains. During cooling, these transform into fine ferrite grains, thereby enhancing the mechanical properties of the final steel product.

The advent of controlled rolling (CR) marked a pivotal development in steel processing, with its primary objective being the precise control of microstructure evolution during deformation. This is achieved by conducting rolling operations within the non-recrystallized austenite region, which promotes the formation of refined ferrite grains upon transformation.

1.3. Applications of thermomechanical processed HSLA steels

HSLA steel processed via TMP are widely used in industries requiring high strength and toughness, including lightweight components with high crash resistance in automotive industry, structural beams and bridges with superior load-bearing capacity in construction; high-strength, weldable steels for oil and gas transportation in pipeline industry; tough and corrosion-resistant materials for marine environments in shipbuilding. In automotive industry in terms of weight reduction enables lighter vehicle designs while maintaining safety and performance, in shipbuilding considering weight saving TMP improves fuel efficiency without compromising structural integrity.

2. Materials and methods

2.1. Sample preparation and characterization procedure

Experimental samples (60×30×10 mm) are machined and prepared in form of rolled plates of steel grade S460, similar to X70 [11-13]. The composition of the steel is shown in Table 1. Evaluated region of samples is rolling-transverse direction. Therefore, deformed samples were cut along in longitudinal direction and the cross section of transverse direction was assessed for microstructural analysis. Then samples were mounted, grounded manually, polished down to 1μm and etched in 2% nital for 20 sec. The samples dimensions are schematically shown in Figure 4.

Table 1. Chemical composition for plate steel S460

Alloying element	%
C	0.13
Si	0.49
Mn	1.49
Ni	0.019
Cu	0.012
Cr	0.061
Mo	0.002
V	0.071
Nb	0.035
Ti	0.003
Al	0.039

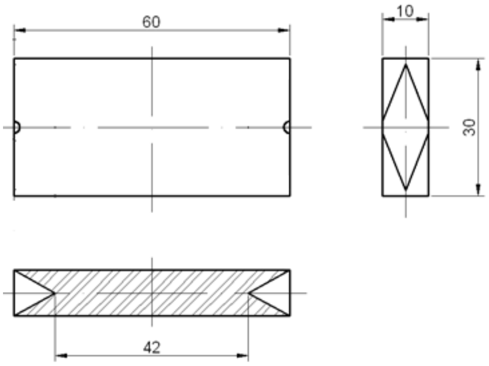

Figure 4. Experimental sample dimensions [4]

2.2. Plain strain compression test

Samples were deformed at four temperatures: 800°C, 750°C, 725°C and 700°C. Chosen temperatures considered as intercritical region on Fe_3C diagram and employed as finishing rolling temperature range for thermomechanical processing. Tools of deformation is shown in Figure 5.

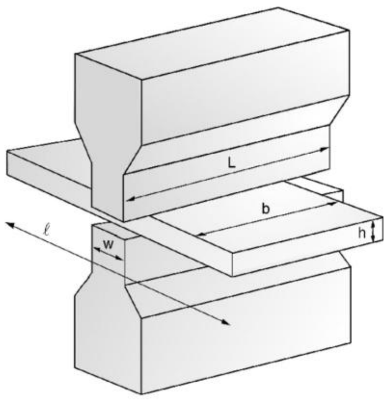

Figure 5. Deformation tool for plane strain compression test [5]

PSC test started with heating of the sample at a rate of 13°C/s up to 1050°C in two minutes. Then the sample was cooled down to the temperature of intercritical region and held up to 250 seconds. Then samples were deformed at $\varepsilon = 0.3$ and further subjected to accelerated cooling (10°C/s) down to room temperature. In Figure 6 PSC test is shown schematically.

2.3. Metallographic analysis

Samples were observed on a light microscope with magnification of 50× and 100×. Each of the micrographs taken was assessed by quantitative method to carry out the metallographic analysis to define ferrite grain size [13].

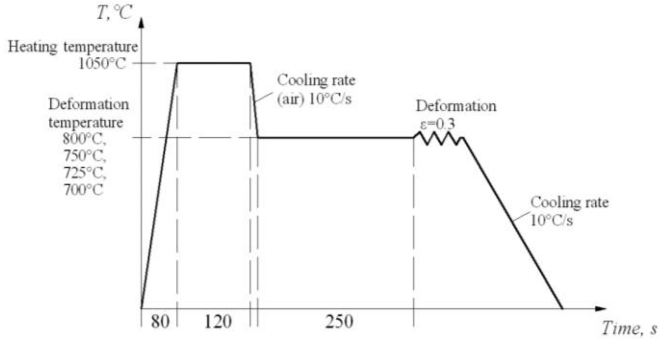

Figure 6. Schematic diagram of PSC test

2.4. Measurement of hardness

Measurement of the hardness of deformed and non-deformed regions of the samples, the Vickers hardness test was employed [14-15]. A measured hardness data is shown in Table 1.

3. Results and discussion

3.1. Modelling of flow stress

The flow stress of samples was measured according to the good practice guideline [5]. The flow stress curves are shown in Figure 7. The maximum stress value (σ = 310 MPa) was indicated at 700°C, whereas the minimum stress value (σ = 255 MPa) was at 750°C. The deformation at 800°C shows stress value equal to 264 MPa.

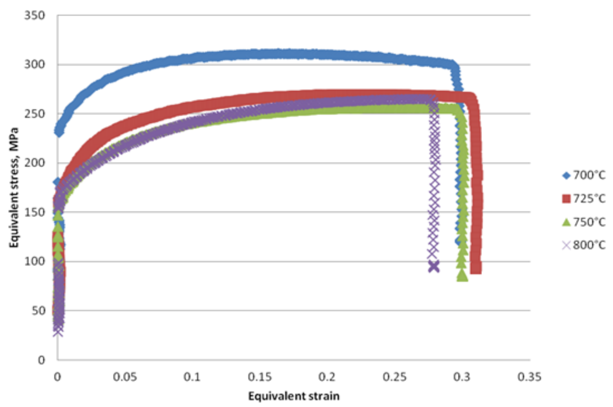

Figure 7. Equivalent stress vs. equivalent strain curve at different deformation temperature range

The flow stress curves of four samples show different yield points. The maximum value was observed at 700°C (σ = 230 MPa), whereas the minimum value was at 800°C (σ = 130 MPa). Nevertheless, the yield point of the deformed specimen at 750°C was higher than that at 725°C, measuring 160 MPa and 155 MPa, respectively.

Static recovery is the primary mechanism and can be applicable in explaining all the observed flow stress curves. The initial rise in stress during work hardening persists until it reaches a stable level, where the increased dislocation density is counterbalanced by dynamic recovery (Figure 7). This is evident in the steady-state strain, which is followed by a constant flow curve. Such mechanism is usual for metals having high staking fault energy [16].

3.2. Microstructural analysis

In the Figure 8(a) the grain size of ferrite in the deformed zone is nearly half that of the undeformed zone, while the volume fraction of ferrite remains approximately the same in both regions (Table 2). The grain size of ferrite in Figure 8(b) of deformed zone is decreased to 38% and the volume fraction is raised approximately to 10% comparing to undeformed zone.

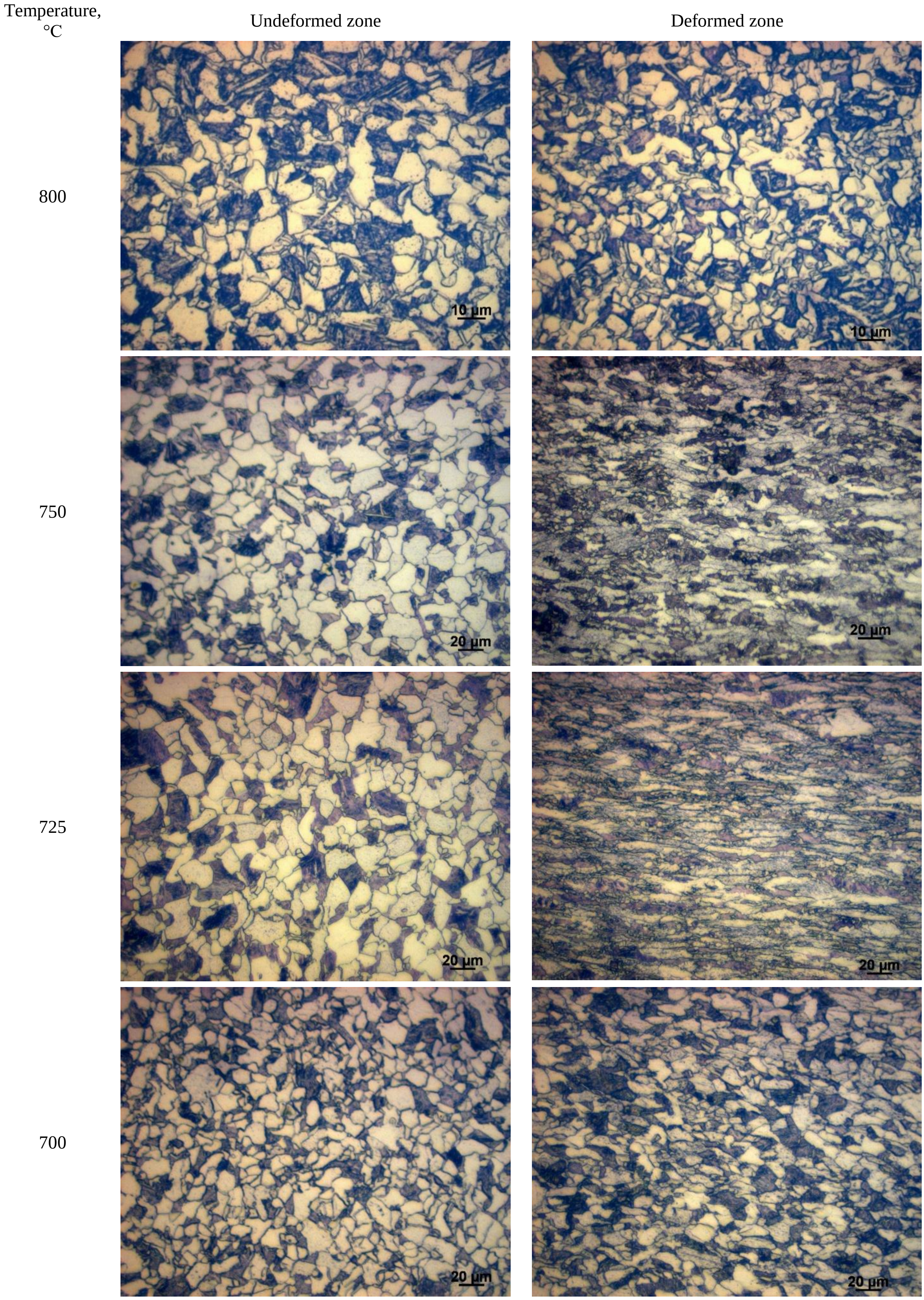

Figure 8. Microstructure of undeformed (left) and deformed (right) zones of the sample at deformation temperature

Table 2. Results of quantitative analysis of micrographs

No. of a sample and deformation temperature	Grain size, $L \pm (t_{0.95, n-1}) \cdot s(L)$, µm		Volume fraction of ferrite, V_V, %	
	Deformed	Undeformed	Deformed	Undeformed
Sample 1 (800°C)	3.5±0.16	6.2±0.25	56.1±3.045	51.7±2.44
Sample 2 (750°C)	7.1±0.37	11.4±0.52	62.6±2.77	57.5±3.31
Sample 3 (725°C)	8.7±0.35	10.4±0.36	66.3±2.30	60.7±3.71
Sample 4 (700°C)	8.7±0.41	9.5±0.41	66.2±2.61	60.6±3.20

The deformation at 725°C shows flattened grains according to the microstructure in Figure 8(c). Nevertheless, the ferrite grain refinement as well as the volume fraction has no significance. There are some coarse ferrite grains in deformed zone after treatment at 700°C Figure 8(d). The ferrite grain refinement and the ferrite volume fraction of undeformed and deformed zones are insignificant according to Table 2.

The deformation at 800°C indicates a tremendous ferrite grain refinement compared to other deformation temperatures. As is shown in Table 2, the difference between the ferrite grain sizes deformed at 800°C (~3.5 µm) approximately three times less than at 700°C (~8.7 µm).

Typical characteristic of all microstructures in the undeformed zones is the presence of distinct ferrite grains with austenite islands, whereas the distribution of the two phases in the deformed zones follows a different pattern. Therefore, the microstructure of deformed zone at 800°C consists of refined ferrite grains along with fine residual austenite. Nevertheless, defamation at 750°C microstructure of the ferrite grains is elongated flattened shaped along the grain boundaries of the austenite-ferrite interface. Microstructure of deformed samples at 725°C and 700°C shows elongated ferrite grains with residual austenite in deformed zones.

The volume fraction of ferrite in the assessed microstructures ranges from 56.1% to 66.2% in the deformed zones and from 51.7% to 60.6% in the undeformed zones (Table 2). Generally, the difference in volume fraction between deformed and undeformed zones among all samples is approximately 5%. Nonetheless, theoretical calculation of ferrite and austenite volume fractions indicate that this difference changes depending on the deformation temperature. As shown in Table 2, the ferrite volume fraction at 800°C is around 65%, whereas at 725°C, it increases to 82%. These values are derived from the Fe-C phase diagram, which does not account for alloying elements. Alloying elements such as Mn, Co, and Ni influence phase transformation temperatures like Ar_1, suggesting that the ferrite volume fraction in the studied HSLA steel may deviate from theoretical predictions. Furthermore, the theoretical calculation of ferrite volume fraction does not consider the impact of deformation at specific temperatures.

3.3. Hardness

As shown in Table 3, the highest hardness (502.1 HV) was recorded in Sample 3 at 725°C, while the lowest hardness (332.7 HV) was observed in the deformed Sample 1 at 800°C. Notably, the hard difference between the deformed and undeformed zones of Sample 1 is minimal, measuring approximately 330 HV in both zones. However, in Samples 3 and 4, this difference is substantial, exceeding 40%. The significant increase in hardness following deformation at 700°C and 725°C can be attributed to the characteristics of the flow stress curves.

Table 3. Hardness of deformed and undeformed zones of the samples

Number of measurements	Hardness by Vickers, HV			
	Sample 1	Sample 2	Sample 3	Sample 4
Deformed zone				
1	352	407	452	532
2	330	378	434	474
3	321	389	507	438
4	348	389	612	413
5	313	401	506	482
Average	332.7	392.8	502.1	467.8
Undeformed zone				
1	304	254	339	245
2	329	297	313	245
3	329	329	317	259
4	348	276	269	290
5	329	283	239	259
Average	327.8	287.8	295.4	259.6

3.4. Summary of thermomechanical processing aspects

Thermomechanical processing is a critical technology for optimizing the properties of HSLA steels. By refining grain size, controlling phase transformations, and enhancing precipitation strengthening, TMP enables the production of steels with superior mechanical performance. Advances in TMP techniques continue to improve the efficiency and applicability of HSLA steels across various industries. Further research into innovative processing methods will pave the way for next-generation high-performance steels.

There was much research fulfilled corresponding to thermomechanical processing of HSLA steels. Plenty of success in this field was achieved by the University of Sheffield. It was found proper cooling rate and intercritical strain during processing to improve steel production performance and mechanical properties of HSLA steels [16, 17]. As it is mentioned in [15], implementing intermediate forced cooling (IFC) shortens the inter-pass holding time, which is a major drawback compared to conventional rolling process [16]. Nevertheless, applying this method in an industrial setting is considered challenging. Therefore, the research was conducted using a plane strain compression test, followed by modeling with the finite element method. The key distinction between this research and the present study is that the former examines the impact of IFC on mill productivity, whereas the current work focuses on microstructural evolution during intercritical processing.

4. Conclusions

To summarize this research, it needs to be emphasized that considerable grain refinement of the ferrite was observed during the deformation at 800 °C, with an average grain size of 3.6 µm. High ferrite volume fraction was assessed for sample 3 at 725°C and obtained 66.3%. The difference between theoretical and actual volume fractions can be explained by influence of alloying elements (Mn, Co and Ni). The highest value of macro hardness was observed in Sample 3 at 725°C (502.2 HV). Thus, hardness increases significantly just above the temperature of Ar_1.

The modelling of flow stress curves shows remarkable increase in stress at intercritical temperatures, influenced by initial work hardening followed by dynamic recovery. Therefore, during intrcritical processing dynamic recrystallization process is not preferred. Deformation in intercritical regions is beneficial for the ferrite grain refinement to obtain ultrafine ferrite grains. Corresponding results suggest warm deformation at 800°C to achive required grain refinement, whereas benefits in hardness can be obtained at 725°C. Therefore, indicated temperatures need to be considered critical during thermomechanical processing.

Author contributions

Conceptualization: UKK; Data curation: UKK, AAK; Formal analysis: UKK; Funding acquisition: UKK; Investigation: UKK, AAK; Methodology: UKK, AAK; Project administration: UKK; Resources: UKK; Software: UKK; Supervision: UKK; Validation: UKK; Visualization: UKK, AAK; Writing – original draft: UKK, AAK; Writing – review & editing: UKK, AAK. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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HSLA болаттарын термомеханикалық өңдеу: шолу

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Аңдатпа. Болаттарды термомеханикалық өңдеу – жоғары берік болаттарды алудың жетілдірілген процесі. Төмен легирленген беріктігі жоғары болат маркалары мұнай мен газды тасымалдауға арналған үлкен диаметрлі құбырларды өндіруде кең ауқымды қолдануға ие. Құбыр илемдеу өндірісінде X70 маркалы болаттарды қолдану металды тұтынуды және оларды өндіруге арналған энергия шығындарын азайтуға әкелді. Жылы илемдеу немесе бақыланатын илемдеу осы мақалада сипатталған болат өңдеудің озық технологиялық режимдерінің бірі болып табылады. Сондықтан, төмен легирленген беріктігі жоғары (HSLA) болаттар жоғары механикалық қасиеттеріне және әртүрлі өнеркәсіптік қолданбаларда үнемділігіне байланысты айтарлықтай назар аударғанын атап өткен жөн. Термомеханикалық өңдеу

(ТМӨ) осы болаттардың микроқұрылымын және механикалық өнімділігін оңтайландыруда шешуші рөл атқарады. Бұл жұмыс бақыланатын илемдеуді, қарқынды салқындатуды және тұнбаға түсумен беріктендіруді қоса алғанда, ТМӨ негізгі принциптерін зерттейді. Өңдеу параметрлерінің дәнді ұсақтауға, фазалық өзгерістерге және механикалық қасиеттерге әсері талқыланады. Тікелей шынықтыру және ультра қарқынды салқындату сияқты ТМӨ әдістерінің жетістіктері де атап өтілген. Бұл процестерді түсіну беріктігі, қаттылығы және пісірілу қабілеті жоғары HSLA болаттарын жасауға мүмкіндік береді. Сондай-ақ мақалада HSLA болаттарының термомеханикалық өңдеуін модельдейтін жазық деформацияны басу сынағы нәтижелеріне қатысты тәжірибелік бөлімі бар.

Негізгі сөздер: *HSLA болаттары, термомеханикалық өңдеу, микроқұрылым, бақыланатын илемдеу, қарқынды салқындату, фазалық түрлендіру, тұнбаға түсумен беріктендіру*.

Термомеханическая обработка сталей HSLA: Обзор

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Аннотация. Термомеханическая обработка сталей является передовым процессом производства высокопрочных сталей. Низколегированные высокопрочные марки стали имеют широкий спектр применения в производстве труб большого диаметра для транспортировки нефти и газа. Применение сталей марки Х70 в производстве трубопроката привело к снижению расхода металла и энергозатрат на их производство. Теплая прокатка или контролируемая прокатка является одним из передовых технологических методов обработки стали, который описан в данной статье. Поэтому необходимо подчеркнуть, что высокопрочные низколегированные (HSLA) стали привлекли значительное внимание благодаря своим превосходным механическим свойствам и экономической эффективности в различных промышленных применениях. Термомеханическая обработка (ТМО) играет решающую роль в оптимизации микроструктуры и механических характеристик этих сталей. В данной статье рассматриваются основные принципы ТМО, включая контролируемую прокатку, ускоренное охлаждение и дисперсионное упрочнение. Обсуждается влияние параметров обработки на измельчение зерна, фазовые превращения и механические свойства. Также освещаются достижения в технологиях ТМО, таких как прямая закалка и сверхбыстрое охлаждение. Понимание этих процессов позволяет разрабатывать стали HSLA с повышенной прочностью, вязкостью и свариваемостью. В статье также содержится экспериментальная часть, касающаяся результатов испытаний на сжатие при плоской деформации, которая моделирует термомеханическую обработку сталей HSLA.

Ключевые слова: *HSLA стали, термомеханическая обработка, микроструктура, контролируемая прокатка, ускоренное охлаждение, фазовое превращение, дисперсионное упрочнение*.

Publisher's note