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STABILIZATION OF LOW-TEMPERATURE IMPACT TOUGHNESS IN HEAVY STRUCTURAL STEEL PLATES BY ADJUSTING NORMALIZING ROLLING PARAMETERS

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The article focuses on optimizing the production technology for structural steel plates with a thickness of 51-100 mm to stabilize low-temperature impact toughness. The study investigates the influence of normalizing rolling parameters, microstructural characteristics, and chemical composition on the fracture energy of steel at –20ºC. Based on the analysis of automated data («Detailing rolling protocol») and Charpy impact test results, it was established that the decisive factor for forming a fine-grained structure (grain size No. 8-10) is the strict adherence to the regulation of the roughing and finishing stages of normalizing rolling, ensuring the necessary deformation forces and inter-pass pauses. It is shown that to ensure stable impact toughness (fracture energy exceeding 27 J), the total reduction in the finishing stand must be at least 15-20% with forces of 29.4-34.3 MN (3000-3500 tf) during the initial passes. It was found that a decrease in these parameters leads to the formation of an inhomogeneous structure with coarse grains, which sharply reduces cold resistance. Additionally, the qualitative influence of non-metallic inclusions and carbon content on mechanical properties was determined. Practical recommendations have been formulated to improve the technological regulations for normalizing rolling, allowing for the avoidance of costs associated with additional thermal treatment of the plates.
Keywords: *normalizing rolling, steel plates, low-carbon steel, impact toughness, microstructure, ferrite grain, rolling force, non-metallic inclusions.*

Problem statement

Steel plates with a thickness of 51-100 mm are widely used in many industries, such as infrastructure construction, shipbuilding, the energy sector, heavy machinery manufacturing, etc. The plates are mainly produced from low-carbon structural steels of strength categories S235JR(J0, J2), S275JR(J0, J2), BVE, P265GH, etc., smelted without the use of scarce alloying elements (Cr, Ni, Mo, Cu), or with microalloying using V, Nb, Ti. In the production of plates, an energy-saving technology of thermo-deformational treatment is used which is a normalizing rolling (NR). The finished plates are underwent a Charpy testing at a temperature of –20ºC, during which the impact energy absorbed for the steel's fracture is determined. A significant portion of the results from primary tests of steel plates does not meet the standard requirements for this indicator (not less than 27 J). This leads to repeated testing or even full-volume heat treatment of the plates (normalization), which significantly increases technological costs and reduces the efficiency of metallurgical production. In this regard, the task arose to improve the low-temperature impact toughness of steel plates by refining the production technology, in particular by optimizing the parameters of thermo-mechanical treatment.

Analysis of the latest achievements on the identified problem

Conventional hot rolling (HR) of steel products starts at 1150-1200 ºC and finishes at a temperature above 1000ºC. Normalizing rolling differs from HR by much lower finish temperature, which is approximately equivalent to the heating temperature used in normalization – a full-volume heat treatment of steel with separate heating [1, 2]. For carbon and low-alloy structural steels, this temperature usually lies in the lower part of austenitic domain, i.e., above the Ac_3 temperature, within 820-950ºC [3, 4]. NR allows obtaining a microstructure with refined ferrite grains, similar to those of normalized steel. At the same time, NR eliminates the need for energy consumption in performing normalization, thus, it has an energy-saving orientation and is therefore attractive to manufacturers of metallurgical products [5]. Due to lower finish rolling temperature, NR allows to inhibit the dynamic recrystallization in the deformed metal, meaning that the accumulated crystal lattice defects are partially retained in the structure contributing to the steel's strengthening [1]. Therefore, normalizing rolling may, in a certain sense, be classified as thermo-deformational treatment [6, 7]. The inhibition of recrystallization under NR is promoted by microalloying the steel with strong carbide-forming elements – Nb, Ti, and V [8, 9]. Niobium is particularly effective, as it precipitates from austenite during rolling in the form of dispersed carbonitrides, which effectively pin dislocations, preventing their movement and annihilation [1, 10]. The mechanical properties of rolled products produced through NR, are less stable and susceptible to fluctuations in various technological factors (slab thickness [11, 12], texture [13], reduction value [2, 14], time pauses between passes [15], etc.). While these negative effects can be mitigated by conventional normalization, this option is unavailable in NR. Consequently, rigorous control over key NR process parameters is essential to guarantee the quality of the finished plates. Since the main microstructural component of steel after NR is fine ferritic grain resulted from austenite recrystallization, the deformation regime in the finishing stage of NR is particularly important, as it determines the degree of austenite pancaking and the kinetics of recrystallization processes [16]. However, insufficient attention has been paid to this issue so far. To address this research gap, the present work was aimed at solving the problem of instability in the impact toughness of steel plates by investigating the influence of normalizing rolling parameters on the microstructure and mechanical properties of the finished rolled product.

The purpose and tasks of the research

The purpose of the article is to develop proposals for improving the technology of producing steel structural plates by optimizing the technological parameters of thermo-deformational treatment, namely the normalizing rolling process.

Materials and methods

The research materials were plates with a thickness of 55-100 mm, the strength categories and chemical composition of which are provided below in the text.

The plates were rolled from slabs with a thickness of 220-250 mm, obtained by the oxygen-converter method with continuous casting of steel. The slabs were heated to 1150-1180ºC and rolled on a 3600 mill to the required thickness using normalizing rolling technology. After air cooling, the workpieces of 150 × 300 (mm) in planes were cut from the plates, from which the samples were prepared for mechanical testing. The absorbed impact energy (KV_{-20^oC}) was determined in accordance with to DSTU ISO 148-1:2022, by the Charpy method, using the prismatic specimens with dimensions 10×10×55 (mm) having a V-notch. The specimens were cut from the samples parallel to the rolling direction, at a depth of ¼ of the plate thickness. The temperature of the specimens at the moment of testing was –20ºC.

The microstructure of the specimens was studied on specimens prepared on the fractured Charpy specimens. The surface of the specimens was polished according to the standard procedure and etched with a 4% solution of nitric acid in ethyl alcohol. The microstructure was examined using an optical microscope «Axiovert 40 MAT» (Carl Zeiss) at magnifications from 100 to 500 times. The ferritic grain size was determined according to the standard DSTU EN ISO 643:2022.

Results and discussion

Normalizing rolling is intended to form a structure in the steel that is as close as possible to that obtained by normalization. Therefore, it is important to ensure an optimal reduction schedule for the slab during normalizing rolling in order to achieve maximum grain refinement. The latter becomes possible with higher reduction in the final passes combined with a decrease in a plate temperature. This approach is aimed at obtaining the deformed austenite, which is prone for recrystallization to form new (undeformed) grains. Preventing the growth of these grains is possible by inhibiting the process of collective recrystallization of austenitic grains due to the reduction in the finishing temperature of normalizing rolling.

According to standard technology, normalizing rolling of plates is carried out in two stages. The roughing stage is intended to reduce the slab to an intermediate thickness at high temperatures. An air cooling pause is then implemented to lower the metal temperature, followed by the finishing stage. Rolling parameters (number of passes, reduction per pass, and pause duration) play a critical role and require additional analysis, as they directly affect the mechanical properties of the finished product. The degree of deformation-induced structural refinement (or «working») of the metal is vital for improving the as-cast structure of the slab. The intensity of deformation can be assessed by the «Maximum Force» applied for each pass – a parameter automatically recorded to form a comprehensive rolling log (or «Detailing force protocol») of the process.

To analyze the influence of NR parameters, an experiment was conducted in which the following were analyzed: 1) the number of passes in the roughing and finishing stages, 2) the maximum rolling force in the passes, 3) the duration of the pause between stages. The study was carried out during the production of a batch of 60 mm thick plates of S355J2+N steel (chemical composition: 0,12% C; 1,55% Mn; 0,24% Si; 0,003% S; 0,12% P; 0,033% Al; 0,016% Ti; 0,036% Nb; 0,050% V).

Analysis of the rolling details showed that variations in the main rolling parameters occurred in different plates, specifically: a) the total duration of the roughing stage varied from 100 s to 200 s with the number of passes ranging from 5 to 10; b) the maximum force in the last passes of roughing rolling changed from 2300 tf to 3000 tf; c) the pause between roughing and finishing stages varied from 232 s to 345 s; d) the number of passes in the finishing stage ranged from 5 to 9; e) the maximum force in the first two passes of the finishing stage ranged from 2800 tf to 3450 tf. As an example, Figure 1 shows the rolling details for four plates from the experimental batch, and their mechanical properties are presented in Table 1. When studying these plates, samples were taken at a depth of ¼ thickness from both sides of the plate («Top» and «Bottom»), as well as from the centerline of the plate.

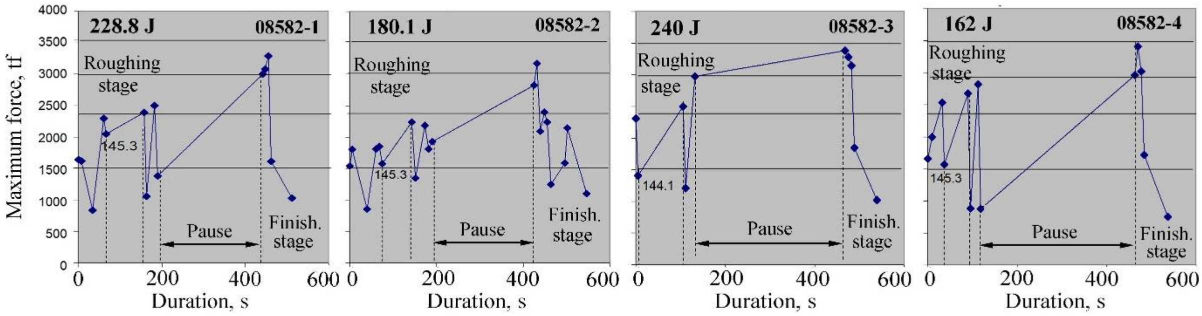

Fig. 1 – The force protocols of the normalizing rolling of the 60 mm thick plates of a S355J2+N grade (numbers of plates: 08582-1, 08582-2, 08582-3, 08582-4).

Table 1

Mechanical properties of the 60 mm thick plates of a S355J2+N grade (after normalizing rolling)

Plate number	Place of cutting	Yield strength, N/mm^2	Tensile strength, N/mm^2	Total elongation, %	Absorbed impact energy at –20°C, J		Grain number
					Current values	Average	
08582-1	Top	469	581	30,5	214, 217, 220	217,0	9
	Bottom	–	–	–	269, 241, 276	262,0	9-8
	Center-line	–	–	–	206, 250, 293	249,7	10-9
	Average for the plate:				**228,8**		
08582-2	Top	443	571	31	140, 194, 185	173,0	10-9
	Bottom	437	576	29	180, 192, 208	193,3	10
	Center-line	429	568	28,4	134, 236, 152	174,0	9-10
	Average for the plate:				**180,1**		
08582-3	Top	479	584	30	241, 256, 260	252,3	9
	Bottom	–	–	–	220, 247, 283	250,0	9-10
	Center-line	–	–	–	224, 300, 228	250,7	9-10
	Average for the plate:				**239,5**		
08582-4	Top	435	586	30	184, 139, 185	169,3	9
	Bottom	430	577	29,5	146, 185, 171	167,3	8-9
	Center-line	407	573	29	175, 135, 176	162,0	9
	Average for the plate:				**166,2**		

Analysis of the results showed that the plates fully met the standard requirements in mechanical properties including the impact energy at –20 ºС, which varied from 135 J to 283 J, with average values for each plate ranging from 166.2 J to 239.5 J (which significantly exceeded the minimum standard limit – 27 J). The highest level of the KV_{-20^oC} was observed in plates # 08582-1 (average value of 228,8 J) and # 08582-3 (239,5 J). Their rolling regime was distinguished by: a) an increased (up to 100 s) pause within the roughing stage after reaching a rolled thickness of 144-145 mm; b) an extended pause between stages, during which the plate cooled to 850-870ºС; c) maximum rolling force (3200-3400 tf) in the first 2-3 passes in the finishing stage.

The microstructure of these plates is shown in Figure 2 consisting of fine-grained ferrite (grain numbers 9-10) and pearlite bands stretched along the rolling direction. Alongside the primerely small grains (1-3 µm), there were individual fairly large grains (20-30 µm) or deformed ones with dimensions (15-20) × (30-35) µm (indicated by arrows in Fig. 2a). However, the presence of these coarse grains did not deteriorate the overall high impact toughness of steel.

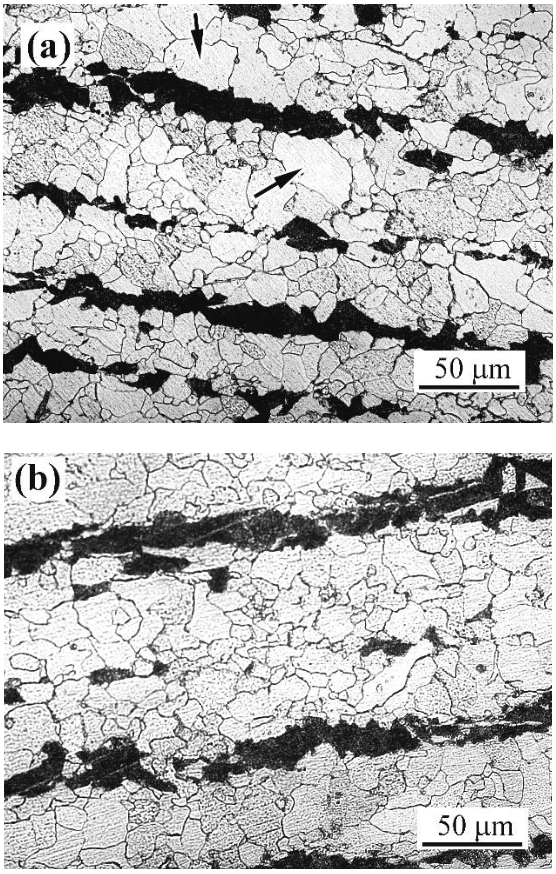

Fig. 2 – The microstructure of the plates:
(a) # 08582-3; (b) # 06875

A similar normalizing rolling scheme was implemented when producing a batch of 60 mm thick plates of S355 steel (0,12% C, 1,50% Mn, 0,22% Si, 0,004% S, 0,012% P, 0,028% Al, 0,014% Ti, 0,036% Nb, 0,050% V) (Fig. 3). The plate processed under this regime exhibited the following mechanical properties: yield strength – 448 N/mm^2; ultimate tensile strength – 546 N/mm^2; total elongation – 29,5%; absorbed impact energy at –20 °C – 152-215 J (average value of 188.8 J). The structure consisted of ferrite and pearlite, with a grain size of No. 9-10 (Fig. 2b).

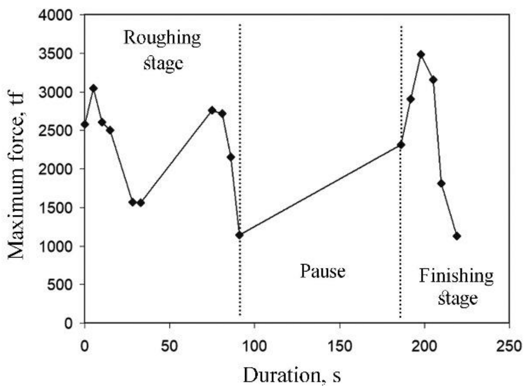

Fig. 3 – The detailed force protocol of the normalizing rolling of 60 mm thick plate (S355 grade)

The advisability of significant reduction in the first passes of finishing rolling was further confirmed during the rolling of S355 steel plates of various thicknesses – from 55 mm to 100 mm. The highest values of absorbed impact energy at –20°C (230-241 J) were recorded for the 55 mm thick plate, for which finishing rolling began with four passes at a maximum force of 3400-3750 tf. If the first finishing passes were performed with lower force (2400-3100 tf), the impact energy was unstable, varying from 13 to 274 J. The lowest impact energy values (3-12 J) referred to the 100 mm thick plate, for which the maximum forces at the start of finishing rolling were only 1350-1650 tf.

Based on the results of the conducted experiments, the optimal rolling scheme for S355 steel plates is formulates as follows (Fig. 4a):

1. Start of rolling in the roughing stage (at 1000-1080°C): the first two passes – at 3000-3500 tf, decreasing to 2000 tf, until reaching a thickness of 140-150 mm.
2. Pause of at least 80 s.
3. After the pause: the first two passes – with a force of 2500-3000 tf, decreasing to 1500 tf, until obtaining an intermediate slab thickness of 102-104 mm.
4. Pause between roughing and finishing stages – until the metal temperature lowers to 850-870°C.
5. Finishing stage: the first 2 passes – with a force of 3000-3500 tf, the 3^{d}-4th passes – 2000 tf, the last ones – at 1000-1200 tf (at 820-840°C).
6. Total reduction degree in the finishing stage – 15-20%.

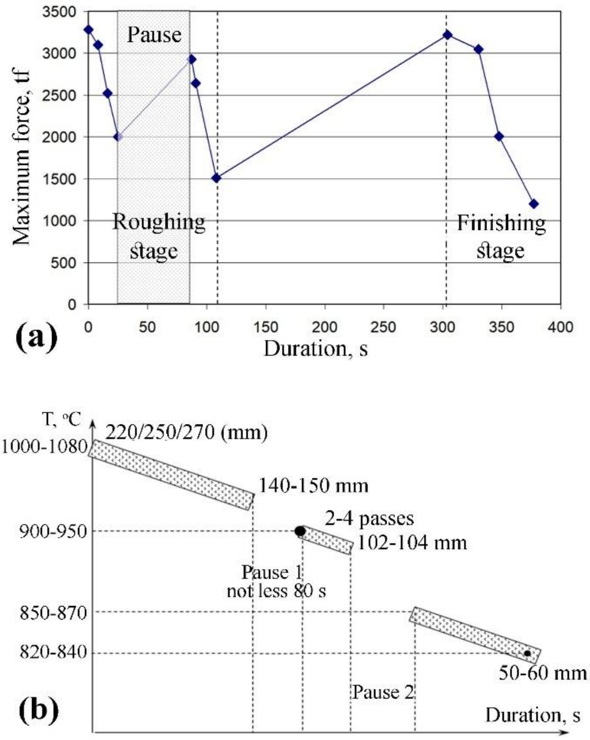

Fig. 4 – (a) Optimal force protocol and (b) a «Temperature-Time» schedule proposed for normalizing rolling of 50-60 mm thick plates (S355 grade)

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The total reduction is very important, as it ensures the degree of austenite deformation necessary for effective grain refinement during recrystallization of the γ-phase and its phase transformation. The total reduction in the finishing stage should be at least 15-20%. With lower total reduction (11,6-12,2%), unsatisfactory impact test results were recorded, which was associated with insufficient deformation working of the metal (Fig. 5). The recommended technological regime for normalizing rolling of steel plates (a «Temperature-Time» schedule) is presented in Fig. 4b.

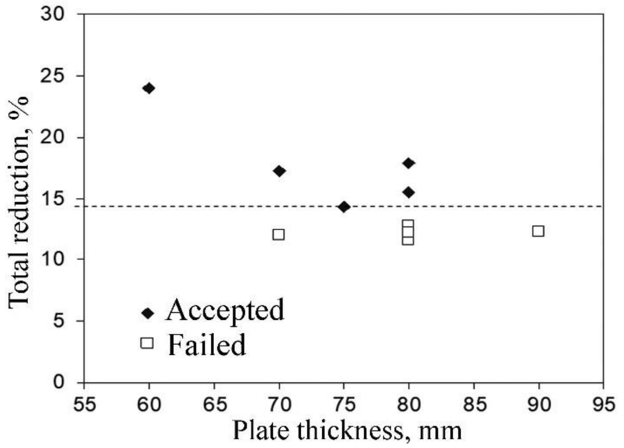

Fig. 5 – Effect of total reduction at the finishing stage of NR on the results of impact testing at –20 ºC (the plates of S355 grade). (Accepted: The result met the standard norm; Failed: The test was not passed)

It is well known that low-temperature impact energy depends on the actual grain size and the contamination of the metal with non-metallic inclusions. The relationship between these parameters was investigated using specimens with different levels of absorbed impact energy (categorized as «ductile» and «brittle»), selected from 75 mm thick normalizing-rolled plates (Nos. 7907, 07376-2, and 07376-3). The microstructural analysis of the specimens revealed that:

a) all specimens contained non-metallic inclusions, namely: non-deformable silicates (NDS) (grade 2-5) and point oxides (grade 1-2). In «brittle» specimens (with absorbed energy below the norm), the contamination with NDS was 0,5-2,5 points higher than in «ductile» ones;

b) «ductile» specimens generally had finer ferritic grain (Nos. 8 or 8-7), while in «brittle» specimens, grains of Nos. 7 and 7-8 were recorded. In addition, «brittle» specimens revealed the presence of individual large grains No. 6 and bainitic bands (the latter are uncharacteristic for the metal at a depth of ¼ plate thickness). The relationship between grain size and impact energy at –20ºC is presented in Fig. 6. It can be seen that the dependencies have a classical character, reflecting an increase in impact energy with an increase in grain size number (which corresponds to grain refinement). At the same time, data relating to different plates do not fit into a single scatter band but form two separate bands that do not overlap. For plates No. 07376-2 and No. 07376-4, this dependence corresponds to a smaller grain size number, meaning that in them high impact energy values (100-150 J) are achieved with coarser grain. This is clearly seen from the comparison of microstructure images of «ductile» specimens taken from plates No. 07907 and No. 07376-2 (Fig. 7). Such behavior was not affected by the contamination with non-metallic inclusions which was approximately similar for both plates. This suggests the presence of another factor that, in addition to grain size, affects the absorbed impact energy. Such a factor may be carbon, which increases the amount of the brittle structural component (cementite), increasing the volume fraction of pearlite. The carbon content in these specimens was 0,15% (No. 7907) and 0,13% (No. 07376-2). Thus, a reduction in carbon content compensated for the coarser grain in the metal of plate No. 07376-2, allowing the achievement of the same improved impact toughness as in fine-grained steel with higher carbon content (No. 7907).

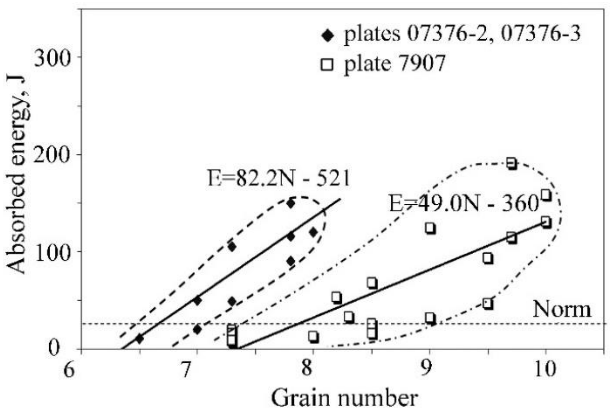

Fig. 6 – Ferrite grain size vs. absorbed impact energy at –20 ºC in plates of 75 mm thick (plates numbers 07907, 07376-2, and 07376-3)

The conducted studies showed that the stability of low-temperature impact toughness of steel plates produced using normalizing rolling, with a thickness of 51-100 mm, depends on various technological factors, among which the main ones are the rolling parameters in the roughing and finishing stages, as well as the carbon content and contamination of the steel with non-metallic inclusions.

Further extensive research is required to fully elucidate the effect of carbon content on the low-temperature impact toughness of steel plates produced by normalizing rolling.

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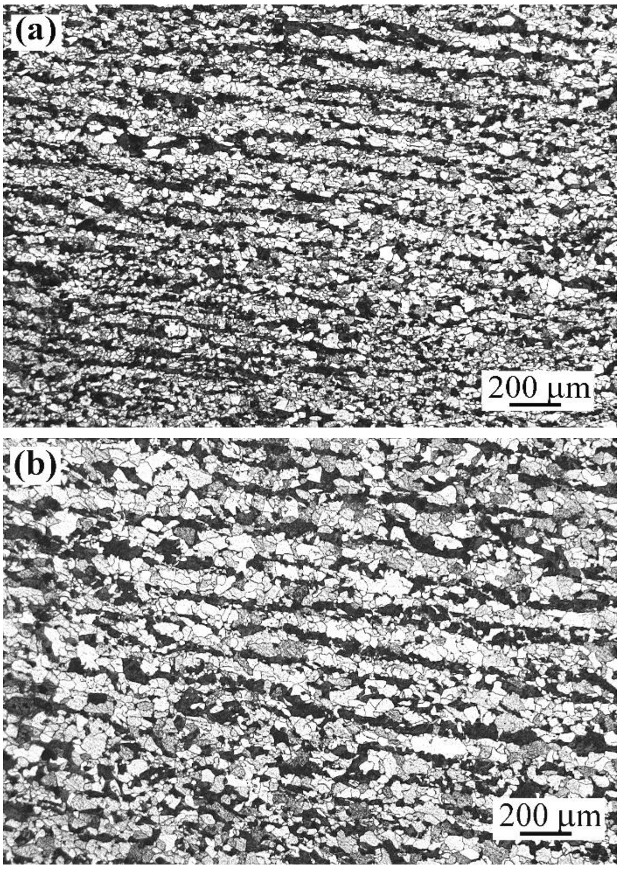

Fig. 7 – The microstructure of the «ductile» specimens taken from the plates: (a) # 07907 (159 J) and (b) # 07376-2 (116 J)

Conclusions

This work was aimed at improving the technology of normalizing rolling of steel plates thicker than 50 mm in order to prevent negative results during low-temperature impact toughness testing. As a result of this work, the following conclusions were drawn:

1. It has been established that the stability of low-temperature impact toughness of steel plates with a thickness of 51-100 mm critically depends on the regime of normalizing rolling, in particular on the duration of pauses between the roughing and finishing stages and the sequence of changes in maximum forces during passes within each stage.

2. It has been shown that to form a fine-grained structure (grain size number 8-10) and ensure impact energy exceeding 27 J at –20 ºC, the total reduction degree in the finishing stage must be at least 15-20 %, with forces in the first finishing passes of 3000-3500 tf (29.4-34.3 MN). Insufficient hot "working" of the metal leads to a heterogeneous structure with coarse grains and bainitic bands, causing the absorbed impact energy to drop to critical values (3-12 J).

3. A direct relationship has been established between unsatisfactory low-temperature toughness and elevated carbon content as well as contamination of the steel with non-metallic inclusions.

4. An optimized technological regime for normalizing rolling of plates from low-alloy steels of strength categories S235-S355 has been proposed, which includes the introduction of inter-rolling pauses for gradual cooling of the intermediate slab to 850-870 ºC and intensive deformation in the finishing stage, ensuring the required cold resistance of the product without additional heat treatment (normalization).

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СТАБІЛІЗАЦІЯ НИЗЬКОТЕМПЕРАТУРНОЇ УДАРНОЇ В'ЯЗКОСТІ ТОВСТИХ ПЛИТ ІЗ КОНСТРУКЦІЙНИХ МАРОК СТАЛЕЙ КОРИГУВАННЯМ ПАРАМЕТРІВ НОРМАЛІЗУЮЧОЇ ПРОКАТКИ

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Стаття присвячена вирішенню важливого технічного завдання, пов'язаного із забезпеченням стабільності механічних властивостей товстолистового конструкційного прокату (плит товщиною 51-100 мм), виготовленого за енергозбережною технологією нормалізуючої прокатки (НП). Хоча НП покликана замінити традиційну об'ємну нормалізацію шляхом подрібнення мікроструктури безпосередньо в процесі деформації, практичне застосування часто виявляє нестабільність показників низькотемпературної ударної в'язкості. Значна частина продукції не відповідає мінімальним вимогам щодо енергії поглинання (27 Дж при –20°С), що зумовлює потребу в дороговартісних повторних випробуваннях або додатковій термічній обробці. У даному дослідженні вивчається складний взаємозв'язок між термомеханічними параметрами прокатки, еволюцією мікроструктури та

хімічним складом для стабілізації якості сталей марки S355, мікролегованих Nb, V та Ti. Методологія дослідження ґрунтується на аналізі автоматизованих протоколів прокатки, які фіксують зусилля у кожному проході та інтервали охолодження, – у зіставленні з результатами випробувань на ударний згин за Шарпі та даними оптичної мікроскопії. Дослідженням встановлено, що визначальним фактором для досягнення високої в'язкості є ступінь деформаційної «проробки» структури на чистовій стадії прокатки. Експериментальні дані доводять, що для плит товщиною від 55 до 100 мм сумарний ступінь обтиснення на чистовій стадії має становити не менше 15-20% для забезпечення ефективної рекристалізації аустеніту та подрібнення феритного зерна. Зокрема, встановлено, що застосування максимальних зусиль прокатки в діапазоні від 29,4 МН до 34,3 МН (3000–3500 тс) під час перших чистових проходів при 850-870°С сприяє формуванню стабільної дрібнозернистої структури «феррит+перліт» із номер зерна 8-10 згідно з ISO 643. Зниження зусилля прокатки до 13,2-16,2 МН (1350-1650 тс) призводить до утворення неоднорідної структури, що характеризується крупним зерном (№ 6-8) та наявністю бейнітних смуг поза осьової зони, через що енергія удару падає до критичних значень 3-12 Дж. Крім того, в статті кількісно оцінено вплив металургійної «чистоти» та хімічного складу на стабільність низькотемпературної ударної в'язкості. Встановлено, що «крихкі» зразки мали значно вищу кількість недеформівних силікатів (у середньому на 0,92 бала вище) порівняно із «в'язкими» зразками. Крім того виявлено взаємокомпенсуючий зв'язок між вмістом вуглецю та розміром зерна: зниження вмісту вуглецю в сталі зменшує частку перліту, тим самим підтримуючи високу енергію удару навіть за наявності укрупненого зерна фериту. За результатами дослідження розроблено вдосконалений технологічний регламент НП, виконання якого забезпечить зниження рівня браку, що гарантує якість продукції без додаткової термічної обробки.
Ключові слова*: нормалізуюча прокатка, сталеві плити, низьковуглецева сталь, поглинена енергія удару, мікроструктура, феритне зерно, зусилля прокатки, неметалеві включення.*

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