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POLYGONIZING CONTROLLED ROLLING OF SLABS FOR CIVIL ENGINEERING

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At present, hot rolling is the most common process used in working slabs of low-carbon steels smelted with no carbide-forming additions. Although this process ensures relatively moderate strength characteristics in plates, such steels possess good weldability and plasticity at relatively low costs [1–6].

Any strengthening is connected with saturation of metals with numerous faults which in its turn results in a necessity of application of complicated processes and high production costs. For the most part, rolled product strengthening by various methods of thermomechanical treatment is economically more feasible than expensive alloying [1–6]. Specifically, an example of such leading-edge processes is controlled rolling used in making plates for the production of large-diameter pipes used in the construction of Arctic oil and gas pipelines.

This R&D work objective was improvement of mechanical properties of the steel plates produced by controlled rolling. The main problems consisted in retention of polygonized structure of hot-deformed austenite and creation of conditions for its inheritance with proeutectoid ferrite precipitated before the finish rolling step.

Temperature and deformation conditions of the controlled rolling are usually realized as follows: heating slabs in a continuous furnace to temperatures between 1100 °C and 1200 °C, homogenizing holding during 4 to 6 hours, rough rolling completed at 980-1100 °C, cooling down to 720-820 °C, finish rolling to a required thickness and slow cooling to room temperature (see Figure 1, conventional schedule). This process has its advantages but it has certain disadvantages as well.

Firstly, it is the necessity of an additional alloying to suppress austenite grain growth through the formation of particles of high-temperature carbonitrides (otherwise, the plate impact toughness can degrade) [1–6].

Secondly, this process has only proved itself well in the production of plates not thicker than 20 mm as the thicker is the rolled product the worse are tensile strength and impact toughness because of smaller total reductions.

Thirdly, it is necessary that temperature-deformation parameters of the controlled rolling process were optimized for each rolling mill and individual plate rolling schedules were corrected depending on the planned service conditions of the rolled product.

This R&D work has resulted in a new schedule for the process of polygonizing controlled rolling featuring a higher deformation fractioning in the rough stand with the final rolling temperature being 10-30 °C lower than Ac_3 temperature and a shorter holding of the intermediate product at the bypass table to prevent recrystallization and maintain the rolling rate. When the temperature of start of working in the finish stand is achieved, rolling is carried out by the design schedule and the rolled product is cooled in a way ensuring retaining of subgrain boundaries in ferrite and escaping formation of special boundaries in the middle layers (see Figure 1, the proposed schedule).

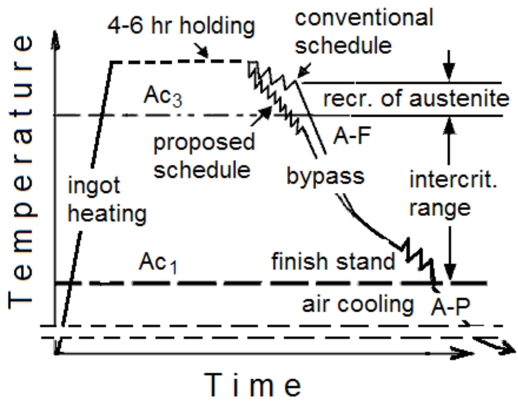


Figure 1. Conventional and proposed controlled rolling schedules.

The larger number of unit cycles at a constant total deformation ratio favors formation of a more developed polygonal austenite structure and the longer deformation time at a lower temperature at the end of rough rolling makes austenite subgrains fixed. The resulting deformed austenite structure saturated with subgrain boundaries is favorable for achievement of homogeneity of the finite ferrite structure [7].

Temperature and deformation conditions of the proposed schedule imply the temperature at the end of rolling in the rough stand to be within a range where there is no recrystallization which is a prerequisite for the formation of fine ferrite grains during cooling in the intercritical temperature range. But if 22 mm and thicker plates are rolled, a possibility of formation of both recrystallized and non-recrystallized regions in the plate body exists.

To prevent recrystallization processes in austenite, the temperature at the end of rough rolling was shifted somewhat below the critical point Ac_3 which along with the reduced time of staying at the bypass table creates conditions in which the deformed austenite is not recrystallized or rerystallized to a minute degree.

The polygonized austenite structure preserved in this way contains a large number of additional sites of heterogeneous nucleation of ferrite (polygonal boundaries, their interfaces and nodes), cf. Figures 2*a* and 2*b*. Reduction of the temperature at the end of rough rolling to the values below Ac_3 results in a formation of fine ferrite nuclei fixing the polygonized substructure and preventing recrystallization and austenite grain growth (Figure 2*d-f*).

Structure investigations of quenched samples have shown that cooling down to the temperatures below point Ac_3 gives rise to nucleation of new crystals of hypoeutectoid ferrite not only at large-angle boundaries but at polygonal ones as well (see Figures 2*c, f*). In particular, Figure 2*f* shows that the internal volumes of the former austenite grains (their boundaries are seen due to the continuous ferrite fringes) are covered with ferrite nuclei of an average size 0.5-1.5 µm.

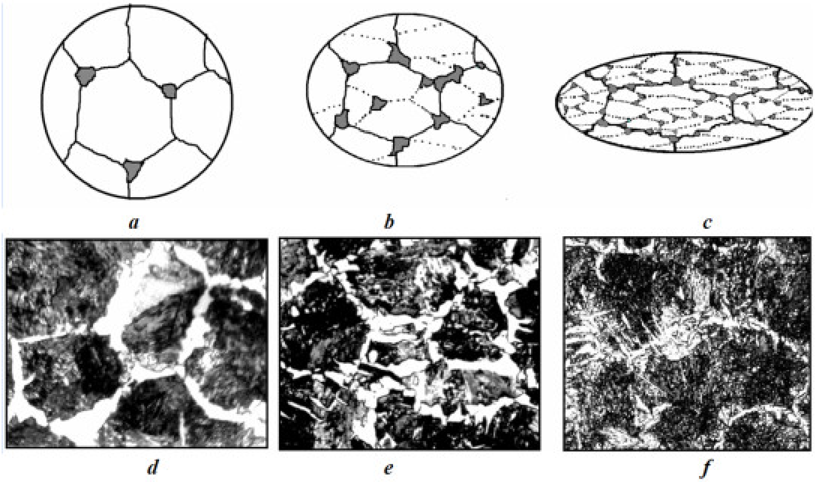


Figure 2. Sequential stages of α-crystal nucleation at polygon boundaries at temperatures reduced down to the values below point Ac_3; *d – f*: precipitation of hypoeutectoid ferrite in steels which underwent austenite decomposition after cooling in air, ×800: *d*: from a single heating by 1050 °C, *e*: after 16% hot reduction at 1000 °C; *f*: after 36% hot reduction at 1000 °C.

In case of very small or zero temperature drops after rough rolling, parameters of the polygonal substructure develop in a reverse order: polygon sizes get smaller and the mean angle of orientation disorder decreases. Furthermore, the ability of polygonal boundaries to serve as the sites of ferrite crystal nucleation decreases.

Additionally, low-angle polygonal boundaries are formed in fine ferrite grains during finish rolling which results in refining of the final structure and a simultaneous upgrade of strength and plasticity of the finished plates.

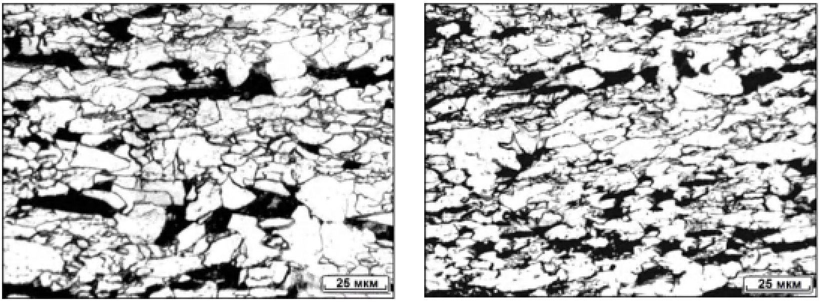
Delivery batch tests of 40 mm thick plates rolled by the proposed schedule have demonstrated simultaneous improvement of tensile strength and stabilization of viscosity as compared to the plates rolled by the conventional technology: tensile strength in Z direction being 1.5-2 times higher (230 to 480 MPa).

It is important that specification of properties in *Z* direction (direction of the rolled product thickness) has to be an integral part of engineering requirements to steels as the steel plasticity can fall abruptly because of an effect of tangential tensile forces, especially forces normal to the plate plane.

Percent narrowing (ψ_Z) is the parameter most sensitive to the variation of all mechanical characteristics of thick plates in Z direction.

Actual percent narrowing in Z direction in the plates produced by the proposed schedule is 20-25 % higher than that in the plates produced by the conventional technology and almost 2 times higher than it is required by the standards for *Z 35* quality rating.

Microstructure of 22 mm thick plates of microalloyed low-carbon steel 10G2FB rolled by the conventional technology and using the proposed schedule is shown in Figures 3*a, b*.



a ***b***

Figure 3. Structure of 22 mm thick plates of low-carbon steel 10G2FB rolled by conventional technology (*a*) and with the use of the proposed schedule (*b*)

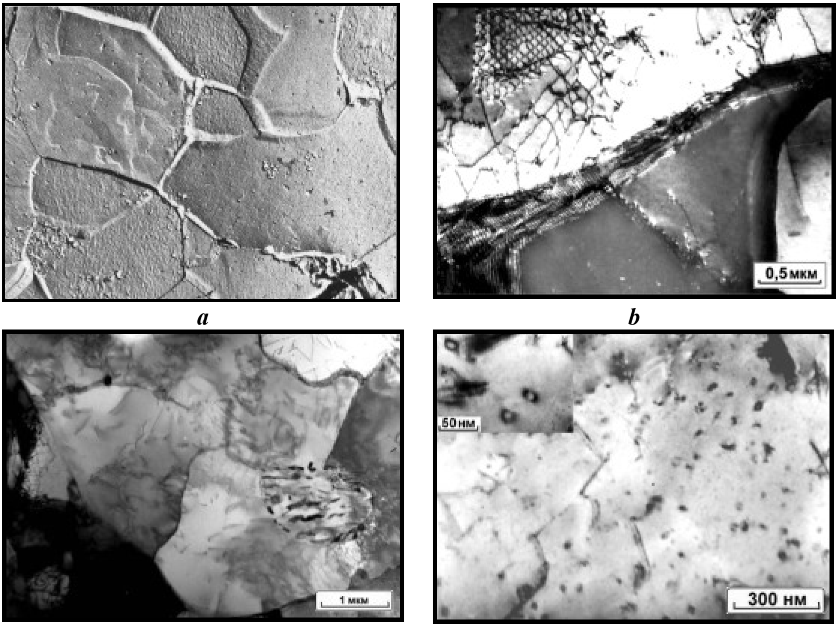
Visual estimate shows that the structure in the plates rolled by the proposed schedule is more dispersed than that in the plates rolled by the conventional technology. Pearlite striation is less pronounced than in case of an ordinary hot-worked metal.

Photographs of shadow-cast replica show that the large-angle and subgrain boundaries interact with their energies and the subgrains can be 0.5 μm in diameter and somewhat elongated in the rolling direction (Figure 4*a*).

Images of thin foils prepared from the metal rolled by the experimental schedule reveal dislocation arrangement of subgrain boundaries (Figure 4*b*) and networks formed by several dislocation families. They contain mostly hexagonal cells and sometimes rectangular ones. Individual dislocations are discernable if the distance between them is 3 to 5 nm, otherwise they merge into a strip with a contrast typical for the large-angle boundaries although their mean off-orientation angle does not exceed 3-6 degrees.

Pearlite colonies demonstrate the results of high-temperature effect, viz. cementite plates and bands suffer partial coagulation changes and a part of the plates divide into a number of smaller plates having fissures and holes. Cementite bands part into short sections with evidently rounded edges. Some of them take a disk or an ellipsoid shape (Figure 4*c*). Such changes in the pearlite component promote growth of plasticity and decrease in strength of the finished plates.

However, a different process is simultaneously taking place. Contrary to the first one, it increases strength and decreases plasticity: precipitation of excess phases. In the ferrite component, a relatively high density of disperse particles is observed. These particles have contrast typical for carbides of (*Nb, V*)*C* type [8, 9]. Figure 4*d* shows their uniform distribution in the entire internal volume of the ferrite grains. Some dislocations are conjugated with carbonitride particles restraining their displacement at critical loads, increasing start stresses and strengthening the metal in this way.



a ***b*** ***c*** ***d***

Figure 4. Thin structure in 22 mm thick plates of low-carbon steel 10G2FB rolled by the experimental schedule: *a, b, c* – electron microscope image of subgrain (polygonal) boundaries; *d* – dispersed carbides of (Nb, V)C type in ferrite

The high-magnification image patch in the upper left corner of Figure 4*d* shows a characteristic 20 mm diameter ring-shaped contrast formed by diffracting electrons. Such contrast reveals itself due to the elastic stresses arising around the carbonitride particles [5]. These particles themselves have smaller sizes, not larger than 3-7 nm. Their diameter is smaller than the light spots in the centre of the ring-shaped images.

Based on the foregoing, the following conclusions can be drawn:

– the proposed hot plate rolling schedule is based on a creation of a polygonized austenite structure being formed during hot working and forcibly kept stable up to the temperatures of the upper part of the intercritical range. The further multiple nucleation of preuetectoid ferrite at both large-angle and polygonal boundaries improves dispersity of ferrite grains in the metal entering the finish rolling stand, therefore a more dispersed final ferrite structure is formed in the finished plates and accordingly better mechanical properties are achieved;

– the proposed plate rolling schedule can be implemented with no capital investments at the existing equipment of Ukrainian metallurgical works;

– the proposed plate rolling schedule promotes gain in and stabilization of plasticity and viscosity at sub-zero temperatures and reduction of plate rejections over unsatisfactory mechanical properties;

– the results of comprehensive studies allow to recommend plates of steel grades 10G2FB and S355j2 for their use as a material for the production of large-diameter oil and gas line pipes and construction of frames for high-rise buildings and large-span floors.

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