Manufacturing Technologies and Applications
MATECA

Influence Degree and Scheme of Hot Reduction on Properties of the Carbon Steel

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ABSTRACT

This study examines the impact of hot plastic deformation at 1250°C on austenite grain refinement and mechanical properties in carbon steel for railway wheels. The deformation strategies—single-step versus two-step compression with equivalent total strain—were compared to assess their effects on austenitic microstructure and material performance. Austenite grain size was quantified via light microscopy and quantitative structural analysis, while mechanical properties were evaluated using a universal tensile testing machine, following the ASTM E8 standard, at room temperature. (strain rate: 10^{-3} s^{-1}) Results reveal that austenite grain refinement occurs proportionally with increasing deformation, irrespective of the compression scheme. However, the deformation strategy significantly influences strength and ductility at lower strain levels. Specifically, two-stage compression at smaller strains (e.g., below 60% total deformation) enhances ultimate tensile strength by up to 10% and ductility by 30–40% compared to single-step compression. This improvement is attributed to partial retention of austenite substructure during interrupted deformation, which alters dynamic recrystallization kinetics and promotes dislocation redistribution. The differential effect diminishes progressively with higher strain levels, and beyond 60% deformation, both schemes yield equivalent grain sizes and mechanical properties due to complete recrystallization and microstructural homogenization. These findings underscore the critical role of deformation sequencing in optimizing mechanical performance during thermomechanical processing, particularly for applications requiring tailored strength-ductility balances in high-temperature-formed carbon steels.

Keywords: *Austenite, Grain size, Hot plastic deformation, Carbon steel, Strength*

Sıcak Haddelemenin Karbon Çeliğinin Özellikleri Üzerine Etki Derecesi ve Mekanizması

ÖZET

Bu çalışma, demiryolu tekerleklerinde kullanılan karbon çeliğinde 1250 °C'de uygulanan sıcak plastik deformasyonun, östenit tane incelmesi ve mekanik özellikler üzerindeki etkisini incelemektedir. Aynı toplam deformasyon oranına sahip tek aşamalı ve iki aşamalı sıkıştırma stratejileri, östenitik mikro yapı ve malzeme performansı üzerindeki etkilerini değerlendirmek amacıyla karşılaştırılmıştır. Östenit tane boyutu, ışık mikroskobu ve kantitatif yapısal analiz yöntemleri kullanılarak nicelendirildi; mekanik özellikler ise oda sıcaklığında (deformasyon hızı: 10^{-3} s^{-1}) gerçekleştirilen çekme testleriyle değerlendirildi. Elde edilen sonuçlar, sıkıştırma şemasından bağımsız olarak deformasyon arttıkça östenit tane incelmesinin orantılı olarak gerçekleştiğini göstermektedir. Bununla birlikte, deformasyon stratejisi daha düşük deformasyon seviyelerinde mukavemet ve süneklik üzerinde belirgin bir etki göstermektedir. Özellikle, toplam deformasyonun %60'ın altında kalan durumlarda uygulanan iki aşamalı sıkıştırma, tek aşamalı sıkıştırmaya kıyasla çekme mukavemetini %10'a kadar, sünekliği ise %30–40 oranında artırmaktadır. Bu iyileşme, kesintili deformasyon sırasında östenit alt yapısının kısmi korunmasına bağlı olup, bu durum dinamik yeniden kristalleşme kinetiğini değiştirerek dislokasyon yeniden dağılımını teşvik etmektedir. Deformasyon seviyesi arttıkça aradaki fark kademeli olarak azalmış ve %60'ın üzerindeki deformasyonlarda tam yeniden kristalleşme ve mikro yapısal homojenleşme neticesinde her iki sıkıştırma yöntemi de eşdeğer tane boyutları ve mekanik özellikler sergilemiştir. Bu bulgular, termomekanik işlem sırasında mekanik performansın optimize edilmesinde deformasyon sıralamasının kritik rolünü, özellikle yüksek sıcaklıkta şekillendirilen karbon çeliklerinde istenen mukavemet-süneklik dengesinin sağlanmasında vurgulamaktadır.

Anahtar Kelimeler*: Östenit, Tane boyutu, Sıcak plastik deformasyon, Karbon çeliği, Mukavemet*

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Received 06.02.2025; Revised 26.04.2025; Accepted 26.04.2025
https://doi.org/10.52795/mateca.1634663
To cite this article: I. A. Vakulenko, S. Plitchenko, A. F. Yılmaz, Influence Degree and Scheme of Hot Reduction on Properties of the Carbon Steel, Manufacturing Technologies and Applications, 6(1), (2025), 150-156.

1. INTRODUCTION

At a constant rate of hot reduction carbon steel, the ratio of temperature and degree of plastic deformation determines balance at development of hardening and softening processes. The simultaneous influence of several process parameters during hot reduction of carbon steel significantly complicates development of measures to stabilize structure of austenite. By analogy with the heating of cold-formed metal, structural changes after hot plastic deformation develop in a similar sequence. The effect of austenite softening, based on the reduction accumulated defects of the crystal structure, depends on their redistribution to a certain extent. The movement of grain boundaries with large angles of disorientation during collective recrystallization allows not only to reduce density of dislocations[1], but also to lead to a complete replacement crystal geometric characteristic of the deformed metal [2,3].

Another process softening of the deformed metal is based on a change at substructure from the development of dislocation recombination [4]. In general, the effect of micro- and substructure elements on a set of properties can be divided into components from the state of solid solution, accumulated density of dislocations, structure and shape of boundaries or subboundaries, etc.[5–7]. The relationship between by increased of defects in the crystalline structure, their annihilation, and distribution in austenite allows one to control at structure formation of the hot-rolled products.

The purpose of the study is evaluation by influence hot deformation scheme of the carbon steel on its structure and properties.

2. MATERIAL AND METHOD

The material for the research was carbon steel from fragments of the all-rolled railway wheel, with a carbon concentration of 0.61 % and other chemical elements in accordance with the requirements of regulatory documentation for wheels. Samples for the analysis of structural changes during hot compression had a shape of cylinders with a diameter of 20 mm and a height of 40 mm [8]. Heating the hot deformation temperature (ε) (1240 °C) was carried out in electric furnaces, preventing oxidation and decarburization of the metal surface. The blanks were deformed by 10-60 %, at a deformation rate of about 10^{-2} s^{-1}. After completion of hot deformation, the blanks were cooled in air. The structure of the metal was examined under a light microscope. To identify austenite grain, steel after hot deformation etched in a sodium picrate solution [9], and structure of the pearlite colony, it was etched in 4 % HNO3 in ethanol. Austenite grain size (dA) was determined using quantitative metallography in accordance with the ASTM E112 standard. [10]. Mechanical properties (yield strength (σy) and tensile strength (σs), relative elongation (δ) and reduction in area (ψ)) were determined from analysis of tensile curves at room temperature and a strain rate of 10^{-3} s^{-1}.

3. EXPERIMENT AND OPTIMIZATION RESULTS

In general, the structure austenite at process of hot plastic deformation carbon steel is determined by the heating temperature, speed and magnitude of compression [11]. Considering that a certain sequence operations of compression work piece, for obtaining individual elements of a railway wheel, is ensured by maintaining a practically identical deformation rate, its contribution to the change grain size of austenite can be considered constant in value.

The temperature ranges for the development of recrystallization, for most metallic materials, is determined by the ratio:

$$T_A \sim K \cdot T_B \tag{1}$$

where T_A is a temperature of the process under study, K is a coefficient, T_B is a solidus temperature, on the phase diagram [3].

At K = 0.4-0.6, the grains after recrystallization have a predominantly elongated shape, and at $K > 0.6$ they are close to equiaxed. Considering the wheel blank deformation temperature about at 1240-1250 °C and $K > 0.8$, the austenite grains correspond to a convex polygon.

Depending conditions of hot plastic deformation, formation substructure can have a qualitatively different effect on the austenite structure. At case of small reductions, when the dislocation density is relatively small, the rearrangement of dislocations during formation of subboundaries can be carried out without significant annihilation [1,2].

The movement of dislocations from the internal volumes of grains to the periphery, against the background of a gradual increase at angle disorientation of subboundaries, will be partially compensated for the inevitable effect of a decrease at dislocation density. Thus, at temperatures significantly below hot reduction temperature of the wheel blank, at relatively low degrees of deformation, it is possible to observe development of austenite recrystallization by different mechanisms (Fig. 1, *a*, *b*).

On other hand, the preservation texture of hot-deformed metal can contribute to growth share of pearlite colonies with a violation of the regular structure (Fig. 1, *c*-*f*). If we take the average size of the structure section, which is separated by a layer of structurally free ferrite (Fig. 1, *c*-*f*) as d_A, the obtained value will not take into account preserved a part of subboundaries of hot-deformed austenite.

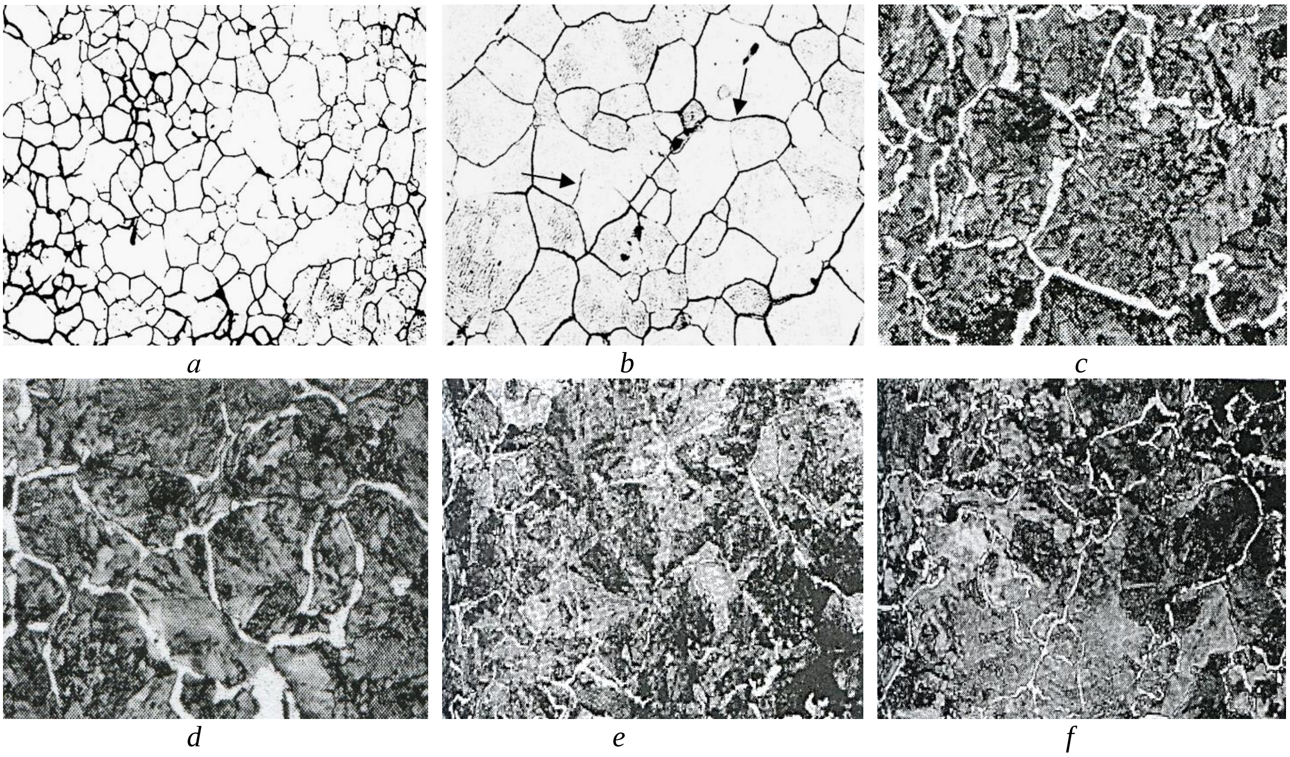

Figure 1. Influence degree of hot reduction (*a*, *b*, *c* – 10; *d* – 18; *e* – 40, *f* – 60 %) at temperature of 950 °C (*a*), 1100 °C (*b*), 1240 °C (*c*-*f*) [7] on the structure of steel with 0.6 % C. Magnification: *a*, *b*, *e*, *f* – 100; *c*, *d* – 150

As a result, the nature influence austenite grain size on the complex properties of the hot-rolled metal will be distorted. This is confirmed by the ambiguous correlation between sizes of the austenite grain and pearlite colony [8,12–14]. Thus, the possible error in estimating d_A, after various degrees of hot deformation, can be taken as constant, not having a qualitative effect on size of the austenite grain. Compared with normal grain boundaries, the boundaries between fragments, in addition to the intermediate position in disorientation between normal boundaries and subboundaries [15], can differ in shape and structure. Considering with an increase in d_A the probability of the decay uniform distribution of dislocations into periodic structures increases [16], fragmentation in a large grain should begin earlier than in a small one and with a smaller number of accumulated dislocations.

Based on this, for a constant deformation rate, the ratio of temperature and degree of compression can change mechanism of austenite recrystallization. Thus, when forming disk of the wheel, the work piece on a press with a force of 100 MN is subjected to deformation about 10%. Considering proximity to critical deformation (8-10 %, [1,2]), at the development of recrystallization, minor deviations in a uniformity distribution of compression along the height of the work piece [8] can lead to a structure heterogeneity of austenite.

A deformation 10 % at a temperature of 950 °C is accompanied by the formation of grains with a shape close to a polyhedron (Fig. 1, *a*). Similar compression at 1100 °C is accompanied by a completely understandable increase in d_A (Fig. 1, *b*). The absence parts of the boundaries and their specific curvature (Fig. 1, *b*, indicated by an arrow) can be considered as evidence formation of “special boundaries” [15].

On other hand, combination of the above-mentioned features indicates development of secondary recrystallization by the coalescence mechanism. Compared to disk, formation other elements of the wheel occur after more significant deformations (40-50 %). Taking into account the high rate of development austenite recrystallization processes during hot reduction [3,4], possible influence of the austenite state on a formation of the pearlite colonies may manifest itself on the dependence properties of the steel (Fig. 2). Secondary recrystallization observed during hot deformation is believed to be influenced by special boundary formation and dislocation cell coalescence. These microstructural evolutions contribute to mechanical property changes and were supported by micrograph observations (Fig. 1b).

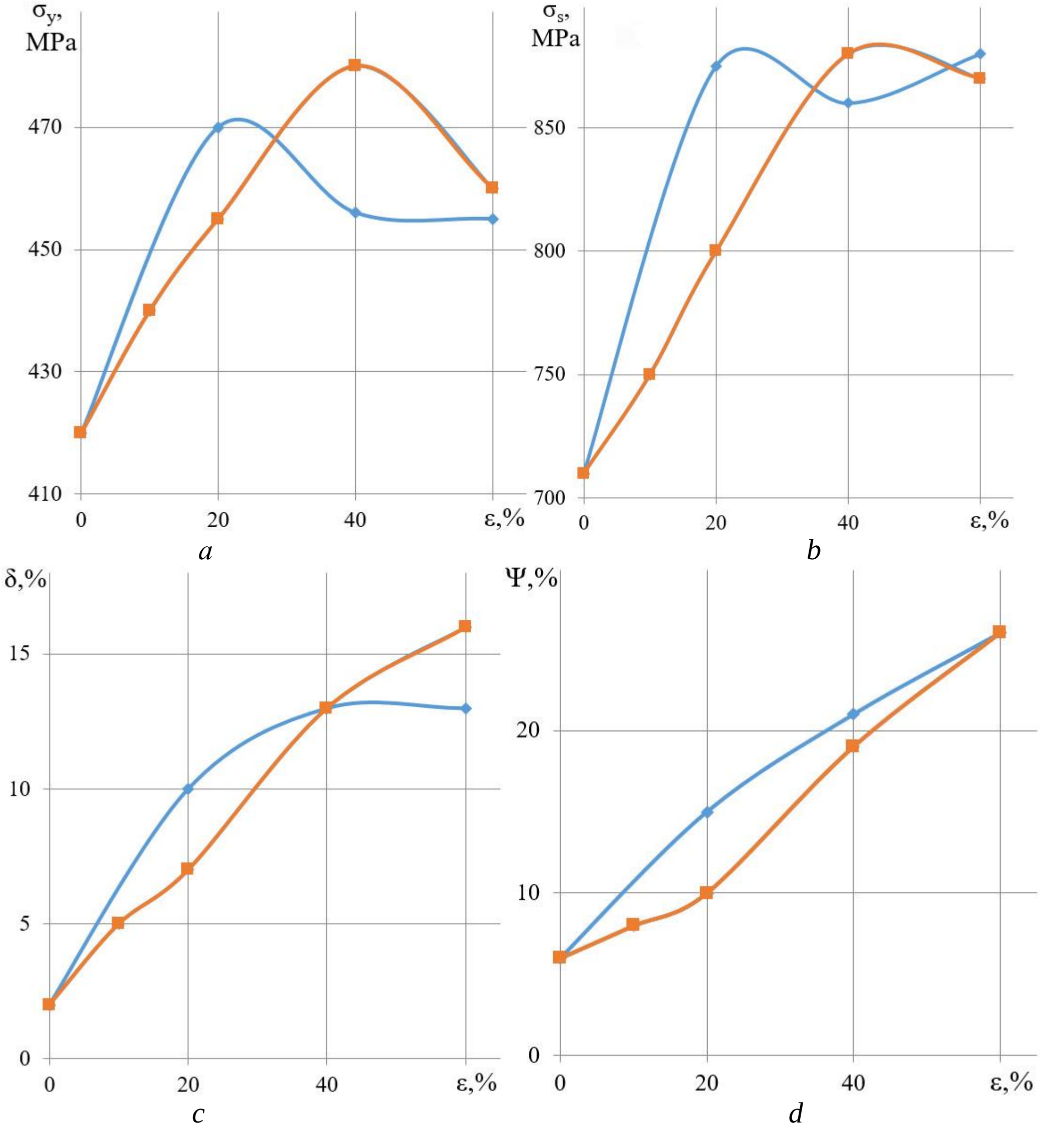

Figure 2. The influence of the degree single (■ – *1*) and double (♦ – *2*) deformation at a temperature of 1240 °C of steel with 0.6 % *C* on σ_y (*a*), σ_s (*b*), δ (*c*) and ψ (*d*)

In addition to a certain dependence on the degree of hot deformation, influence of the deformation scheme is revealed, from the replacement of a single reduction by a double reduction with the same shares (Fig. 2, curves *1* and *2*, respectively). The growth of ε single reduction is accompanied by a monotonic increase in σ_y, σ_s, δ and ψ.

Against the background of qualitative coincidence of the nature change in properties after a single compression, the effect of double deformation has certain features. Replacing a single 20 % deformation with a double one led to an increase in σ_y to 3 %, and σ_s to 10 %. Such an effect can be associated with the influence of a part preserved austenite substructure on the pearlite transformation.

Moreover, if the effect of replacing a single 20 % deformation with a double one (10 + 10 %) can somehow be explained by the proximity to critical deformation during development of recrystallization (10 %) and the formation of a certain number of special boundaries (Fig. 1, *b*), the nature of change in properties after compression of 40 and 60 % requires additional explanation.

Fig. 3 shows the structure of steel after double compression. It is difficult to detect the structural features of pearlite colonies from the structural elements, although there seems to be a greater presence of small fragments after replacing a single deformation (Fig. 1, *e*) with a double one (Fig. 3, a). The nature of the dependence d_A on the magnitude and scheme of deformation is shown in Fig. 4, *a*.

With an increase in the degree of single hot compression, d_A decreases monotonically. Replacing single compression with double compression did not change the nature of dependence but had an insignificant effect on the absolute values of d_A. If for single compression of 40 and 60 %, d_A are respectively equal to 120 and 107 μm, then after double ε = 20 + 20 %, d_A = 140 μm, and after ε = 30 + 30 %, a match with single compression (106 μm) was obtained. It can be expected that in proportion to the decrease total compression, the differences at structural state of austenite after single and double deformation should increase, which in turn must affect d_A.

This tendency is evidenced by the value of d_A (75 μm) after compression according to the scheme 10 + 10 + 10 % [16] (Fig. 4, *a*, point 3). For a detailed analysis possibility preserving of the part effect substructure after hot deformed of austenite on d_A, used the relationship [17]:

$$F = A\varepsilon^{-b} \quad (2)$$

where *F* is the grain area, $d_A = k\sqrt{F}$; *k* is the grain shape coefficient; *ε* is degree of deformation in %; *A* and *b* are constants.

For the shape of austenite grains close to a polyhedron, *k* = 1.86 [9]. After taking the logarithm of (2), we obtain:

$$lgF = lgA - blg\varepsilon \quad (3)$$

at $lg\varepsilon \rightarrow 0$, $lgF = lgA$, and $b = -\Delta lgF / \Delta lg\varepsilon$.

As a result of extrapolation of the ratio $lgF \sim f(lg\varepsilon)$ (Fig. 4, *b*) at $lg\varepsilon = 0$, the values of lgA were determined. For the studied steel, with a single deformation, the value of lgA = 5.3, and *b* = 1.13.

Similar values were obtained for double compression: lgA = 5.3, and *b* = 1.36. Formally, value of *A* does not depend on the deformation scheme, which is confirmed by Fig. 4, *b* and corresponds to value d_A = 830 μm. Considering that, according to various estimates, d_A during heating of a railway wheel blank can vary at range of 800 to 1000-1500 μm [8], the obtained extrapolation result (Fig. 4, *b*) illustrates good agreement.

a

b

Figure 3. Influence of two-step hot compression (a: 20%+20%, b: 30%+30%) at 1240 °C on the austenite grain morphology of 0.6% C steel. The micrographs indicate finer fragmentation in the two-step deformation scheme, especially at lower compression stages.

As follows from [18], the exponent b is a structurally sensitive characteristic and obeys the relation:

$$b = b_1 - (m + g + s) \quad (4)$$

where b_1 is a certain value; *m* is the contribution from hot work hardening of austenite; *g* is the presence of a substructure and *s* is the duration of pause after deformation.

From (4) it follows that in proportion to the decrease at effect of *m*, *g* and *s*, *b* will increase up to a maximum value (b_1), but not more than 2 [17].

According to the wheel blank compression technology, the contribution s is practically constant for different deformation schemes. By representing (4) as (5) and substituting $b_1 = 2$, we can estimate the influence of the hot compression scheme on the total contribution of hot work hardening and presence substructure of the austenite, on the grain size:

$$(m + g) = 2 - b \quad (5)$$

After calculations, we found that for the identical degree of hot deformation, after a single compression, the substructure effect is preserved to a greater extent $(m + g) = 0.87$ than after a double compression $(m + g) = 0.64$.

The current model describing the relationship between deformation degree and austenite grain size is based on a power-law correlation, as shown in Equations (2) and (3). This aligns with classical models such as those presented by Verner [17] and Holt [16].

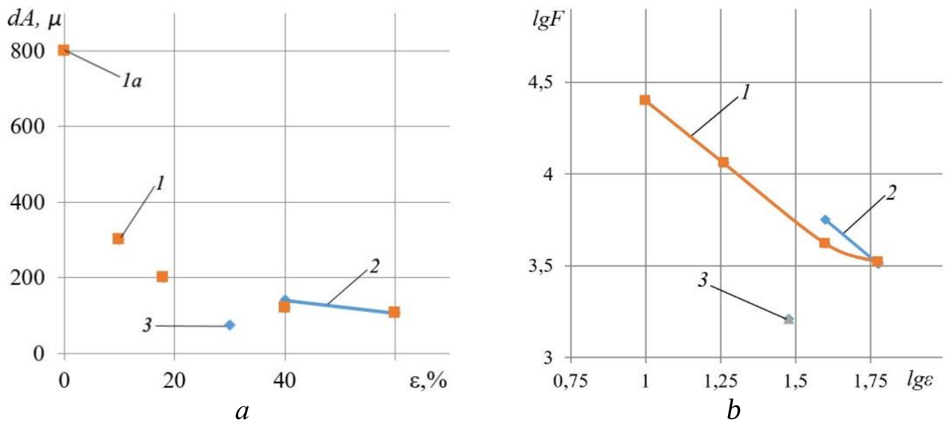

Figure 4. (a) Evolution of austenite grain size (dA) with respect to total strain and deformation scheme. (1a – heating only, 1 – single-stage, 2 – double-stage, 3 – triple-stage). (b) Log-log plot of grain area (F) vs strain (ε) for determination of model parameters (A, b).

With continuous deformation, the effect of the austenite substructure on the development collective recrystallization is proportional to the degree of deformation, which is determined by the condition of its continuity of propagation. With constant holding after deformation, dA will be inversely proportional degree of compression. With fractional compression, conditions of deformation propagation change, which can affect the development of recrystallization processes.

Compared with a single compression, dividing the deformation into certain parts should lead to a decrease at intensity of strain hardening of austenite and number of defects at crystalline structure as a whole.

Indeed, after first compression, in addition to the twice lower degree of deformation, the high-rate development of dislocation recombination will lead to certain substructure changes, such as polygonization or fragmentation. At process of repeated deformation, substructure changes will already be dependent on the previous deformation of the metal. The more developed substructure observed in single-stage deformation is attributed to continuous dislocation accumulation, which enhances polygonization and inhibits early recrystallization. This differs from the double-stage where partial relaxation occurs between stages.

Based on this, the austenite substructure after a single compression will inevitably differ from the deformation in two stages, which is confirmed by the complex of metal properties. The obtained qualitative result requires additional experimental confirmations, in order to explain the mechanism of the observed phenomenon in more detail. Despite this, the obtained result of the influence of the hot deformation scheme of carbon steel can be useful in developing the technology of thermal strengthening of rolled products using heating for hot reduction of metal.

4. CONCLUSIONS

The evolution of austenite grain size (dA) and the mechanical response of carbon steel under varying hot deformation schemes demonstrates a consistent trend with increasing strain. Specifically, dA decreases from 140 μm at 20% deformation to approximately 106 μm at 60% strain during single-stage processing. Regardless of the deformation mode employed, increasing the degree of compression exerts a qualitatively similar influence on grain refinement and the overall mechanical performance of the steel. However, at moderate strains ($\varepsilon \approx 20\%$), the application of a two-stage deformation approach significantly enhances the strength–ductility balance, yielding up to a 10% increase in tensile strength and an improvement in ductility by as much as 40% when compared to single-stage processing. This can be attributed to alterations in the recrystallization dynamics and substructure development of austenite, where two-stage deformation facilitates more controlled grain evolution. As strain approaches or exceeds 60%, the differences in grain size and yield strength between single- and double-stage deformation become negligible due to the completion of dynamic recrystallization. Consequently, for thermomechanical processing routes where the total strain remains below the critical threshold of 60%, a double-stage deformation strategy is recommended to optimize the synergy between strength and ductility without compromising microstructural stability.

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