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USE OF ACCELERATED COOLING TO IMPROVE THE MECHANICAL AND PROCESSING PROPERTIES OF ROLLED PLATES USED TO MAKE LARGE-DIAMETER GAS-LINE PIPE

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A process called controlled thermomechanical rolling has been developed to make low-alloy steels used in the production of large-diameter pipes. The process, carried out on plate mills, combines thermomechanical (controlled) rolling with accelerated cooling done after the rolling operation. The results of commercial trials of the technology lead to the following conclusions: 1. Compared to conventional controlled rolling (CR), use of the additional operation of accelerated cooling (AC) makes it possible to significantly increase strength properties without lowering impact toughness or cold resistance. Accelerated cooling also makes it possible to broadly vary the properties of rolled products of a given chemical composition and thickness. 2. The accelerated cooling of plates makes it possible to replace the ferritic-pearlitic structure usually formed in steel after conventional controlled rolling with a fine-grained ferrite-bainite stucture having a diminished level of striation. 3. Compared to traditional controlled rolling, CR + AC makes it possible to attain a prescribed level of strength with lower quantities of carbon and alloying elements. That in turn improves the weldability of the steel. 4. The use of accelerated cooling reduces the load on the mill because a higher finishing temperature is used than in traditional CR. Thus, it also becomes possible to increase rolling speeds through a reduction in the number of pauses made to cool the slabs on the mill.

Customers have recently been demanding that higher standards be met in regard to the quality of low-alloy steels used to make large-diameter pipes. On the one hand, the more exacting service conditions to which pipelines are being subjected are making it necessary to increase strength and fracture toughness while maintaining good ductility and weldability. On the other hand, there is also pressure to reduce the cost of producing tube steels. A controlled thermomechanical process (TMCP) [1] has been developed to make such steels on plate mills. The process combines thermomechanical (controlled) rolling (CR) with accelerated cooling (AC) after the rolling operation is completed. Realizing the new technology requires equipping the rolling mill with a modern automated unit which ensures that the rolled product will be cooled to the required temperature at a specified rate. The unit also makes sure that the cooling of the steel is uniform and that no warpage of the rolled product takes place. The only state-of-the-art AC unit that presently exists in Russia is installed in the line of the 5000 plate mill at the Severstal' Metallurgical Combine.

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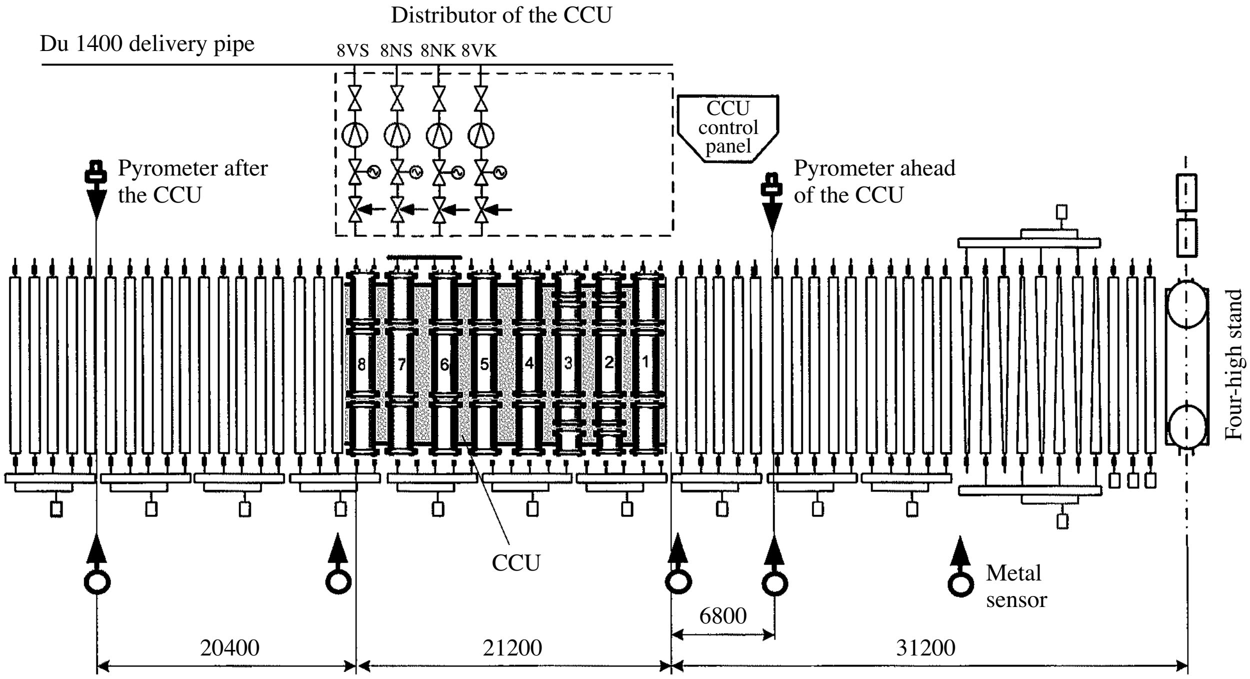


Fig. 1. Diagram of the location of the equipment of the controlled-cooling unit (CCU) on the 5000 mill.

As part of the reconstruction of the shop that includes the mill, in 2002 the institute VNIIMT designed and built a controlled cooling unit (CCU) in the line of the 5000 plate mill to create a single production line for plates that can be used to make electric-welded pipe up to 1420 mm in diameter [2].

The CCU (Fig. 1) is designed for the accelerated cooling and quenching (from rolling heat) of a wide range of thick plates (slabs) ranging up to 100 mm in thickness, 4850 mm in width, and 30000 mm in length. The unit can also perform accelerated cooling of intermediate (between the roughing and finishing stages of the rolling operation) slabs up to 120 mm thick. If necessary, it can be used for the accelerated cooling of slabs exceeding the design thickness. The main specifications of the CCU are shown below:

Number of sections	8
including:	
intensive cooling	3
cooling at a reduced rate	5
Dimensions of the cooling section, m:	
width	4.85
length:	
overall	21.2
intensive cooling	5.8
slower cooling	15.4
Consumption of water on the CCU, m^3/h	196.5
Working pressure range in the manifolds during slab cooling, MPa	0.07–0.28
Slab speed through the CCU, m/sec	0.2–4.5 ± 2.5%

The CCU includes the following main components: eight cooling sections; protective entry guide; distributing element and water delivery pipes; CCU control post; pyrometers to determine temperature at the beginning and end of cooling; sensors to detect the presence of slabs; pneumatic distributors to control the valves that admit coolant water and shut

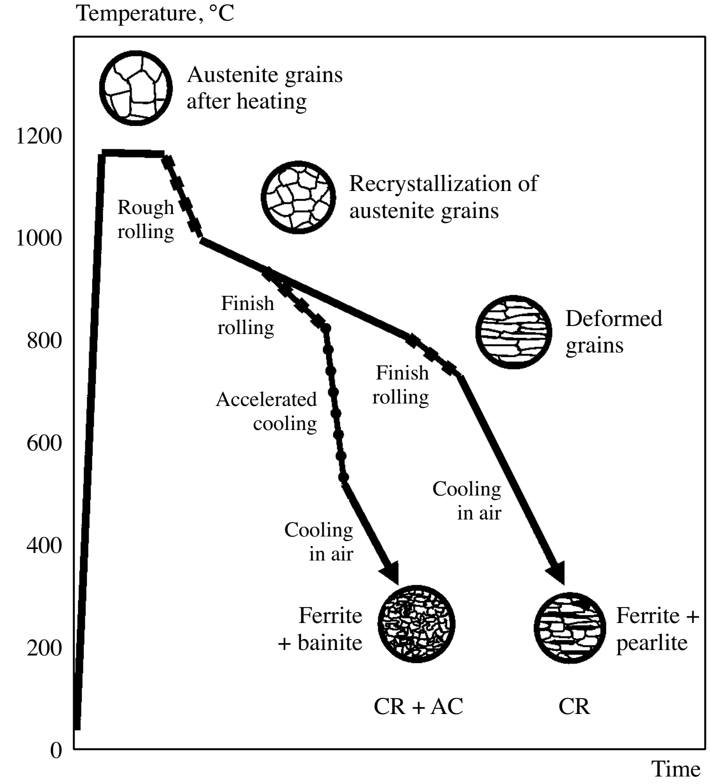


Fig. 2. Diagram of the processes that take place during controlled rolling (CR) and controlled rolling with accelerated cooling (CR + AC).

off the water supply; sensors to warn that a slab has undergone a dangerously severe amount of “ski-like” bending. The lower sections of the unit are installed in a fixed position under the roller conveyor and consist of manifolds with nozzles and pipes located between the rollers. The upper sections consist of supporting metal structures and movable frames, nozzle-equipped water manifolds installed on the frames, air manifolds to blow water off the top surface of the slabs, and shields equipped with drain pipes to cut off the flow of water to the side edges of the slab.

Sections 1 and 4–8 of the CCU are divided into three subsections over the width of the unit: a central subsection 3 m long; two 1-m-long outer subsections on each side of the central subsection. To provide for greater control over the flow of water across the slab, sections 2 and 3 are also divided into three subsections over the width of the unit: a 3.0-m-long central subsection and to 0.5-m-long lateral subsections. Water flow rate in top and bottom sections, the central subsections, and the outer subsections is regulated independently and can be varied (by a factor of roughly two).

Lengthwise, the CCU is divided into zones characterized by high and low cooling rates. The high-rate zones rapidly cool the slab in the high-temperature region, and the low-rate zones cool the slab to the required final temperature while eliminating dangerous over-cooling of the surface layer and ensuring that the inner layers cool at satisfactorily high rates.

To provide for uniform cooling over the width of the unit, water is fed onto the slab from above and below by flat-jet nozzles designed by VNIIMT. The water leaves the nozzles in the form of planar fan-shaped flows that merge with one another on the surface of the slab.

Cooling of the slabs after rolling and the quenching of slabs up to 50 mm thick are done in one pass through the CCU. When thick slabs are being quenched, the direction of the slab is reversed after it travels through the unit once. Here, the slab is moved in the opposite direction inside the cooling zone until it has been completely cooled. Slabs of intermediate thickness can be cooled in one or two (forward and reverse) passes in the TMCP process.

The CCU can be operated in two regimes: the main regime – an automated regime in the control system controls the overall process and chooses and monitors the cooling parameters [3]; the auxiliary regime – a regime in which the operator at the control post chooses the cooling regime and the parameters of the CCU and monitors its operation. The auxiliary regime is used during startup, as well as when adjustments are being made to the unit or the process is being modified. The cooling regimes are controlled using a mathematical model developed by VNIIMT.

Introduction of the CCU on the 5000 mill and the use of AC in the production of tube steels is making it possible to make the transition from low-temperature controlled rolling (LCR) – in which the transformations in the steel are completed in the $\gamma + \alpha$ region – to high-temperature controlled rolling (HCR) – in which the transformations are completed in the γ region and cooling is then accelerated. It has been found that it is possible to fundamentally alter the approach taken to the production of plates for high-strength tubes and the rolling of thick (30 mm or more) plates of steels with special properties (such as steels that are resistant to hydrogen sulfide).

In controlled rolling with accelerated cooling (CR + AC, Fig. 2), it is necessary to control the parameters of the following main processes:

- the heating of the slabs prior to rolling; during this operation, the carbonitride phase dissolves and austenite grain growth takes place (the parameters to be regulated are heating temperature and holding time);
- rough rolling, during which the initial austenite grains are refined due to the crystallization that occurs during deformation (the parameters to be regulated are deformation temperature and the draft);
- finish rolling in the range in which no recrystallization takes place, when the equilibrium austenite grains are elongated as a result of the deformation and the work-hardening increases the number of nucleation centers for the ferrite phase [4] (the parameters to be regulated are the initial and final temperatures and the total reduction);
- accelerated cooling, the temperatures at the beginning and end of this process affecting the quantitative relationships between the structural components and the types of components formed after cooling;
- the cooling process as a whole; here, the cooling rate also affects the type and quantity of phases and structural components formed (F + P, F + P + B, F + B, F + B + M, etc.).

The main advantages of the CR + AC process compared to conventional controlled rolling are:

- the formation of a finely dispersed, uniform structure in the metal with reduced levels of striation, internal stresses, and property anisotropy;
- the possibility of decreasing the contents of iron and alloying elements for the given level of strength of the steel, which makes it possible to reduce the production cost and improve the weldability, toughness, and cold resistance of the rolled product and alleviate segregation in the slab;
- the fact that the loads on the mill will be reduced as a result of the higher finishing temperature; also, rolling speed will be increased due to a reduction in the number of pauses that must be made to allow the slab to cool.

Tube steels of strength classes up to X60 (K52) have traditionally been delivered in the normalized state. These steels (of type 17G1S-U) have contained up to 0.2% C and have been characterized by a relatively coarse grain and the formation of pronounced bands of pearlite. Thermomechanical (controlled) rolling makes it possible to significantly refine the ferrite grains and obtain steels of type 10G2FB, i.e., steels with properties corresponding to strength class X70 (K60). These are low-alloy ferrite-pearlite tube steels with carbon contents up to 0.1%. A further improvement in strength properties can be realized without adversely affecting toughness and cold resistance only by replacing the ferrite-pearlite structure of the steels obtained by controlled rolling by steels with a ferrite-bainite structure. Steel having this structure can be obtained by additional alloying with such elements as Mo, Cr, Ni, and B. However, alloying with these elements necessarily increases production costs and decreases weldability. Another approach is the use of AC, which makes it possible to obtain higher strength without introducing large quantities of additional alloying elements. Carbon content can be reduced to 0.04–0.08% in this case. Accelerated cooling is the method used to produce steels of types X70 and X80 [5]. If the degree of alloying is increased and intensive AC is used with high cooling rates, then it is possible to obtain tube steels in strength classes up to X100.

In accordance with the thermokinetic curve for steels of type X70 (10G2FB), a ferrite-pearlite structure is formed by cooling steel from the austenite region in air at a rate of 2.5°C/sec; when the cooling rate is increased to more than 4°C/sec, bainite is formed in the structure along with ferrite and pearlite. If the cooling rate is increased to above 10°C/sec,

TABLE 1. Chemical Composition of the Steels Rolled with AC

Steel	C	Si	Mn	S	Ti	V	Nb	Others	C_{eq}
05KhG 1NDB (X65)	0.046	0.20	1.4	0.004	0.013	–	0.05	Cr–Ni–Cu	0.37
05G1MB (X65–X70)	0.05	0.2	1.43	0.003	0.015	–	0.05	Mo–Ni–Cu	0.36
10G2FB (X70)	0.1	0.4	1.59	0.002	0.014	0.07	0.05	–	0.39
05G2NDMB (X80)	0.05	0.12	1.81	0.004	0.011	–	0.09	Mo–Ni–Cu	0.43

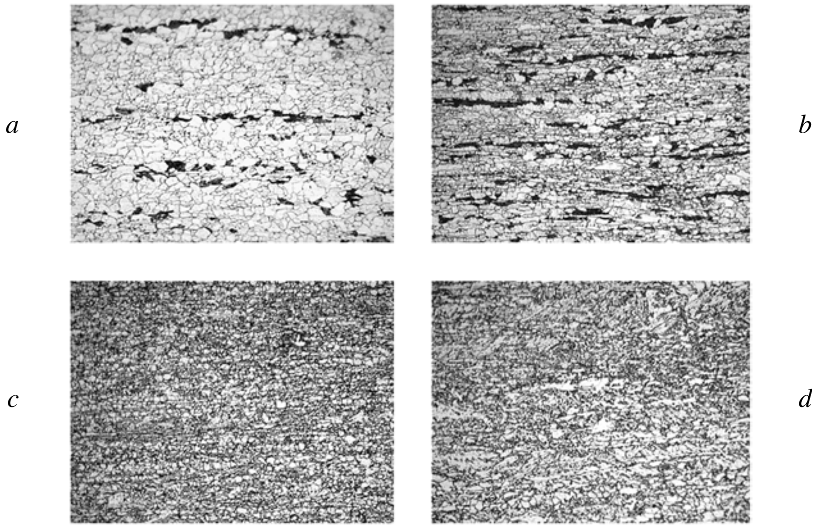


Fig. 3. Typical microstructures of tube steels: after CR (*a* – 05G1MB; *b* – 10G2FB) and after CR + AC (*c* – 05G1MB; *d* – 05G2NDFB), ×500.

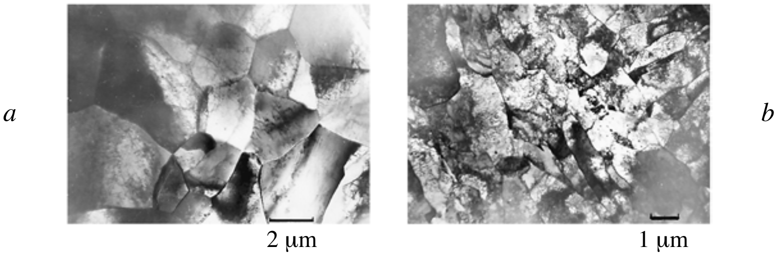


Fig. 4. Electron micrographs of polygonal (*a*) and acicular (*b*) ferrite in tube steels.

a ferrite-bainite structure is formed in the steel. The steel has mainly a bainite structure when it is cooled at rates higher than 50°C/sec.

Table 1 shows the chemical composition of steels obtained on the CCU of the 5000 mill during commercial trials.

Figure 3 shows the typical microstructure of tube steels produced by the CR and CR + AC regimes. Steels made with the use of AC (Fig. 3*c* and *d*) have a finer and more homogeneous ferrite-bainite structure, which accounts for their greater strength and toughness compared to steels obtained by controlled rolling and subsequent cooling in air (Fig. 3*a* and *b*).

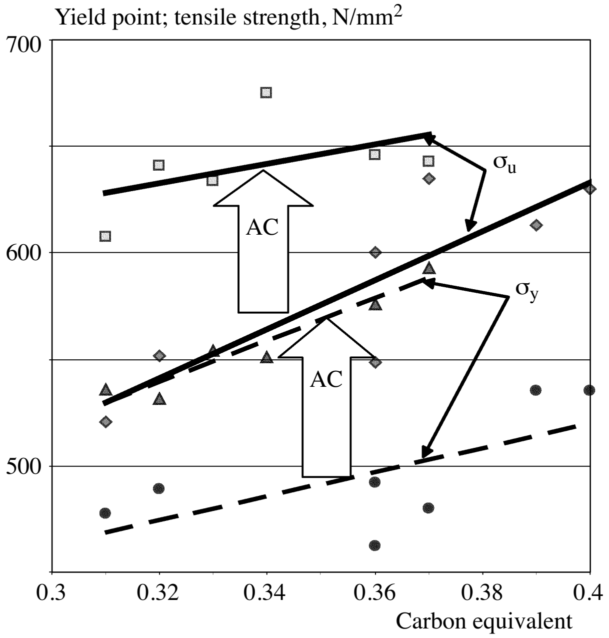


Fig. 5. Effect of accelerated cooling on the strength properties of tube steels.

The difference between the properties of steels with a ferrite-pearlite structure and a ferrite-bainite structure is due to features of their structural components (Fig. 4). The average ferrite grain size after CR is ≈5 μm, while the minimum size is ≈2 μm. At the same time, small quantities of acicular ferrite in ferrite-bainite steels have an effective grain size of about 1 μm when rolling is completed in the lower part of the austenite region and the steel then undergoes AC. The width of individual plates of the ferrite may reach 0.2 μm, which is consistent with the results of previous studies [6]. Dislocation density in bainite is 4–5 times greater (due to the shear formation mechanism) than in ferrite [7], which makes it possible to achieve an additional increase in strength and toughness in steels with a ferrite-bainite structure.

The use of AC allows metallurgists to significantly strengthen steel without additional alloying (Fig. 5). Commercial trials have shown that the use of AC after CR can increase yield point by up to 70 N/mm^2 and tensile strength by up to 90 N/mm^2 without additional alloying of the steel.

In the production of thick plates of tube steels, AC is an effective means of ensuring the required strength in combination with exceptional impact toughness – which is an average of 70–100 J/cm^2 greater than for the same steel made by a technology that involves low-temperature CR. The new steel also has greater cold resistance (a lower ductile-brittle transition temperature) (Fig. 6).

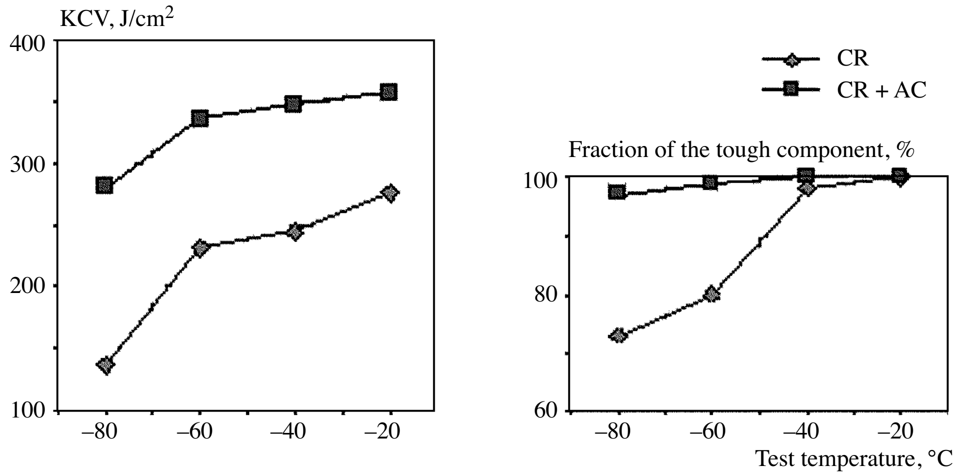
The production of a trial batch of 32-mm-thick plates of steel X70 confirmed the data on the positive effect of AC on impact toughness KCV^{-30}. Comparison of the results of tests of X70 plates made by the CR and CR + AC regimes showed that the use of AC increased impact toughness from 162 J/cm^2 for steel made with low-temperature CR to 308 J/cm^2 for steel made by the CR + AC technology. Here, the minimum value of impact toughness for the CR + AC metal was 200 J/cm^2. To ensure attainment of the necessary strength properties for thicker plates subjected to low-temperature CR, it was necessary to end the rolling operation within the range 670–690°C. The increase in finishing temperature increased the load on the final stand, reduced the productivity of the mill, and led to an unfavorable property ratio. At the same time, deformation was completed at a temperature 100°C higher when the CR + AC regime was used. That made it possible to decrease the load on the stand and increase rolling speed.

Unlike the case when CR steel was used, no sharp reductions in yield point occurred in the production of tubes from plates obtained with the use of AC.

TABLE 2. Mechanical Properties of Steel L450MC (average values)

Mechanical properties of plate			Change in the mechanical properties in the tube conversion		
σ_u, N/mm^2	σ_y, N/mm^2	$\delta_{2''}$, %	σ_u, N/mm^2	σ_y, N/mm^2	$\delta_{2''}$, %
CR:					
601	529	36	5	–21	–2
CR + AC:					
574	505	38	6	–4	1

Note. Flat transverse ASTM specimens 38.1 mm wide. Tube with a diameter of 610 mm and a wall thickness of 12.1 mm.



a *b*

Fig. 6. Impact toughness (*a*) and cold resistance (*b*) of 18.4-mm-thick plates made from a trial heat of steel 05G1MB: CR – controlled rolling ending in the lower part of the $\gamma + \alpha$ region; CR + AC – controlled rolling ending in the γ region or the upper part of the $\gamma + \alpha$ region and followed by accelerated cooling.

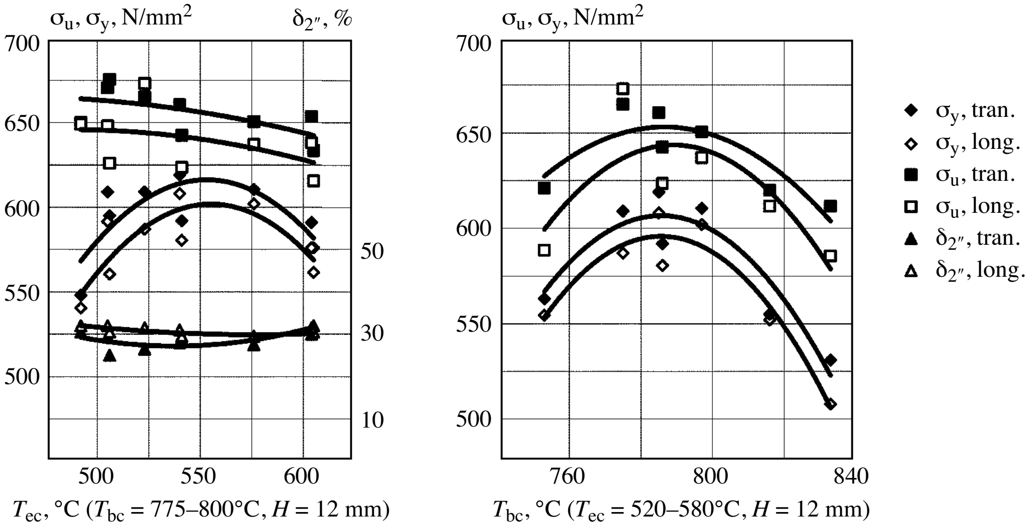
It can be seen from Table 2 that the average decrease in yield point seen in the plate-tube conversion on transverse specimens of steel made with the use of accelerated cooling was more than five times less than the corresponding decrease for the steels after controlled rolling.

Using specimens from an experimental batch of plates of steel 05G1MB (chemical composition shown in Table 1) as an example, we studied the effect of the main AC parameters (the temperatures at the beginning and end of cooling) on the steel's strength properties (Fig. 7*a*). The plates were cooled from the austenite region (T_{bc} = 775–800°C) at a rate of 25–30°C/sec. As we decreased the temperature at the end of the cooling operation (T_{ec}) from 620°C to 490°C, we observed that the tensile strength of the steel continuously increased and elongation continuously decreased. The yield point initially increased, but it began to decrease after it reached a maximum in the region T_{ec} = 500–550°C. This reversal was related to disappearance of the physical yield point on the stress-strain diagram.

The temperature at the beginning of cooling in AC also affects the mechanical properties of plates of steel 05G1MB (Fig. 7*b*). For steel of the given chemical composition, the optimum temperature for the beginning of cooling is in the lower part of the austenite region and the upper part of the $\gamma + \alpha$ region. With a further decrease in T_{bc}, strength decreases due to a decrease in the quantity of bainite in the steel. The lower strength of the metal at high values of T_{bc} (greater than 820°C)

TABLE 3. Impact Toughness and Results of Drop-Weight Tear Tests of Steel 05KhG1NDB Made by Different Regimes

Manufacturing technology	KCV^{-60}, J/cm^2	$DWTT^{-20}$, %
High-temperature CR (HCR)	345–363	100/100
Low-temperature CR (LCR)	278–319	100/100
HCR + accelerated cooling	341–366	100/100
HCR + direct quenching	312–339	100/100



a *b*

Fig. 7. Effect of the finishing temperature (*a*) and the temperature at the beginning of accelerated cooling (*b*) on the mechanical properties of steel 05G1MB (12-mm-thick plates).

is related to the coarser structure and, according to certain studies, to the precipitation of a coarser carbonitride phase when rolling is completed (cooling is begun) in the high-temperature region [7].

We used the 5000 mill to perform an experiment that illustrates the possibilities of AC. Four 22-mm-thick plates of steel 05KhG1NDB were rolled in different regimes. One of the plates was rolled without AC by the HCR regime, with deformation being completed in the lower part of the γ region. Another plate was rolled without AC in the LCR regime, with deformation ending in the $\gamma + \alpha$ region. Two other plates were rolled in the HCR regime, with one then being subjected to accelerated cooling (CR + AC) and the other undergoing direct quenching from the rolling heat (CR + DQ) in the CCU. Figure 8 shows the results of mechanical tests of plates made by different regimes and the requirements on strength properties incorporated into the standard API 5L. Also shown is the level of the properties of steel 05G2NDMB (with a high manganese content and an addition of molybdenum) after CR + AC.

A decrease in the finishing temperature by 90–100°C in the LCR regime compared to the HCR regime made it possible to increase σ_y by 70 N/mm^2 and increase σ_u by 60 N/mm^2. The use of AC has allowed steelmakers to additionally increase yield point by 30 N/mm^2 and increase tensile strength by another 35 N/mm^2. Use of the CR + DQ regime makes it possible to increase the σ_u of steel by another 50 N/mm^2 relative to the level obtained after AC. Thus, by varying the production practice, it has become possible to change the yield point of steel 05KhG1NDB within the range 430–550 N/mm^2 and change this steel's tensile strength within the range 500–650 N/mm^2. Increasing the manganese content of the steel,

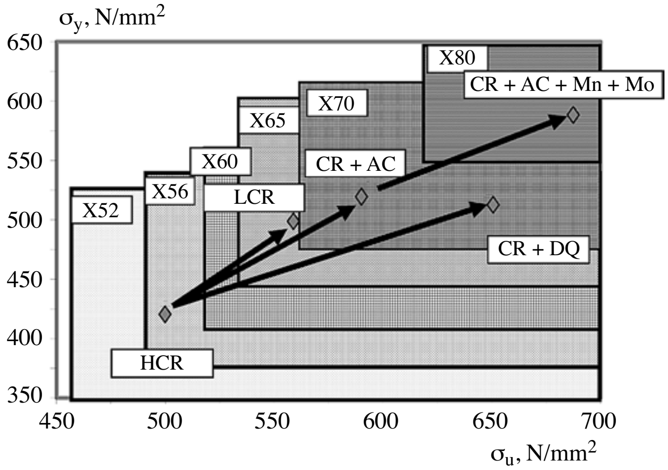


Fig. 8. Mechanical properties of 22-mm-thick plates of a steel of type X65 (05KhG1NDB) made by different regimes, as well as steel 05G2NDMB additionally alloyed with Mn and Mo.

adding molybdenum, and using accelerated cooling bring the properties up to the level corresponding to strength class X80 under the standard API 5L.

It is apparent from Table 3 that plates made by the regimes CR + AC and CR + DQ have nearly the same impact toughness as plates made by high-temperature controlled rolling. For the stronger plates, use of the CR + AC and CR + DQ regimes produces higher values of impact toughness than the use of low-temperature controlled rolling. All the plates demonstrated exceptional properties in drop-weight tear tests.

The results obtained from experiments involving use of the above-described accelerated cooling technology permit the following conclusions:

1. Compared to traditional CR, the use of AC significantly increases the strength properties of products without lowering impact toughness or cold resistance. The use of AC also makes it possible to broadly vary the properties of rolled products having a given chemical composition and thickness.

2. The accelerated cooling of plates makes it possible to replace the ferrite-pearlite structure obtained in the steel after conventional CR by a fine-grained ferrite-bainite structure with a reduced level of striation.

3. Compared to conventional controlled rolling, CR + AC allows steelmakers to achieve a specified level of strength in steel while lowering its content of carbon and alloying elements. This leads to an improvement in the steel's weldability.

4. The use of AC reduces the loads on the mill because of the higher finishing temperature used compared to conventional CR. The use of AC also makes it possible to increase rolling speed by shortening the pauses made for cooling of the slab.

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