STRUCTURES AND PROPERTIES FORMATION BY PLASTIC DEFORMATIONS

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Abstract

Theoretical approaches of hot plastic deformations by rolling with the aim of structure formation are discussed. The influence of reheating conditions as are reheating temperature and holding time on reheating temperature on diameter of grain size is presented. From observation is resulting the strong effect on grain growth of course grain structures during steel reheating has temperature, while holding time on reheating temperature has a minor effect. The hot plastic deformations at spontaneous static recrystallization of austenite and retard region of static recrystallization of austenite and their influence on diameter grain size are discussed. The effective way for increasing of strength and plastic properties is grain refinement of final structure which can be achieved by plastic deformations at spontaneous recrystallization region of austenite, plastic deformations at nonrecrystallized region of austenite, plastic deformation at dual phase region ($\gamma+\alpha$) with followed by phase transformation to ferrite. The conditions of phase transformations and their influence to structure development and mechanical properties are presented. The controlling of austenite grain size and ferrite grain size by process parameters as are temperature, deformation, cooling rate is very important tool from point of view making of final mechanical properties directly by metal forming processes. The observed materials are steels.

Keywords: Diameter of grain size, mechanical properties, plastic deformation

1. INTRODUCTION

Classification of metal materials from point of view grains or crystals dimensionality can be characterized as follows:

- CG (coarse-grained) structure - traditional engineering materials (d $\in$ <1; 100) [µm])
- FG (fine-grain) structure (d $\in$ <10; 1000) [nm])
- UFG (ultra fine grain) (d $\in$ <100; 1000) [nm]),
- NC (NG) (nano crystalline) structure (d $\in$ <10; 100) [nm]).

The thermal stability of CG and FG structures is important parameter not only from technological but also from scientific aspects. The classical theoretical basis of grain growth were given by authors [1, 2]. The comprehensive review of grain growth theory can be Atkinson's work [3] and work [4]. Grain growth theory for NG materials was reviewed by authors [5 - 7]. The process of grain growth which is controlled by the external parameters (temperature, strain, strain rate, time) can be divided into two types: normal grain growth and abnormal grain growth (sometimes called as secondary recrystallization).

1.1. Grain growth in CG metal materials

The two different approaches are used for describing average austenite grain size (average AGS) growth on reheating conditions:

a) a general model based on the physically - metallurgical approach authors [8] described by formula:

$$d_\gamma^n - d_{\gamma,0}^n = \left[A \cdot \exp\left(- Q_{gg} /(R \cdot T)\right)\right] \cdot t \tag{1}$$

b) a statistical model based on the numerical data processing of measured values using non-linear regression analysis authors [9] in form:

$$d_\gamma = a_1 \cdot T_{reheat}{}^{a_2} \cdot t_{hold}{}^{a_3} \tag{2}$$

In real metal materials is very often observed normal and abnormal grain growth are described in details in literatures [10 - 13].

1.2. Grain refinement

The grain refinement CG structures of polycrystalline material in/after plastic deformation processes can be obtained by following roads:

- hot plastic deformations at spontaneous recrystallization region (SRR) of austenite (named as normalized controlled rolling - NCR)
- hot plastic deformations at nonrecrystallized region (NRR) of austenite (named as controlled rolling - CR)
- hot plastic deformations at dual phase region ($\gamma + \alpha$) of austenite
- severe plastic deformation - SPD methods realized at hot or cold conditions

The classic methods of grain refinement are effective in the range of CG structure and additional possibilities towards to structure refinement below limiting level 1 μm by those methods are not capable. The influence of plastic deformations in mono phase region of austenite and dual phase region austenite + ferrite ($\gamma + \alpha$) with followed by phase transformation are very important from point of view final structure formation. From the experimental results of authors [14, 15] can be done following conclusions for structure development:

- phase transformation from reheating temperature is producing very course-grained ferrite size (FGS) depend on reheating condition
- plastic deformation conditions realized in:
    - mono phase austenite region at temperatures:
        - spontaneous recrystallization region (SRR) of austenite is producing polyhedral austenite grain size (AGS) with diameter $d_\gamma \approx 20 - 30$ μm which transformed to polyhedral FGS with diameter $d_\alpha \approx 10 - 20$ μm
        - non recrystallization austenite region (NRR) (narrowly up A_{r3}) is producing deformed elongated austenite grains with effective ferritic nucleation surface calculated from grain boundaries and deformation bands $S_v(gb+db) \approx 50 - 500$ [1/mm] which is responsible of correcting austenite diameter $d_{\gamma,\infty r} \approx 4 - 40$ μm which transformed to polyhedral FGS with diameter $d_\alpha \approx 4 - 10$ μm
    - dual phase ($\gamma+\alpha$) region
        - (non recrystallized austenite + deformed ferrite) bellow A_{r3} temperatures with $S_v(gb+db) \approx 700$ [1/mm] which is responsible of $d_{\gamma,cor} \approx 4$μm which transformed to ferrite
        - (non recrystallized austenite → polyhedral FGS + deformed ferrite → ferrite subgrains) with diameter $d_\alpha \approx 1 - 4$ μm

2. MATERIALS AND EXPERIMENTAL METHODS

As experimental material was used the steels with chemical composition given at **Table 1**. The samples for study of the influence of reheating conditions on austenite grain growth were reheated in temperature intervals $T_{Reheat} \in \langle950; 1250\rangle$ [°C] with holding time $t_{Hold} \in \langle600; 3600\rangle$ [s].

Plastic deformations were realized as hot rolled in temperature region of spontaneous static recrystallization of austenite ($T_{Deform} > 950°C$), nonrecrystallized austenitic region ($T_{Deform} \in \langle850; 950\rangle$ [°C]) and dual phase

29

region ($T_{Deform} \in$ <700; 850> [°C]). The optical microscopy for structure identification was used. Static tensile test realized according to standard STN EN 10002-1. Measurement data were treated by software Excel.

Table 1 Local chemical analysis of study metals (wt. %)

Chemical conception	C	Mn	Si	P	S	Nb	V	Ti	Al	Cu
C-Mn	0.1	1.5	0.12	0.009	0.008	-	-	-	0.02	
C-Mn-Nb	0.1	1.5	0.12	0.005	0.004	0.03			0.014	-
C-Mn-Nb-V	0.12	1.54	0.12	0.004	0.001	0.048	0.18	0.01	0.015	-

3. RESULTS AND DISCUSSION

3.1. Grain growth

The dependence of average austenite grain size diameter (AGS) on reheating conditions is shown at **Fig. 1**.

From graphical dependence is resulting that normal grain growth was observed up to temperature 1150 °C. From this temperature can be observed start abnormal grain growth because of the pinning effect of precipitates is vanished. The reheating temperature and holding time has a minor effect on AGS diameter changes up to 1050 °C. This is caused by strong pinning effect of V(C,N) and Nb(C_X,N_Y) precipitates to grain boundary motion. The dissolution of VN precipitates was determined by authors [9] on temperature 1000 °C. The stronger influence of reheating temperature on a additional grain growth was

Fig. 1 Dependence of the average AGS growth on the reheating temperature and holding time

observed at interval $T_{Reheat} \in$ <1050; 1150> [°C]. This temperature interval is characterized by dissolution of complex Nb(C_X,N_Y) [9] which is follow by abnormal grain growth. The influence of holding time on grain growth is weaker as reheating temperature. From experimental data were derived two equations:

- equation based on the physically - metallurgical approach:

$$d_\gamma^3 - d_{\gamma,0}^3 = (3.28725 \cdot 10^{22} \cdot \exp(-460/(R \cdot T_{Reheat}))) \cdot t_{Hold} \tag{3}$$

- equation based on a statistical model:

$$d_\gamma = 6.589 \cdot 10^{-28} \cdot T_{Reheat}^{9.51} \cdot t_{Hold}^{0.2437} \tag{4}$$

3.2. Refinement of structures on CG level

The structural refinement of AGS diameter with NCR technique is running by repeating of cycle plastic deformation - static recrystallization. This cycle has limitation on formation of final refinement of recrystallized AGS which diameter was experimentally specified for low carbon steels (C-Mn) as $d_{\gamma,rec,min} \in$ <50; 80> [µm] and for microalloyed steels C-Mn-Nb or C-Mn-Nb-V as $d_{\gamma,rec,min} \in$ <20; 30> [µm] according to dependences given in **Fig. 2**.
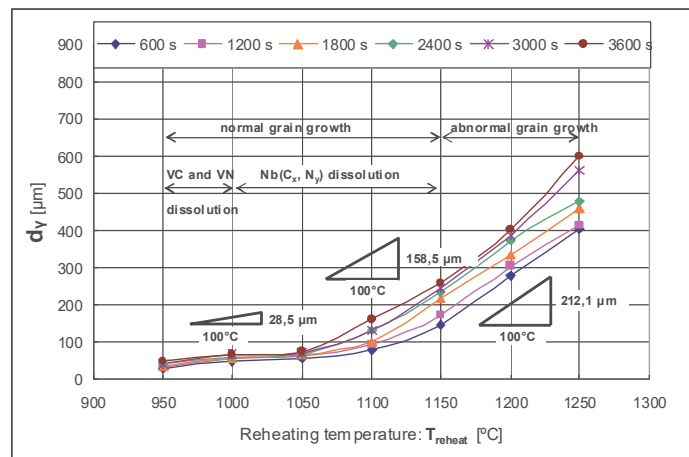
If experimentally data were treated by numerical statistical methods, so following regression equations were derived for describing diameter of AGS:

- for C-Mn steel:

$$d_\gamma^0 = 56 + 12{,}8 / \varphi \tag{5}$$

- for C-Mn-Nb-V steel:

$$d_\gamma^0 = 16{,}9 + 17 / (\varphi + 0{,}0245) \tag{6}$$

The phase transformation from recrystallized austenite processed by NCR to ferrite with consideration of cooling rate can be described by regression equation:

$$d_\alpha = 7.347 \cdot v_{cooling}^{-0.1925} \cdot (d_\gamma^0)^{0.3596} \tag{7}$$

and graphical dependence is given in **Fig. 3**. From graphical dependences is resulting that dimensionality final FGS diameter after phase transformation from recrystallized austenite deformed with NCR technique is for low carbon steels (C-Mn) $d_\alpha \in <17; 31>$ [μm] and for microalloyed steels C-Mn-Nb or C-Mn-Nb-V is $d_\alpha \in <12; 22>$ [μm] in depend on cooling rate and diameter of AGS nearly before phase transformation to ferrite. The additional refinement of FGS diameter by NCR technique is noneffective and practically impossible. The next way for additional refinement of FGS diameter is possible by plastic deformations at nonrecrystallized austenite region which formed elongated austenitic grains described by the effective nucleation surface of austenite before phase transformation to ferrite. The effective nucleation surface consists of increments from grain boundaries (gb) and deformation bands (db) was described by formula [14]:

$$S_v(gb + db) = 1000 \cdot \left[\frac{0{,}429 \cdot (1 - \varepsilon)}{d_\gamma^0} + \frac{1{,}571}{(1 - \varepsilon) \cdot d_\gamma^0} \right] + (157{,}2 \cdot \varepsilon - 59{,}47) \tag{8}$$

With increasing of $S_v(gb+db)$ is increase number of nuclei for transformation from austenite to ferrite and diameter of FGS will be decrease. The application of CR technique for microalloyed steels is the way for additional refinement FGS diameter which can be described by formula:

$$d_\alpha = 1.2919.10^{-0.1618} \cdot v_{cooling}^{-0.1618} \cdot (d_\gamma^0)^{0.4364} \cdot \varphi^{-0.3675} \tag{9}$$
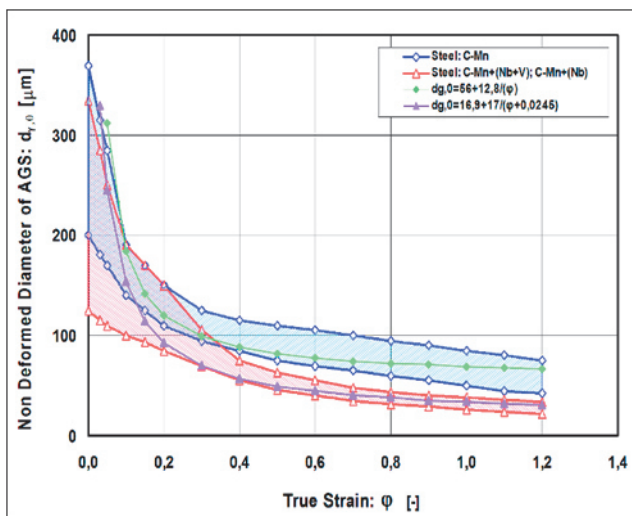

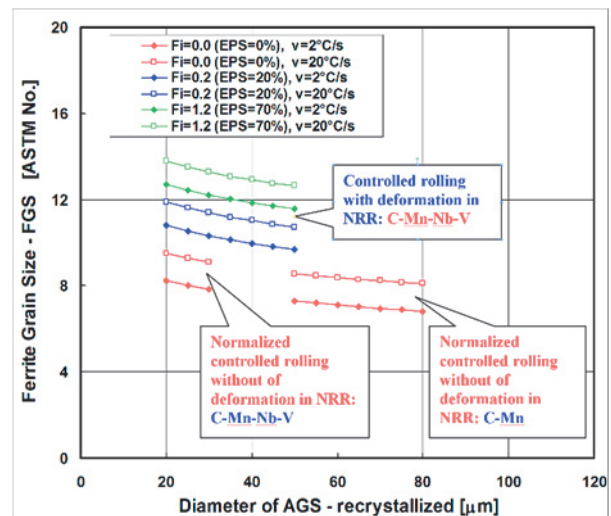**Fig. 2** Non deformed AGS on strain processing by NCR

Fig. 3 FGS transformed from austenite

The graphical interpretations of eq. (9) are shown in **Fig. 4** from which is resulting that the dimensionality of FGS diameter of microalloyed steels C-Mn-Nb or C-Mn-Nb-V processed by CR technique is $d_\alpha \in <3; 12>$ [μm]. If diameter of AGS is decreasing, strain and cooling rate are increasing, so reducing of diameter of FGS can be achieved. From graphical dependences is also resulting, that minimal level of FGS diameter which is possible obtain from recrystallized austenite is $d_{\alpha,NCR,min} \approx 20$ μm and from deformed with elongated grains of austenite is $d_{\alpha,CR,min} \approx 3$ μm.

If from eq. (8) is separated diameter of AGS, so the formula will be in form:

$$d_\gamma^0 = \frac{429 \cdot (1-\varepsilon)^2 + 1571}{(1-\varepsilon) \cdot [S_v(gb+db) - 157,2 \cdot \varepsilon + 59,47]} \tag{10}$$

When eq. (10) is substituted to eq. (9) then final formula for calculation of FGS diameter on processing condition of CR will be in form:

$$d_\alpha = \left[\frac{429 \cdot (1-\varepsilon)^2 + 1571}{(1-\varepsilon) \cdot [S_v(gb+db) - 157,2 \cdot \varepsilon + 59,47]} \right]^{0,4364} \cdot 1,2919 \cdot v_{cool}^{-0,1618} \cdot \varphi^{-0,3675} \tag{11}$$

The eq. (11) describing diameter of FGS more precisely than eq. (9) because of calculated not only with effective nucleation surface of austenite grain boundary (gb), but also with effective nucleation surface of deformation bands (gb + db). The effective nucleation surface of austenite before phase transformation Sv(gb + db) is depending on deformation in NRR and diameter recrystallized AGS before deformation in NRR as is showing in **Fig. 4**.

Graphical interpretation of eq. (11) is given in **Fig. 5**, from which is resulting that refinement FGS diameter is depending on following parameters: Sv(gb + db) and cooling rate. The stronger refinement effect on FGS diameter up to Sv(gb + db) ≤ 140 [1/mm] is observed from deformation realized at NRR of austenite, when the increment is: Δ = ΔFGS/ΔSv(gb + db) = 10 μm/100mm⁻¹. The weaker refinement effect on FGS diameter from Sv(gb + db) > 140 [1/mm] is observed from deformation realized at NRR of austenite, when the increment is: Δ = ΔFGS/ΔSv(gb + db) = 0,8 μm/100mm⁻¹. The influence of cooling rate on FGS refinement is weaker then deformations realized at NRR of austenite. Moreover the plastic deformations realized in NRR of austenite are non effective and next refinement of final grain size below 2 μm by this technique is today limited.

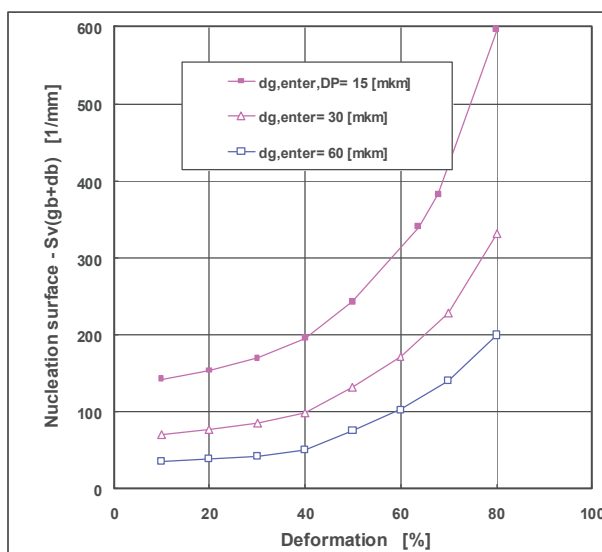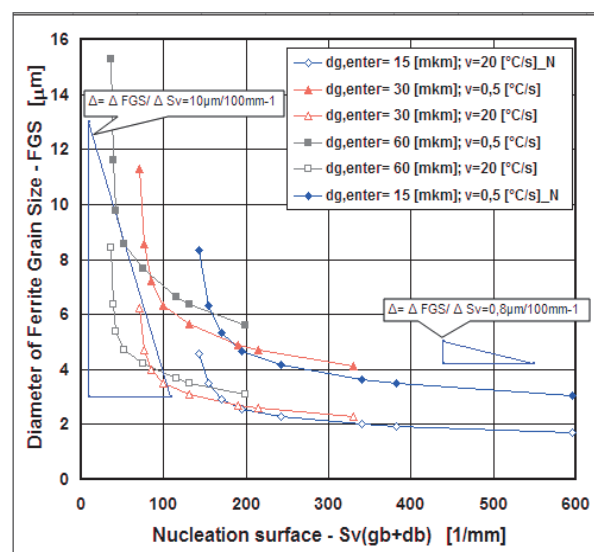**Fig. 4** Sv(gb+db) in dependence on deformation

Fig. 5 FGS in dependence on CR conditions

3.3. Influence of CG structures on mechanical properties

The strengthening contributions on yield strength of steel materials can be described by formula [16]:

$$R_e = \Delta R_{e,PN} + \Delta R_{e,IN} + \Delta R_{e,SE} + \Delta R_{e,Pearlite} + \Delta R_{e,Precip} + \Delta R_{e,FGS} \quad [MPa] \tag{12}$$

Increment from interstitial element can be suppose is $\Delta R_{e,IN}$=0 MPa. Increment from Peierls-Nabarovo stress is $\Delta R_{e,PN}$ = 45 MPa. Increment from substituted element can be calculated according to following formula:

$$\Delta R_{e,SE} = 84 \cdot (wt.\%Si) + 37 \cdot (wt.\%Mn) + 32 \cdot (wt.\%Ni) + 38 \cdot (wt.\%Cu) + 680 \cdot (wt.\%P) = 99,48 \doteq 99 MPa \tag{13}$$

Increment from pearlite content is $\Delta R_{e,PN}$ = 30 MPa. Increment from precipitates can be calculated according to following formula:

$$\Delta R_{e,Precip} = 620 \cdot (wt.\%V) + 1200 \cdot (wt.\%Nb) = 120 \; MPa \tag{14}$$

The sum of previous strengthening contributions on yield strength has a value:

$$\Delta R_{e,par} = \Delta R_{e,IN} + \Delta R_{e,PN} + \Delta R_{e,SE} + \Delta R_{e,PN} + \Delta R_{e,Precip} = 294 \; MPa \tag{15}$$

Increment from FGS diameter can be calculated according to following formula:

$$\Delta R_{e,FGS} = 15,1.d^{-0,5} = 15,1.(3,1^{-3})^{-0,5} = 271 \; MPa \tag{16}$$
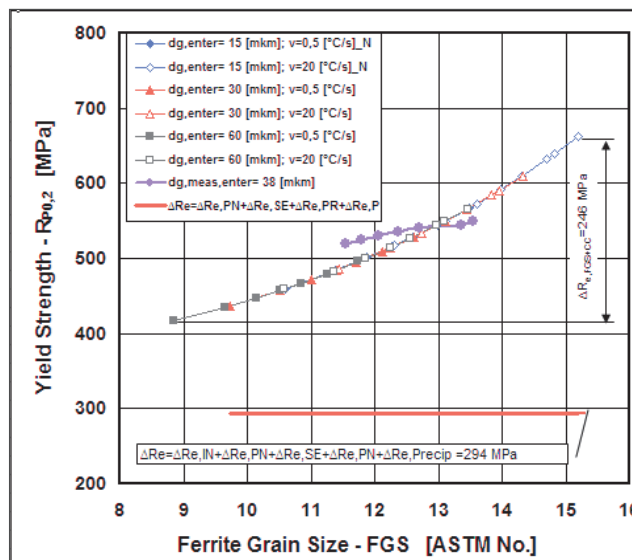

Fig. 6 Dependence of yield strength on strengthening contributions

Graphical dependence of yield strength on FGS diameter and cooling rate is given in **Fig. 6**. From graphical dependence is resulting that yield strength is changing in depend on grain size refinement and cooling rate as is given in **Table 2**.

Table 2 Increment to YS in depend on FGS diameter

Interval for FGS diameter [μm]	Increment to YS [MPa/1μm]: $\Delta R_{e,FGS+CR}$	Increment to YS [MPa/1μm]: $\Delta R_{e,par} = \Delta R_{e,IN} + \Delta R_{e,PN} + \Delta R_{e,SE} + \Delta R_{e,PN} + \Delta R_{e,Precip}$
$d_\alpha \in <2; 4>$	56	
$d_\alpha \in <4; 15>$	10	294
$d_\alpha \in <2; 15>$	20	
$d_\alpha \in <2; 15>$	246	

Moreover from **Table 2** is resulting that all strengthening contributions summarized into $\Delta R_{e,par}$ are constant and depend on chemical composition of steel, strengthening contribution from FGS diameter and controlled

cooling $\Delta R_{e,FGS+CR}$ is possible control by process parameters as are temperature, deformation, cooling rate in wide interval. Because of strengthening contribution $\Delta R_{e,FGS+CR}$ can be defined as very effective tool for controlling of mechanical properties of steels. The calculated values according to theoretical model have good conformity with measured properties.

CONCLUSION

In present study were described the ways for structure grain growth and refinement of metals materials. On the base of experimentally studies can be made following conclusions:

- the strong effect on grain growth of CG structures during steel reheating has temperature, while holding time has a minor effect,
- abnormal grain growth was observed when pinning effect of precipitates of microalloying elements were eliminated by their dissolution,
- effective way for common increasing of strength and plastic properties is grain refinement of final structure which can be achieved by plastic deformations at spontaneous recrystallization region of austenite (NCR), plastic deformations at nonrecrystallized region of austenite (CR), plastic deformation at dual phase region ($\gamma+\alpha$) with followed by phase transformation to ferrite. These techniques of plastic deformations have been used as the compensation for high level of metal alloying and heat treatment,
- controlling of AGS diameter and FGS diameter by process parameters as are temperature, deformation, cooling rate is very important tool from point of view making of final mechanical properties directly by metal forming processes.

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