Effect of pearlite morphology on recrystallization behaviour in cold rolled high strength automotive steel sheets

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Abstract The present study is mainly focused on recrystallization behaviour and associated microstructure and texture evolution with the effect of second phase as pearlite. Two cold rolled sheets with 80% cold reduction consisted of coarse and fine pearlite bands along with ferrite. Cold rolling was followed by interrupted annealing at different soaking time to study the kinetics and recrystallization texture evolution. Results are analysed with the help of micro-Vickers hardness, microstructure and texture analysis through SEM and Electron Backscattered Diffraction (EBSD). Results clearly show the effect of pearlite band size on recrystallization kinetics and texture evolution. Faster recrystallization is observed for fine pearlite band compared to coarse band. Heterogeneous nucleation of grains took place at ferrite pearlite interface, grain boundaries of RD-ND orientations and within the deformed ferrite. Fragmentation and spherodization of pearlite lamellae takes place inside the colony of pearlite with increase in soaking time.

1. Introduction
High strength steels (HSS) generally consist of second phase mainly to enhance the strength. HSS have high strength to weight ratio and low formability, which is the major drawback for these steels in automotive applications. Formability of steels is determined by their microstructure, texture, grain size and second phase distribution [1-2]. Formability can be enhanced by formation of {111}//ND fibre orientation on recrystallization in single phase or extra low carbon steels [2]. As HSS consists of two phases, continuous efforts are being made to increase the formability of these steels by varying initial microstructures ferrite with pearlite/ bainite/martensite [3-4]. The microstructure evolution, recovery, recrystallization texture of initial ferrite pearlite microstructure to final ferrite martensite microstructure of dual phase steels has been reported [5]. After that study it was concluded that the effect of cold rolled ferrite –pearlite banded microstructure on recrystallization is topic of interest, as the pearlite banded structure was completely transformed to martensite on intercritical annealing [5]. The banded structure consists of carbon rich pearlite and low carbon ferrite and on intercritical annealing the carbon rich region of pearlite was transformed to martensite. The reasons for banding and their effects are reported in [6]. This banded structure was not well understood in terms of recrystallization. However, Recrystallization
kinetics, grain size and texture are influenced by the presence of second phase [7]. Recrystallization behaviour is affected in terms of driving force for recrystallization, sites of nucleation, size and distribution of second phase [7]. Whereas least importance was given to the softening and recrystallization behaviour with 80% cold reduction of initial ferrite-pearlite banded microstructure.

The aim of the present work is to study the recrystallization behaviour and texture evolution of 80% cold rolled C-Mn high strength steels with the effect of second phase as pearlite having variation in its morphology.

2. Experimental procedure
Material used in this investigation is high strength steel with composition C-0.09, Mn-1.65, Si <0.028, Nb-0.001 and Cr-<0.057. The alloy was casted and pre rolled up to 24 mm thick plate at Tata Steel Europe. Further hot rolling was carried out, first one at high temperature having recrystallization of austenite to occur and second one at lower temperature where austenite recrystallization did not occur. Both hot rolling scheme were followed by coiling at pearlite start temperature to create ferrite pearlite microstructure. Coarse grained ferrite-pearlite microstructure (here after referred as CP) was obtained by hot rolling above the austenite recrystallization temperature, whereas fine banded ferrite-pearlite microstructure (here after referred as FP) was obtained by hot rolling below the austenite recrystallization temperature. Subsequently hot rolled sheets are cold rolled to 1.2 mm thickness with 80% reduction. Interrupted annealing was carried out in salt bath furnace at 700°C with varying soaking time. Hardness was measured by micro Vickers indenter with 500 gm load and 20 seconds dwell time. Microstructural details and texture data were acquired from field emission gun scanning electron microscope combined with EBSD of TSL OIM. Microstructural observations were performed on the Rolling and Normal direction (RD-ND) plane of the sheet. Samples were polished as per the standard procedure for microstructural observation and etched with 2% nital. TSL OIM version 7.2 was used to analyse the data. Grain orientation spread criteria (GOS) was used in the range of 0.2-1.4 and grain size greater than 1 micron was used in partitioning of the deformed and recrystallized ferrite. Partitioning of the recrystallized grains from deformed grains by GOS criteria reported by [9].

3. Results
3.1 Effect of pearlite morphology on recrystallization annealing
Cold rolled microstructures consists of ferrite and pearlite. Pearlite band thickness was varied as shown in figure 1(a) coarse pearlite (CP), 1 (b) fine pearlite (FP). The variation of hardness in ferrite pearlite and recrystallization fraction of only ferrite in CP and FP microstructures after interrupted annealing at 700°C for different soaking times are shown in figure 1(c). Hardness values are reported from the bulk of the samples consisting of ferrite-pearlite. Whereas recrystallization fraction of only ferrite calculated from EBSD maps using GOS criteria is reported in the figure 1(c). Hardness curve shows two characteristics differences, increase in hardness from initial condition for first 10 s and starts to decrease thereafter with increasing soaking time, partitioned by dashed line as in figure 1. Increase in hardness form cold rolled condition for first 10 s is designated as part A, indicates hardening of ferrite-pearlite microstructure. Hardness decrease after 10 s is designated as part B, shows initiation of softening in ferrite pearlite microstructure. Softening consists of both recovery and recrystallization. This hardening behaviour is similar in CP and FP microstructures for first 10 s. Softening (recovery and recrystallization) behaviour varies with changing the behaviour of pearlite morphology with CP and FP microstructure with increase in soaking time.

In case of coarse pearlite (CP) microstructure it was observed that hardness starts decreasing below the cold rolled condition after 150 s of soaking time. In case of fine pearlite (FP) hardness decreases below cold rolled condition slightly before 60 s of soaking. Recrystallization of ferrite fraction shows that recovery dominates up to 60 s of soaking time and recrystallization starts thereafter in case of CP, whereas in case of FP, recovery starts at 10 and finishes by 20 s of soaking time, recrystallization starts thereafter from 30 s. Two horizontal dotted lines were drawn to track changes of recrystallization in initial 10 %, intermediate 38% and final stage 55 % recrystallization fraction. In initial stage, time
taken to reach 10% recrystallization fraction of ferrite with two different pearlite morphology was different. In case of CP time taken was 180 s, whereas in FP it reaches in 60 s of soaking time as indicated by the dotted line in figure 1. In intermediate stage, the time taken to reach the 38% recrystallization was 300 s for CP and 150 s for FP microstructures. In final stage, the time to reach 55% recrystallization fraction was 420 s in CP and 180 s in FP. This indicates that rate of recrystallization is faster in the FP microstructure, whereas recrystallization in CP microstructure is slower. In summary, hardening takes for first 10 s of annealing time in CP and FP microstructures. Changing the morphology of pearlite showed significant changes in the softening behavior. Recovery time decreases and recrystallization fraction increases in time with the FP microstructure, whereas recovery time increases, followed by slower recrystallization in the CP microstructure.

![Figure 1](image1.png)

**Figure 1.** Shows (a) coarse pearlite (CP) (b) fine pearlite (FP) cold rolled microstructure, (c) variation of hardness in ferrite-pearlite and recrystallization fraction of ferrite after annealed at 700°C for different soaking time in coarse pearlite. (P-Pearlite) and (F-Ferrite)

3.2 Evolution of Microstructure during recrystallization:

Microstructures of CP and FP after interrupted annealing of specimens at 700°C for different soaking time are shown in figure 2. High resolution inserts of the pearlite phase are placed on the top right corner of each image, allowing to compare the changes of pearlite in hardening and softening stages. Changes in ferrite and pearlite morphologies were tracked after hardening, at initial 10% recrystallized, intermediate 38% recrystallized and at final stage 55% of recrystallized volume fraction. The microstructure consisted of ferrite in grey colour, a pearlite colony of white colour, recrystallized ferrite and fragmented pearlite.

The microstructures of figure 2 show coarse and fine severely pancaked ferrite-pearlite microstructure after hardening stage; the ferrite pearlite microstructure remains unchanged after 10 s of soaking time compared to the cold rolled condition. The closely spaced lamellar morphology of the CP microstructures is retained as shown in figure 2(a). In the case of FP microstructures, a fragmented cementite morphology appears, cf. figure 2(a). In the initial stage of recrystallization, ferrite recrystallizes at the ferrite-pearlite interface, as indicated by dotted circles figure 2(b). In the same figure it is observed that fragmentation of the lamellar structure near the ferrite-pearlite interface, inside the colony of the lamellar structure is still maintained as observed in the high magnified image.
Figure 2. Microstructure of annealed (a) 10 s (b) 180 s (c) 300 s (d) 420 s time in coarse pearlite CP and (e) 10 s (f) 60 s (g) 150 s (h) 180 s of soaking time in fine pearlite FP. DF- deformed ferrite  P- pearlite FC- Fragmented Cementite
In the FP microstructure a fragmented cementite morphology was present in the pearlite colony with coarse cementite particles at the ferrite-pearlite interface; recrystallization of ferrite takes place at the interface as indicated by the dotted circles in figure 2 (f). In the same figure it can be seen that ferrite grains recrystallize at the fragmented cementite particles indicated by the rectangular box. At the intermediate stage with increasing soaking time, the ferrite recrystallization fraction increases to 38% and the lamellar structure is getting fragmented in fine spherical cementite particles and pearlite spheroidizes, cf. figure 2 (c). In the FP sample, as the recrystallization fraction increases, ferrite grains recrystallize at the ferrite pearlite interface as well as in the vicinity of fragmented cementite particles, while pearlite colonies remain unchanged. In the final stage of recrystallization, recrystallization fraction increases and, as shown in figure 2(d), the lamellar pearlite structure is now completely spheroidized. The recovered ferrite is present, still mainly adjacent to pearlite and in between two pearlite colonies. In the FP microstructure, fragmentation of plates takes place and coarsening of cementite plates is observed mainly at the interface, cf. figure 2(h). In the overall microstructure there was no recrystallization observed in the pearlite lamellar structure neither with coarse nor fine pearlite bands.

![Figure 3](image-url)  
**Figure 3.** IPF of recrystallized ferrite grains (a) 180 (b) 300 (c) 420 s soaking time in CP and (d) 60 (e) 150 (f) 180 s of soaking time in FP microstructures

### 3.3 Evolution of Recrystallization texture:

The recrystallization textures of CP and FP specimen were investigated by EBSD. The ODFs were plotted for $\phi_2=45^\circ$ sections of both deformed and recrystallized grains, cf. figure 4.

#### 3.3.1 In Coarse pearlite microstructure, in the initial stage of recrystallization, where the recrystallized fraction was 10%, fragmentation of pearlite lamellar structure appears at the ferrite-pearlite interface as in figure 2(b). A strong texture appeared at cube and near cube orientations with secondary maxima on the RD fibre near to $\{112\} <1\text{-}10>$. In the intermediate stage, with 38% of recrystallized volume fraction,
where pearlite lamellar structure gets fragmented, cf. figure 2 (c), a weak texture appears near \{111\} <1-10> and \{111\} <0-11> on the ND fibre and on \{112\} <1-10> on the RD fibre, along with some minor components of \{114\} <5-91> and \{115\} <0-51> orientations, cf. figure 4 CP (d). In the final stage of recrystallization (55%) where complete sperodization of pearlite lamellar morphology takes place, as shown in figure 2 (d), the overall texture intensity decreases on the RD fibre with maxima at \{114\} <1-10>. The ND fibre weakens and the Goss component appears. With the increase in recrystallization fraction, we see that deformed ferrite and pearlite consists of a strong RD fibre and very weak ND fibre texture components as shown in figure 4(a-c-e).

![Figure 4. ODF of \(\phi_2 = 45\) section of deformed (ferrite-pearlite) and recrystallized (ferrite) in coarse and fine pearlite microstructures](image)

Ferrite-pearlite (F-P), Ferrite (F)

3.3.2 **In the fine pearlite microstructure**, in the initial stage of recrystallization with 10% of recrystallized volume fraction, the RD fibre texture dominates with texture maxima at \{113\} <1-10> with 9.2x mrd. Whereas weak ND fibre components are present with \{111\} <1-10> and near to \{111\} <1-1 2> with 3.2x mrd. Along with it some minor components of \{114\} <1-92> and \{223\} <7-10 2> orientations, cf. figure 4 FP (b). In the intermediate stage, with 38% recrystallized volume fraction, weakening of the texture takes place as shown in figure 4 (d), with texture maxima at \{114\} <1-10> and \{114\} <2-61> on the RD fibre. Whereas maxima intensity on the ND fibre appeared at \{111\} <1-10> and \{111\} <0-1 1> with 3x mrd. In the final stage (55% recrystallized volume fraction), coarsening of cementite at the ferrite-pearlite interface, the intensity increases to 4x mrd on same components as mentioned above for 55% recrystallized volume fraction.

4. Discussion:
Cold rolled microstructure with two distinct pearlite morphologies of coarse and fine pearlite bands showed characteristic differences in terms of recrystallization kinetics, microstructure and texture in initial, intermediate and final stage of recrystallization at 700°C. In the coarse pearlite (CP) microstructure, the pearlite exhibits a lamellar morphology, whereas in the fine pearlite (FP)
microstructure a fragmented pearlite morphology is shown, with RD-ND fibre textures after 80% cold rolling, irrespective. The cold rolled microstructures and textures of CP and FP microstructures are well reported in [9]. The cold rolled pearlite band size and morphology had a clear effect on the annealing kinetics, cf. figure 1(c), whereby two distinct stages A and B are present. In part A, after 10 s of soaking time, hardening takes place within the ferrite pearlite microstructure. The reason for hardening can be attributed to pinning of dislocations by the carbon atoms, similar to bake hardening behaviour [10]. In part B, softening takes place both in CP and FP microstructures, which consists of recovery and recrystallization. The recrystallization was slower and sluggish till the hardness reaches its cold rolled value. Once the hardness drops below the cold rolled condition, the recrystallization fraction increases with soaking time. From ferrite recrystallization curves as shown in figure 1, it was evident that slower and more sluggish recrystallization takes place in the CP samples as compared to FP samples. In the CP microstructure, cf. figure 2 (b) and figure 3 (a), it was confirmed that concurrent recovery and recrystallization taking place, whereby recovered grains exhibit bigger grain size when compared to the recrystallized grains. It was further confirmed with ODF maps of figure 4 (b) in the CP microstructure, that recovered grains were of Cube (\{001\}<010>) and near to cube orientation. As these orientations are having low stored energy, recrystallization of these grains is not possible. The grains recovered faster due to higher amount of cold deformation and low substructure present in them. The reason for concurrent recovery and recrystallization, might be due to spheroidization of the pearlite lamellar structure at the ferrite-pearlite interface. Spheroidization leads to carbon dissolution into the ferrite grains and pin the dislocation by reprecipitation and inhibit the progress of recrystallization. It is also the reason for the increase in initial hardness from cold rolled condition [10-11]. Initially, due to prolonged recovery in the CP microstructure the amount of stored energy decreases for nucleation and growth. Spheroidized particles also pin the migration of high angle boundaries with Zener solute drag effect and retard recrystallization mainly at the interface of ferrite and pearlite [11]. With the increase in recrystallization fraction the amount of carbon in ferrite is increasing due to spheroidization and it weakens the ND fibre and strengthens the Goss component (\{110\}<001>), cf. figure 4 (f), which is in good agreement with results reported by [12-13]. In the final stage of recrystallization overall weakening of texture takes place where the pearlite lamellar structure is spheroidized.

5. Conclusions
In the present work two distinct types of pearlite bands consisting of different morphologies were studied during recrystallization at 700°C with varying soaking time
- At the very early stage of annealing, a sudden increase in hardness has been observed.
- The micro Vickers hardness results shows different softening behaviour for coarse and fine pearlite. Steel sheet with fragmented lamellae of fine pearlite bands soften faster in comparison to lamellar, coarse pearlite bands.
- The recrystallization fraction of ferrite is influenced by the pearlite morphology. In the case of coarse pearlite recrystallization, the fraction is lower in comparison to fine pearlite.
- Recovery and recrystallization is slower and more sluggish in case of coarse pearlite due to spheroidization of cementite. Whereas recrystallization dominates in the case of fine pearlite band.
- Weakening of the texture takes place with increase in recrystallization fraction mainly due to solute carbon and C-Mn interaction.
- In the very early stage of annealing (part A) hardening occurs, which might be due to dislocation pinning by carbon diffusion to free mobile dislocations.

6. References
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