Effects of Finish-rolling Temperature and Carbon Content on Microstructure and Mechanical Anisotropy of 0.04~0.13 % C Steels*

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Synopsis

Steels with carbon content from 0.13 to 0.04 % were rolled in temperature range 1 220 to 750°C and subsequently air cooled. The microstructure as well as mechanical properties were investigated. The grain size in steels is first gradually decreased with lowering rolling temperature, and then it is fastly increased with further lowering of rolling temperature down to ferrite range. The microstructure is the more coarse and heterogeneous the less completed was the interpass recrystallisation of austenite and the more ferrite was present in steel during the rolling. The rolling in ferrite range produces a strong anisotropy in tensile ductility.

Key words: low carbon steels; hot rolling temperature; microstructure; recrystallisation and recovery; grain size; mechanical properties; anisotropy in tensile ductility.

I. Introduction

The microstructure of steel evolves during the rolling of steel frequently in a way, which can not be extrapolated on the basis of single pass rolling. The cause is in the fact that interpass recrystallisation, recovery and grain growth are connected from one pass to the following and may be interlaced also with strain induced precipitation.¹⁾ In low carbon steel rolled at temperature below the transformation point of austenite during the rolling ferrite is introduced as additional factor of influence. While static recrystallisation of austenite is initiated at straining near 10 %, ²⁾ the recrystallisation of ferrite would require a per pass deformation of above 60 %. ³⁾ The accumulation of straining in more passes rolling does not attain the required value because of the very fast interpass recovery of ferrite. In an earlier work in which several steels were investigated, it was found that the evolution of grain size in as rolled steel is very different in low carbon steel than that in steel with approx. 0.15 C. ¹⁾ The aim of this work was to investigate in detail the influence of rolling temperature in range of carbon content from 0.04 to 0.13 %, where an important part of hot rolling would be performed also in ferrite range.

II. Experimental

The composition of investigated steels is given in Table 1. All steels were of industrial heats. The soaking temperature was of 1 220°C and sufficient to ensure the solution of aluminium nitride in austenite. ⁴⁾ After soaking, part of the specimens was rolled with the initial temperature of 1 220°C and part was air cooled to lower temperatures and then rolled according to the same deformation schedule. The finish-

rolling temperature was in the range between 1 032 and 750°C. The drop of temperature of steel during the rolling reached approx. 160°C at high initial temperature and approx. 120°C at low initial temperature. The rolling of 55 mm slabs to 11 mm plates was carried out in 7 passes with an average per pass deformation of above 20 %. That is sufficient for the recrystallisation of austenite in interpass time of approx. 8 s at high temperature, ²⁾ insufficient for the completed recrystallisation of austenite at intermediate temperature and too low for interpass recrystallisation of ferrite. ³⁾ In specimens air cooled from finish-rolling temperature the evolution of microstructure was much more evident than in those water quenched. For that reason all investigations were performed on steels air cooled from finish-rolling temperature. The investigation consisted of the assessment of the linear intercept grain size, the evaluation of microstructure and the determination of mechanical properties in rolling and transverse directions. For the determination of mechanical properties standard specimens of 8 mm of diameter, 60 mm of gauge length and with screwed head were used.

III. Microstructure of As Rolled Steels

1. General Observations

After rolling at high finish-rolling temperature the microstructure consists of polygonal and regular grains of ferrite and pearlite in all steels, pearlite being less with the decrease of carbon content in steel. Examples of microstructure obtained at high rolling temperature are given in micros. A and B in Figs. 1 to 3. Below an initial rolling temperature (approx. 950°C in steels with 0.12 C) lenticular clusters of grains with size and form different than those in the matrix were observed (Figs. 1(C) and 1(D)). Such clusters were reported earlier ¹⁾ and explained as

Table 1. Composition of investigated steels.

Steel	Element (wt%)						
	C	Mn	Si	P	S	Al	N
K	0.13	0.46	0.22	0.007	0.033	0.058	0.0057
M	0.12	0.44	0.21	0.008	0.04	0.050	0.0054
T	0.12	0.41	0.28	0.011	0.04	0.10	0.0053
L	0.07	0.39	0.24	0.018	0.03	0.049	0.0052
S	0.04	0.34	0.01	0.009	0.01	0.025	0.0049
Z	0.04	0.34	0	0.007	0.02	0.003	0.0032

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A: *FT* 1 008°C B: *FT* 820°C
C: *FT* 790°C D: *FT* 774°C

Fig. 1.
Microstructure of steel K air cooled from finish-rolling temperature (*FT*).

A: *FT* 980°C B: *FT* 847°C
C: *FT* 820°C D: *FT* 800°C

Fig. 2.
Microstructure of steel L air cooled from finish-rolling temperature.

A: *FT* 946°C B: *FT* 867°C
C: *FT* 850°C D: *FT* 817°C

Fig. 3.
Microstructure of steel Z air cooled from finish-rolling temperature.

produced during the cooling from finish-rolling temperature by transformation of austenite grains which remained unrecrystallised over the whole process of rolling. In ferrite formed during the cooling from rolling temperature from recrystallised and unrecrys-

tallised austenite, no substructure was observed. This shows that at the transformation of austenite strain hardening and polygonisation are removed.

Below the temperature of approx. 870°C, a substantial volume fraction of ferrite appeared in some steels

during the rolling, and that strongly affected the further evolution of microstructure when the rolling was continued.

Beside ferrite grains produced by the transformation of austenite at cooling, two additional types of ferrite were observed: one is mostly in coarse and elongated grains with marked polygonisation substructure, and the other is mostly in coarse and elongated grains without substructure but having concave boundaries and many neighbours. Ferrite of these two types is shown in Figs. 1(C), 2(C), 2(D), 3(C) and 3(D). Substructure and coarse grains size indicate that ferrite appeared during the rolling did not recrystallise and eliminated the strain hardening by recovery and polygonisation. This process continued also during the cooling from finish-rolling temperature until the temperature permitted the rearrangement of dislocations and point defects introduced in the metal by the straining. The polygonisation observed in optical microscope is the more evident the lower was the rolling temperature.

A specific form of ferrite observed in steels rolled at low finish-rolling temperature is in form of coarse grains free of internal substructure and grown by deformation induced grain boundary migration³⁾ (DIGBM). The coarse size of these grains of ferrite and concave boundaries with many neighbours indicate that the process of DIGBM is very fast in interpass time and during the air cooling after the rolling. It is evident that ferrite without substructure was formed during the cooling from the finish-rolling temperature, while ferrite formed in interpass time developed a polygonisation substructure after the following rolling pass.

DIGBM is explained as recrystallisation *in situ* with as nuclea polygonisation grains more stable than neighbours because of size, form or orientation, occurring at straining lower than that required for interpass recrystallisation of ferrite.

2. Microstructure

In steels K and M a small volume fraction of ferrite appeared during the rolling. At low rolling temperature the microstructure consists of a mixture of polygonal grains formed by transformation of recrystallised austenite, clusters of grains produced by the transformation of unrecrystallised austenite and polygonised ferrite, while no ferrite formed by DIGBM was observed. That signifies that in order to initiate the DIGBM a higher strain than that imposed in the last pass is required. By the transformation of unrecrystallised austenite grains, the greater size prevailed over the effect of straining. That explains the coarse microstructure produced at the transformation from unrecrystallised austenite. The carbon content in steel T is identical to that in steel M. In spite of this a substantial volume fraction of ferrite produced by DIGBM is observed at the lowest finish-rolling temperature in steel T. The explanation is probably in the higher content of aluminium and silicon in this steel. These higher contents shifted the austenite-ferrite transformation to a higher temperature and

caused the earlier presence of ferrite during the rolling. In the group of steels with low carbon, three compositions are involved. Steel L differs from steel K mostly in carbon, steel S in carbon, silicon and aluminium, while steel Z with the same level of carbon as steel S is unkilld and therefore free of silicon and aluminium. At high finish-rolling temperature a similar microstructure is found in steel L as in steel K, only the quantity of pearlite is smaller. Polygonised ferrite and ferrite produced by DIGBM are found at higher finish-rolling temperatures. In steel L ferrite formed from unrecrystallised austenite is found only at very attentive observation. (That is explained in terms of erosion of coarse unrecrystallised austenite grains by the transformation advancing during the cooling during the rolling.) After the finish of rolling, the complete transformation of austenite occurred, during air cooling. At this moment the size of grains was too small to cause such a marked difference in size and morphology of ferrite and pearlite as in case of steels with higher carbon.

At high finish-rolling temperature the microstructure in steels S and Z is similar to that of steel L. At low rolling temperature the microstructure consists of polygonised ferrite and ferrite formed by DIGBM after the end of rolling (Figs. 3(C) and 3(D)). More polygonised ferrite is found after the rolling of steel at the lowest finish-rolling temperature. Pearlite which was found at triple boundary points at high rolling temperature, is found at grain boundaries and sometimes also in the interior of grains grown by DIGBM at low finish-rolling temperature.

IV. Grain Size

In Fig. 4 the relationship between finish-rolling temperature and the linear intercept grain size for ferrite grains is shown. The significance of the curve requires a careful consideration because the assessed grain size represents ferrite of different origin. After rolling at high temperature ferrite is produced by the transformation from recrystallised or unrecrystallised austenite after the rolling. In intermediate range of temperature ferrite appears during the rolling. However, the microstructure depends still mostly upon the behaviour of the predominant austenite during the rolling. At still lower rolling temperature the microstructure is produced mostly by the rolling of ferrite with recovery and DIGBM in interpass time and at the cooling of steel from finish-rolling temperature. In the range of finish-rolling temperature down to approx. 870°C in all steels the grain size is gradually decreasing in a similar way. At finish-rolling temperature of 1 000°C, grains are the coarsest in unkilld steel Z. The difference in size with respect to steel S with similar composition, except aluminium, is approx. 0.5 ASTM number. It results from the inhibition of interpass grain growth of recrystallised austenite due to the precipitation of aluminium nitride during the rolling.¹⁾ The difference between other steels is partly connected to the difference in precipitation of aluminium nitride and partly to the difference in the level of alloying elements.

Fig. 4. Influence of finish-rolling temperature on linear intercept grain size of steels.

The minimal grain size is obtained at a temperature ensuring the most of interpass recrystallisation of austenite, a moderate volume fraction of unrecrystallised austenite and the less of ferrite appeared during the rolling. In steels K and M the formation of ferrite during the rolling is reflected by the less steep decrease of grain size, when the rolling temperature is lowered below approx. 870°C. It has been explained already that in both steels at the rolling in low temperature range, polygonised ferrite was observed. That is a reliable evidence that ferrite was present in steel before the last rolling pass. In other steels an increase in grain size, after the minimum of grain size, is obtained when the rolling temperature is further lowered. The increase is very fast, f.i. in low carbon steels S and Z the grain size is decreased by approx. 1.5 ASTM numbers when the finish-rolling temperature is lowered from 1 000 to 870°C. When the temperature is further decreased to 800°C grain size is increased by approx. 2.5 ASTM numbers. That gives a good evaluation of the rate of grain growth in deformed ferrite in interpass time and during the cooling after the end of rolling. The growth of ferrite by DIGBM is evidently much faster than the interpass growth of recrystallised austenite. Figure 5 shows that the grain size obtained by the finish-rolling at 800°C decreases proportionally to the increase of carbon content in steel. That leads to the conclusion that the grain size due to the rolling of steel in ferrite range is the coarser the more of ferrite is present in steel. The quantity of ferrite depends upon the composition of steel and upon the transformation temperature of austenite during the rolling. Additionally, it is possible, on the base of Fig. 5, to conclude that the greater

Fig. 5. Relationship between the carbon content and the linear intercept grain size of steel finish-rolled at 800°C.

was the deformation during the rolling, or more precisely, to the more passes ferrite was rolled the grain size is the coarser.

In steel T an increase in grain size is observed by rolling at the lowest temperature in spite of the identical content of carbon as in steel M. The explanation is, as already stated, in the increase of γ - α transformation temperature due to the content of alloying elements, which as silicon and aluminium counterbalance the effect of carbon. In Table 2 some examples of assessment of grain size of ferrite produced by the transformation of recrystallised and unrecrystallised austenite are presented. The difference amounts of approx. 2 ASTM numbers and it seems to be independent upon the rolling temperature. In low carbon steels such measurements were not possible. While in the microstructure of steel rolled in intermediate range, ferrite produced from unrecrystallised austenite was identified, the clusters were too small for reliable assessment of grain size. As explained earlier unrecrystallised austenite grains in low carbon steels were eroded by the advancing transformation and therefore grains did not transform as entirely when the steel was cooled from finish-rolling temperature as in the case of 0.12 C steels.

By rolling in high temperature range equiaxed grain are obtained. At rolling at low temperature ferrite grains were the more elongated the lower was the temperature (Fig. 6). That is partly due to the absence of interpass recrystallisation of ferrite and partly also to the axial growth of grains because of DIGBM. It is not clear whether the uniform growth was hindered by fine pearlite respectively austenite grains that are frequently found at ferrite grain boundaries. The small number of such grains and the fact that are observed also in the interior of ferrite grains produced by DIGBM indicates a stronger effect of rolling texture of ferrite which was already reported.^{3,5)}

V. Mechanical Properties

The influence of finish-rolling temperature on mechanical properties of two steels is shown in Figs. 7 and

Table 2. Linear intercept grain size of grains formed from recrystallised (RA) and unrecrystallised austenite (UA) during the cooling of steel from finish-rolling temperature.

Steel	Finish-rolling temp. (°C)	Grain size (μm)		Ratio RA/UA
		RA	UA	
K	820	7.5±0.7	12.4±2.8	0.62
	774	6.3±0.5	11.2±1.2	0.55
M	803	6.1±0.6	11.7±2.6	0.52
T	850	8.6±1.03	13.1±2.1	0.66

Fig. 7. Influence of finish-rolling temperature on mechanical properties of steel K.

8. The effect on properties of other investigated steel was basically similar.⁶⁾ In the lower part of both figures the properties in rolling direction are shown, in the middle the ratio of properties in transverse and rolling direction, and in the upper part the ratio of axes of fracture surface of tensile specimens. In steel K tensile strength and yield point in rolling direction are slightly increased when the finish-rolling temperature is lowered. The increase is smaller than it could be expected on the basis of the difference in grain size after the Hall-Petch equation. In steel S the tensile strength and yield point slightly decrease at low rolling temperature without connection to the evolution of grain size shown in Fig. 4. In steel K elongation and reduction of area are virtually constant in most of

Fig. 6. Influence of finish-rolling temperature on the ratio g_{st}/g_{sr} , with g_{st} : linear intercept grain size in through thickness direction and g_{sr} : linear intercept grain size in rolling direction.

Fig. 8. Influence of finish-rolling temperature on mechanical properties of steel S.

the finish-rolling temperature range. The elongation decreases significantly only at the two lowest finish-rolling temperatures. At the lowest rolling temperature also reduction of area decreases slightly. In view of the strong anisotropy of tensile ductility at this temperature is questionable whether the decrease of reduction of area is significant. On the total the effect of finish-rolling temperature on properties in rolling

direction is small when compared to the variation of grain size which occurs in the same range of rolling temperature.

The lower than expected influence of grain size on strength properties in rolling direction is explained by the heterogeneous microstructure. It seems that at high rolling temperature the influence of coarser components of microstructure, which result from the transformation of unrecrystallised austenite, is greater than it could be expected from their volume fraction, while at low finish-rolling temperature the effect of grain coarsening due to the rolling in ferrite range is lower than expected from the variation of grain size. On some samples the hardness of polygonised ferrite and ferrite produced by DIGBM was measured. It was found that the first was harder (Table 3). It is possible to conclude at this point that the properties of steel after rolling in ferrite range are influenced by grain size and the volume fraction of ferrite of different origin in steel.

In both steels the anisotropy in mechanical properties is increased with the lowering rolling temperature. Tensile strength and yield point are increased and ductility decreased in transverse direction with respect to rolling direction. The greatest is the anisotropy in reduction of area, especially on specimens with tensile axis in rolling direction. The anisotropy in ductility can be better understood on the basis of Fig. 9, where the effect of finish-rolling temperature on anisotropy in reduction of area is shown for all

Table 3. Vickers hardness of polygonised ferrite (PF) and ferrite produced by DIGBM.

Steel	Finish-rolling temp. (°C)	PF	DIGBM
S	783	175	164
Z	850	143	121
	817	150	129

Fig. 9. The relationship between finish-rolling temperature and the anisotropy of fracture of tensile specimens machined in rolling direction. The anisotropy is defined as ratio of the short and long axes of elliptical fracture surface.

tested steels. At high rolling temperature a virtually constant nearly circular shape of the tensile fracture surface is observed independently upon the content of carbon in steel.

When the finish-rolling temperature is lowered below 870°C approx. the anisotropy is increased in all steels, however faster in steels S, T and Z in spite of the lower level of sulphur in these steels than in steels with higher carbon. On all specimens the short axis of elliptical fracture surface corresponded to the short transverse direction, *i.e.*, the through thickness direction of rolled steel. If the effect of inclusions was predominant on anisotropy an opposite effect would be expected not only because of the effect of inclusions, but also because the relative plasticity of sulphide inclusions is higher when the steel is rolled in austenite than in ferrite range and therefore longer inclusions are obtained by the rolling in austenite range.⁷⁾

In a simplified model of planar flow for the deformation of tensile specimens localised in the reduction of area (striction) the fracture would occur when the ductility of steel in one of the axes: rolling, transverse and short transverse direction was attained. In this simple model the length of the axes of elliptical fracture surface can be taken as a qualitative measure of relative ductility. If the fracture strain is expressed as

$$S = \ln d_0/d_i$$

with d_0 : the initial diameter of tensile specimens

d_i : the axis of the elliptical fracture,

the effect of finish-rolling temperature upon the relative ductility of steel in different directions in Fig. 10 is obtained. In the evaluation of the relationship it must be considered that in every test the limit of ductility was attained only for the direction of the longer axis, which is the transverse direction on specimen machined in rolling direction and the rolling direction in transverse specimens. In both cases the limit of ductility was not attained in short transverse direction.

The connection rolling temperature-relative ductility is very similar in all steels, however significant differences are observed between steels and between the direction of testing. In high finish-rolling temperature range the ductility is independent upon the temperature. Also the initial ratio of ductilities is conserved, low ductility in rolling direction, higher in transverse direction and the highest in short transverse direction. The difference between the three directions is higher in steels K, L and T than in steel S. That corresponds to the difference in the content of sulphur in steels and suggests that the anisotropy observed in steel after rolling at high temperature is due mainly to the presence of sulfide inclusions in steel. In fact no variation of relative ductility was observed at temperature when the interpass recrystallisation of austenite was uncompleted. That proves evidently that the presence of lenticular clusters of coarse grains, which are produced by the transformation from unrecrystallised austenite grains, is without significant effect on anisotropy in reduction of area. In low temperature range the relative ductility in short transverse

Fig. 10. The relationship between finish-rolling temperature and the relative ductility of steel in the reduction of area of tensile specimens. The relative ductility is expressed as $d = \ln d_i/d_0$ with d_i : the corresponding axis of the fracture surface and d_0 : the initial diameter of the specimen.

direction is fastly increased with the decrease of finish-rolling temperature in comparison to that observed after rolling at high temperature in austenite range. The rolling in ferrite range is reflected not only in grains size increase but also in an increase of ductility of steel in through thickness direction in area of striction of tensile specimens. The opposite is observed for the rolling and transverse directions, the ductility is decreased with respect to that found in steel rolled in austenite range and by completed interpass recrystallisation. It seems logical to conclude at this point that the anisotropy in ductility of steel in phase of reduction of area of tensile specimens is connected to the microstructure and the texture produced by the rolling of steel in ferrite range in several passes. The rolling of steel with uncompleted interpass recrystallisation produces pancake shaped grains in the rolling plane, similar grains are probably obtained also by DIGBM. That would explain the similar relation between the rolling temperature and the ductility of steel in rolling and transverse directions in the striction area of tensile specimens.

The anisotropy is greater in steel S in which a predominant volume fraction of ferrite obtained by DIGBM was observed than in steel K, in which only polygonised ferrite was found. The difference in ani-

sotropy is much lower than the difference in grain size. The latter amounts to approx. 4 at a finish-rolling temperature of about 800°C, while the ratio of anisotropy is only about 1.4 between steels S and K. That suggests that the anisotropy is connected also to the texture of ferrite. At this moment no evidence is available which would permit to separate the part of anisotropy due to the microstructure from that due to the texture. Also no data on the effect of polygonisation and DIGBM texture are available.

VI. Discussion

In all steels a homogeneous and polygonal microstructure of ferrite and pearlite is obtained if the rolling is carried out in temperature range of completed interpass recrystallisation of austenite. The uncompleted interpass recrystallisation of austenite introduces in steel clusters of grains with size of approx. 2 ASTM numbers coarser and of different shape than those found in the matrix obtained by the transformation from recrystallised austenite.

From ferrite formed during the rolling the strain hardening is removed by recovery respectively polygonisation and a fast grain growth occurs because of strain induced grain boundary migration. Nuclea for this grain growth are polygonised subgrains more stable because of size, form or space orientation.

The effect of grain size on mechanical properties of steel, when the rolling is performed in austenite range, is smaller than that expected from the change in ferrite grain size in terms of the Hall-Petch equation. A strong anisotropy is introduced in steel by the rolling in presence of ferrite and it is manifested to the most in the reduction of area of tensile specimens machined in rolling direction.

The interlacing of different phenomena introduces ferrite of the following four origins in steel air cooled from finish-rolling temperature:

- 1) polygonal ferrite obtained at the transformation from recrystallised austenite,
- 2) mostly acicular ferrite obtained at the transformation of unrecrystallised austenite,
- 3) polygonised ferrite, and
- 4) ferrite produced by DIGBM from polygonised ferrite at the cooling of steel from finishing temperature.

Ferrite obtained by transformation is free of substructure, independently of the fact that it may be obtained by transformation of recrystallised and unrecrystallised austenite. Also ferrite formed by DIGBM is free of substructure and softer, while polygonised ferrite is harder. That, the different grain size, the texture of polygonised ferrite and ferrite formed by DIGBM confound the connection between grain size and the strength as well as yield point of steel, which can not be interpreted in terms of the Hall-Petch relation. The anisotropy found in steel at high temperature is due to sulphide inclusions. The anisotropy found in steel at low finish-rolling temperature, when the rolling is carried out in presence of ferrite, is connected to the microstructure as much as the texture of polygonised ferrite and ferrite obtained

by DIGBM. The relative influence of these factors was not investigated.

VII. Conclusions

(1) At high rolling temperature the interpass recrystallisation of austenite is completed and in steel a homogeneous and polygonal microstructure is observed with grain size decreasing with decreasing rolling temperature.

(2) At a definite temperature interpass recrystallisation of austenite is not completed. By transformation of unrecrystallised austenite a microstructure is produced with approx. 2 ASTM numbers coarser grain size, then that of grains produced by transformation from recrystallised austenite. The microstructure of steel rolled with uncompleted interpass recrystallisation is heterogeneous.

(3) When the rolling is carried out in presence of ferrite, strain is removed from ferrite by interpass recovery. In ferrite formed during the rolling and deformed and polygonised when the rolling is continued, a fast process of deformation induced grain boundary migration occurs. That leads to fast coarsening of ferrite grains and a microstructure which is even coarser than that obtained by the rolling at finish temperature higher over 200°C.

(4) The temperature of uncompleted interpass recrystallisation depends upon the composition of the steel. The temperature of formation of ferrite during the rolling depends mostly on the content of carbon in steel, however it is influenced also by other alloying elements.

(5) In steels containing aluminium and nitrogen, aluminium nitride is formed during the rolling. The precipitates of aluminium nitride hinders the grain growth of recrystallised austenite. That is reflected

in a difference of approx. 0.5 ASTM numbers in grain size in as rolled steel with respect to the steel without aluminium nitride.

(6) The influence of rolling temperature on mechanical properties in rolling direction is relatively small and it can not be explained in term of evolution of grains size in the same range of rolling temperature. The most plausible explanation seems to be in the heterogeneity of microstructure.

(7) When the rolling temperature is decreasing, the difference in mechanical properties between rolling and transverse direction is increased. Yield point and tensile strength increase faster in transverse direction while the increase of deformability is opposite.

(8) At rolling in ferrite range a strong deformation anisotropy is produced. The most evident measure of this anisotropy is the oval fracture of tensile specimens. The anisotropy is caused by the deformation and polygonisation of ferrite as much as deformation induced grain growth of ferrite, through grain size and shape as much as texture.

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