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New Inline Process for Thermomechanical Treatment of Steel Bars

Integration of the process of radial-displacement rolling stage into the Thermomechanical Treatment (TMT) allows to provide a flexible and economic production of a broad dimensional range of steel bars with high geometric tolerance and an optimum use of the potentials of material properties. The high degrees of deformation achieved per pass during the radial-displacement rolling stage results in a fine grain (subgrain) structure with improved mechanical properties. The paper introduces the new system design for thermomechanical treatment and, furthermore, highlights the first results of the tests performed on heat treated steel. Compared to conventionally tempered material, remarkable increases in strength are possible while maintaining the same toughness.

Key words: *radial-displacement rolling, thermomechanical treatment, steel bars, mechanical properties, grain structure.*

Introduction

Despite remarkable success in the development of new and alternative materials, steels will continue to play a key role among constructional materials as an environmentally friendly and recyclable material. In many areas where great forces and torques have to be transmitted, there are still no alternatives available to steel. The market requirements for weight and cost reductions in steel products are the driving forces for the continuous development of materials and the search for existing property reserves. High-strength steels are used by the automotive industry in their drive and steering technology that meet the high demands for geometric tolerances and mechanical properties.

Advanced alloy and processing concepts lead to high-strength steels design, and optimal combination of deformation and heat treatment stages in one technological process can be utilized fully with the help of TMT realization.

1. Grain refinement through thermomechanical treatment

Thermomechanical treatment is a proven method to improve properties, and it is used, for example, in production of steel plates or in continuous wire and steel bar mills.

A large share of steel products are produced with the use of heat treatment, and the technical concept of these facilities has not been changed significantly during the last 50 years.

By integrating a deformation stage with a high degree of independent forming, the HDQT (High Deformation Quenching and Tempering) process changes the conventional steel bar heat treatment technology into a thermo-mechanical treatment (see Fig. 1).

This combination of mechanical forming and defined heat conduction prompts recrystallization processes in the rolling blanks that are temperature-, deformation- and time-dependent. The resulting fine-grain structure leads to improved material properties. The combination of high strength/toughness will be of particular interest to the automotive industry without having to fall back on expensive alloy concepts.

If it is possible in the future to obtain a fine grained microstructure by means of the thermomechanical treatment, incredible reserves of the construction material steel could be revealed.

2. Technical concept of the HDQT-process

While the steel bar that is heated to the austenite forming temperature is tempered immediately (see Fig. 2), the HDQT system layout provides integration of a radial-displacement rolling stand into the technological line of a single steel bar heat treatment facility. After the induction heating, the steel bar passes through a conventionally heated intermediate roller table. The deformation in the radial-displacement rolling stand to a predefined final diameter is done immediately after the steel bar exits the reheating furnace. During the forming process, recrystallization is induced in relation to the stretching rate and the temperature pattern that are used specifically for the grain size and crystalline structure. After completing the deformation, the steel bar passes through the accelerate cooling section. In analogy to the conventional system, the structure of the traversing steel bar is subsequently tempered in an inductive heating facility and then air cooled.

The complexity of the interaction of the various technological parameters requires a sophisticated control of the entire facility. The technical concept provides computer controlled automatic operation from the heating of the steel bar in the inductive facility, to control the rolling process, and up to the cooling in the intensive cooling section followed by subsequent tempering process.

3. The High Deformation Radial-Displacement Cross Rolling stand

The desired thermomechanical grain refinement effects are obtained only by means of an extensive overcritical plastic deformation required for the start of recrystallization processes. Therefore, the stand must be able to apply very high reduction rates in one step. When radial-displacement rolling with the High Deformation Radial-Displacement Cross Rolling (HDCR) stand, the deformation is realized with 3

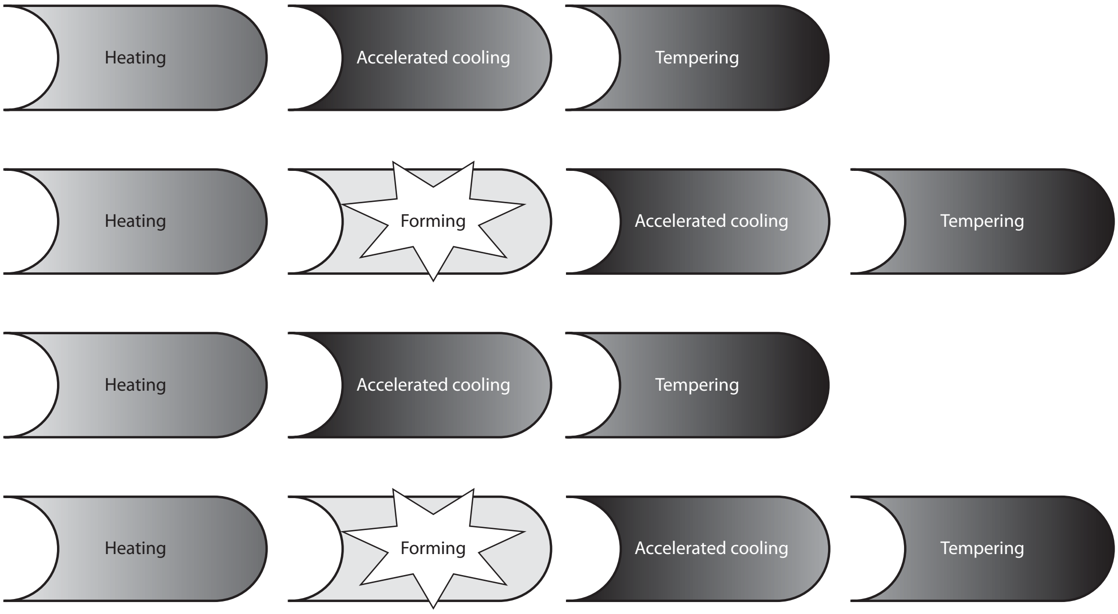

Fig. 1. Integration of a high reduction stage into the steel bar heat treatment technology

cone-shaped rolls that are offset by 120°. One of the specific features of radial-displacement rolling is that the deformation takes place over very small contact surfaces between roll and rolling blank (Fig. 3).

With this process, high reductions are applied locally in the contact area with relative low rolling forces. Due to the incremental deformation, extremely high reduction rates are realized in one passage with the 3-roll cross-rolling mill (see Fig. 4).

The dimensional flexibility of the rolling process is a major advantage of this concept. Thanks to an axially adjustable roll adjustment, it is possible to roll different rolling piece diameters within a dimensional range predefined by the cut, without having to reset the stand. In order to ensure high limits of diameter accuracy over the entire length of the steel bar, the rolling mill is equipped with an automatic gauge control system and an on-line roll adjustment under load. In addition, the facility is provided with a temperature guiding system.

Diameter tolerances and ovalities of < 0.5 % over the entire length of the steel bar are possible with the HDCR stand.

4. Kinematics of radial-displacement rolling

The kinematics of helical movement of surface elements in metal lying out of the deformation zone is described with total velocity $V_{\beta 0(1)}$, its axial $V_{X0(1)}$ and circumferential $V_{\varphi 0(1)}$ components and the angle of flow helical line $\beta_{0(1)}$

The total velocity of element movement on the billet surface is vectorially combined of axial and circumferential components, in which case its absolute magnitude is equal to

$$V_{\beta 0(1)} = \sqrt{V^2_{x0(1)} + V^2_{\varphi 0(1)}} \qquad (1)$$

The kinematic metal flow pattern can be represented as flow helical trajectory and helical lines. The angle of flow

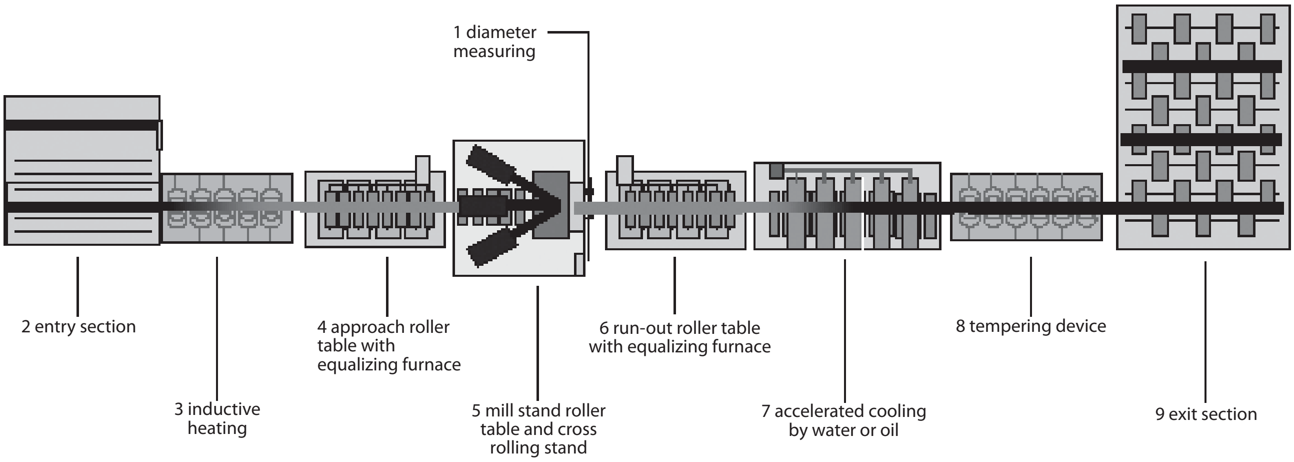

Fig. 2. System layout of High Deformation Quenching and Tempering (HDQT) treatment facility

Fig. 3. Geometry of the roll arrangement with the HDCR stand

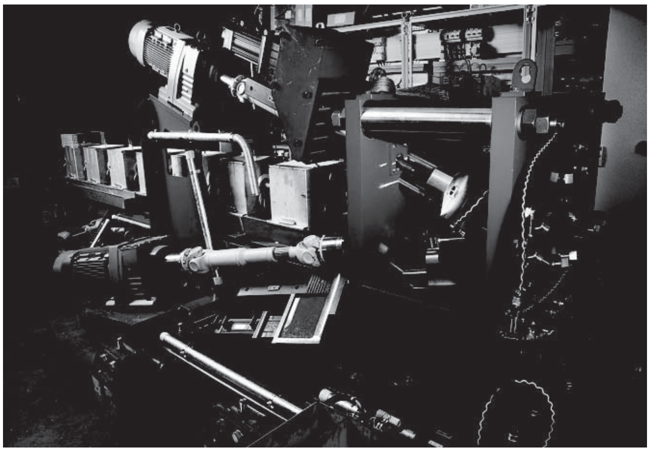

Fig. 4. The HDCR stand

helical line $\beta_{0(1)}$ (total velocity vector inclination angle to the plane of cross-section) is determined geometrically with a ratio of axial and rotational components:

$$tg\beta_{0(1)} = V_{x0(1)} / V_{\varphi(0)} \tag{2}$$

Index «0» corresponds to initial billet of d_0 in diameter; index «1» – to resulting rolled feed of d_1 in diameter. The reduction in rolling amounts to $\mu = (d_0/d_1)^2$.

The kinematic result of radial-displacement rolling can be measured with the kinematic reduction μ_V representing the ratio of total final metal velocity to the initial one.

$$\mu_V = V_{\beta 1} / V_{\beta 0} = \mu \sqrt{\frac{tg^2\beta_1 + 1}{tg^2\beta_1 + \mu^3}} \tag{3}$$

In view of the stationary state of the process, μ_V shows the length change of the helical trajectory as a result of reduction as well. For the process of lengthwise rolling and stationary pressing stage, the ratio of total velocities is equal to the mill length to billet length ratio, i.e. it is equal to the reduction.

Equation (1) and the diagram show the metal element movement velocity variation to depend not only on the change in overall billet dimensions (reduction μ), as is the case in lengthwise rolling, but on the internal geometry of the helical trajectory of metal movement, i.e. on β-factor.

The angle of movement trajectory ascent decreases permanently from minimum β_1 on the billet surface to 90° on the axis. Accordingly, the trajectory-velocity result of rolling varies as well acquiring the character of the specific non-uniformity. The outer layers undergo metal flow slowdown and the central layers do acceleration. There is neutral cylindrical surface in the bulk of a billet, the points on the surface of which sustain the absolute velocity and change no length of their trajectories. In case of stationary flow of incompressible material, the decrease of outer layer particle travel velocity is necessitated with formation of expanding flow tubes (see Fig. 5).

Every small trajectory-oriented element of the outer layer is subject to compression deformation along the billet radius (Fig. 6), compression deformation in the line of movement (along the helical trajectory), and consequently tensile deformation across the helical trajectory.

In case of stationary flow of incompressible material, the decrease of outer layer particle movement velocity is necessitated with formation of expandable metal flow tubes (diffusers) (Fig. 6, a). The elements of metal structure, which are subject to expandable flow with two-sided upset (along the trajectory and the radius), assume the shape of isolated isotropic particles of high dispersion ability.

Particle velocity in the axial fiber and its length increase proportionally to the reduction in the manner as during lengthwise rolling. The section of central flow tubes decreases. Metal structure processing proceeds by type of lengthwise rolling in the grooves with many-sided reduction or pressing. The elements of metal structure are stretched and thinned with formation of structural banded orientation .

The outer layer retardation and inner layer acceleration create in the deformation zone the effect of three-dimensional macro-shear intensifying the structural fine crushing.

Thus, the method allows us to produce elongated rolled products with isotropic fine-dispersed, down to submicrocrystalline and nano-structural, outer layer and fibrous inner layer. Such a structural state can be classified as naturally composite layered one. Inasmuch as the outer layer performs often the main operating function, such metal structure is also named as functionally gradient one.

Formation of locally expanding metal flow tubes (diffusers) in the integrally tapering (confuser) deformation zone represents one of the fundamental features of the radial-displacement rolling with controlled trajectories. The advantages of this method are stipulated by the availability of namely this zone that is lacking in other stationary processes

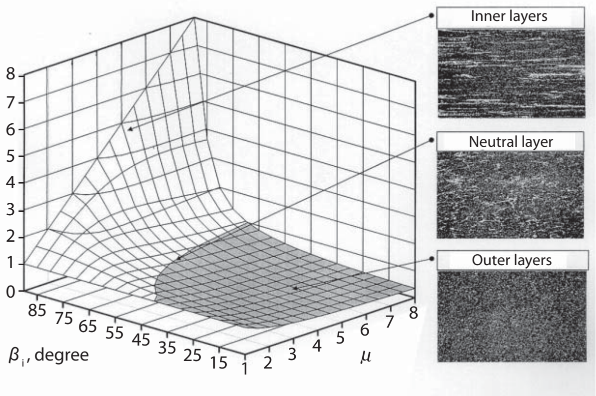

Fig. 5. The effect of trajectory ascent angle β_1 and reduction μ on trajectory reduction μ_V and the kind of metal structure processing

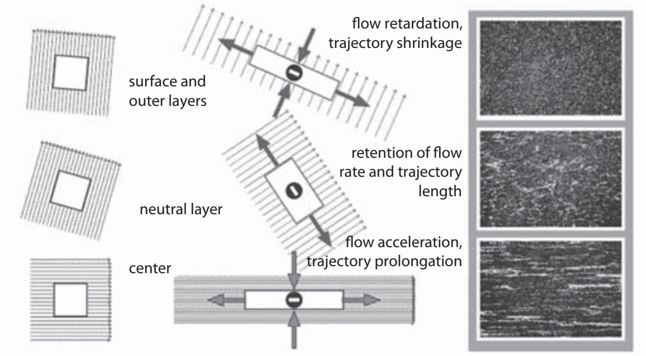

Fig. 6. Forming of trajectory-oriented elements during radial-displacement rolling and the kind of metal structure processing

of producing elongated rods, such as lengthwise rolling, pressing, and even screw rolling of pipes. Such a method of metal outflow diagram is lacking in the mechanical-property test techniques. The experiments have proved the opportunity of producing rods with submicrocrystalline and nanostructural state of metal by means of trajectory-controlled radial-displacement rolling.

5. Material aspects and utilizing effects

With the HDQT process, structural effects with regard to grain refinement and subsequent microstructural transformation are strategically used to optimize properties with the help of a defined dimensional change and temperature guidance (see Fig. 7). Different mechanisms for the grain refinement may be used. On the one hand, it is possible to activate dynamic recrystallization processes in the range above the recrystallization temperature (1) after surpassing a critical dimensional change. After exiting the stand, an equiaxial fine-grained dynamically recrystallized structure is transformed in this case. A deformation below the recrystallization temperature (2) but still above A_{c3}, will lead to the formation of stretched austenite grains that transform into a fine acicular martensite or austempered structure. At this point, formation of a distinct fragmented substructure for the grain refinement becomes apparent.

An additional beneficial effect is based on the torsional forming pattern (see Fig. 8) of radial-displacement rolling that as the result of the forming process causes a spiral crystalline structure (texture) respectively stranding of the structure, and therefore the rolled products will exhibit special properties during torsional loads. Furthermore, the development of a very fine-grained structure can be observed particularly near the surface.

Last year, two HDQT test facilities were setup and put into operation.

The first tests have been done on spring steel, Type 54SiCr6, and on heat treatable steel 42CrMo4.

The task for the spring steel 54SiCr6 was to adjust to very high strength values (above 2000 MPa) while maintaining its toughness characteristics. Therefore, the rolling parameters of the HDQT technology were designed in such a way that as a result of the deformation, a dynamically recrystallized grain is transformed into a martensitic structure. During the forming process, the medium grain size was reduced to ASTM 10-11 (see Fig. 9) compared to the conventional heat treatment of ASTM 8-9. With this process, it was possible to set strength values of up to 2200 MPa with the same toughness characteristics as with conventionally heat-treated materials.

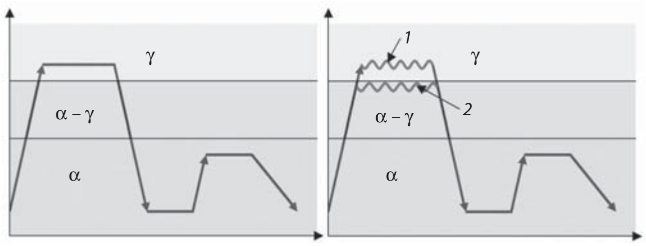

Fig. 7. Conventional and HDQT heat treatment

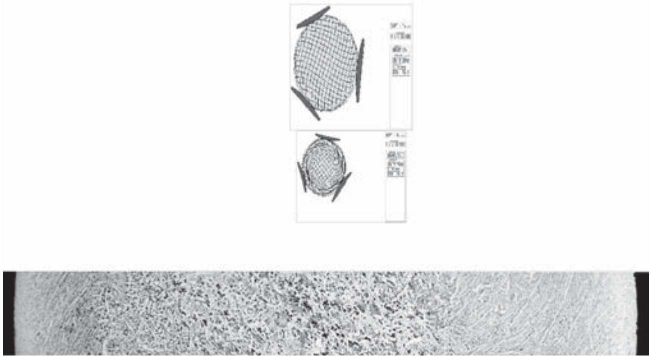

Fig. 8. Ferritic-pearlitic structure, a torsional-forming pattern with stranding of the structures and very fine-grained structure near the surface. First results from radial-displacement rolling tests

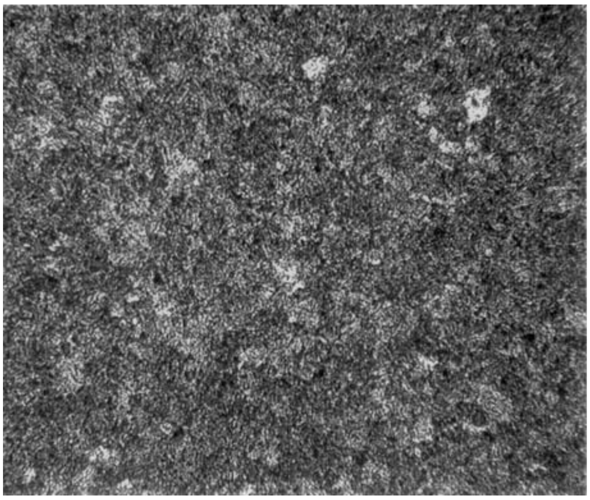

Fig. 9. Structure of 54SiCr6 steel, diam. 12.5 mm, φ = 0.6, grain size ASTM 10-11 (scale 220:1), treated in the HDQT

The test results show that heightening of strength in the range of approx. 10-15% can be achieved on spring steel of type 54SiCr6 by integrating the deformation step into the heat treatment line.

Different variants were examined during additional tests to reduce the grain size of heat treatable steel 42CrMo4. The reductions and temperatures were varied and its influences on the development of grain sizes examined. The rolling results showed that grain sizes in the range of ASTM 13 can be obtained.

Conclusions and outlook

The integration of the radial-displacement rolling step into the heat-treatment technology provides an optimized utilization of the potential of material properties by strategically adjusting the grain size.

In the HDQT process, different combinations of temperature guiding and reductions values can be realized to obtain the specific crystalline structure.

First tests on spring steel 54SiCr6 using the HDQT process resulted the heightening of tensile strength in the range of appr. 10-15 % while maintaining the same strength characteristics compared to conventional processes.

Diameter tolerances and ovalities of < 0.5 % over the entire length of the steel bar are possible with the HDCR stand.

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