The output of crude steel in China was 152 million tons in 2001. Among this, structural steels occupied about 95% of total steel production. In Oct. 1998 Chinese government opened R & D project: “Fundamental Research on New Generation of Iron and Steel Materials in China” (N.G. Steels). The progress of on-going project has been briefly reported in this paper. In order to get microstructure refinement in structural steels, the following 5 ways have been studied:

For Ferrite + Pearlite microstructure in plain carbon steels and low-alloy steels:
1. Purified steel-making→Fully equiaxed continuous casting→Rough-mill with higher Zener–Hollman parameter (γ-DRX refinement)→Finishing-mill rolling by Deformation Induce Ferrite Transformation (DIFT) technology.
2. For thin-slab continuous casting and rolling (CSP) process, ultra-fine sulfides (20–60 nm) and oxides (5–20 nm) controlling technology.
3. For Low Carbon Bainite (and Ultra Low Carbon Bainite) microstructure (LCB/ULCB) in microalloyed steels, combination of Deformation Induced Precipitation (DIP) and subsequent middle temperature phase transformation controlling.

For quench-tempered martensite microstructure in alloy structural steels:
4. Ultra-fine γ grains by innovated heat treatment and alloy design;
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ratio reaches 98 % in a billet.

3. Rough-mill rolling with high Zener–Hollomon parameter. At temperature for rough-mill rolling, dynamic recrystallization or dynamic recovery will take place. An example for plain carbon steel Q235 (according ISO standard, Q235 in Chinese designation is E235 in ISO designation) at modern metallurgical production, strain-rate is normally around 10/s (\(\dot{e}\) ranges between 1–30/s). At true strain \(\varepsilon/H11005\) 90 %, condition to get \(\gamma\rightarrow\alpha\) phase transformation can be expressed as follows:

\[
\Delta G = -V\Delta G_v + V\Delta G_e + \Delta G_s + \Delta G_D \tag{1}
\]

Where

\(\Delta G_v\): Free energy change in volume, this is chemical driving force for phase transformation.

\(\Delta G_e\): Elastic strain energy change.

\(\Delta G_s\): Surface free energy change.

In case of deformation process, one new term should be added to formula (1). That is stored deformation energy \(\Delta G_D\). Deformation energy is not usually considered in free energy change process because phase diagram we use is under normal pressure with 1 atm. Deformation energy is released by recovery, heat transfer, but it can be partly stored in material under rolling. If deformation energy could partly be stored and change to be driving force for phase transformation under some conditions, the formula (1) should be rewritten as following expression:

\[
\Delta G = -V\Delta G_v + V\Delta G_e + \Delta G_s + \Delta G_D + \Delta G_D \tag{2}
\]

More strictly speaking, \(\Delta G_D\) term should be described as \(V\Delta G_D\). Here we just simply and conceptually express it. \(\Delta G_D\) should be related with dislocation parameters and Zener–Hollomon parameters by following calculation:

\[
\Delta G_D = \mu(\rho - \rho_0)b^2
\]

\[
\sigma = \frac{Mab(\rho - \rho_0)}{\varepsilon = A(\sinh(\alpha\sigma))^{\frac{1}{n}} \exp(-Q/RT)}
\]

\[
Z = A(\sinh(\alpha\sigma))^n
\]

\[
Z = \varepsilon \exp(Q/RT)
\]
At higher rolling temperature, as mentioned before and seen in upper part of Fig. 3, $\Delta G_D$ is released by DRX or DR process in rough-mill rolling. At lower rolling temperature where is near to A3 point, A3 point should be varied due to $\Delta G_D$ induced; A3 is seen in Fig. 4. Now A3 line is changed to $\Delta G_D$ (A3 at deformation case), the larger the $\Delta G_D$ is induced and stored, the higher the AD3 is. In the temperature region between AD3 and Ar3, this is $\gamma \rightarrow \alpha$-unstable area where $\gamma \rightarrow \alpha$ might take place. Many experiments with varied plain carbon steel and low alloy steel have been done which confirms this “Deformation Induced Ferrite Transformation” process as show in Fig. 5 at some heating and cooling conditions, as an example martensite microstructure can be got without deformation, ultra-fine ferrite has been got with $825^\circ C / \varepsilon = 60\%$ deformation. The lower part of Fig. 3 shows DIFT process in the same kind of plain carbon steel.

Thin-slab continuous casting and rolling process (CSP, for example) is more popular used in plain carbon steel strip production. The capacity for this process is about 10 million tons per year in China by 2005. In order to get UFG in this production, investigation and developing work in Zhujiang Steel CSP have been performed. As shown in Table 2, there is high cleanliness steel-making workshop, sulfur content in average reaches 52 ppm, the difference between total Al content with soluble [Al] is 10 ppm in average. In the case of purified steel-making, sulfides precipitate at 1100–1150°C region as shown in Fig. 6, where is direct-rolling without any $\gamma \rightarrow \alpha$ process before rolling. By TEM investigation as shown in Fig. 7, sulfides and oxides have been ultra-fined, the refinement of sulfide is accompanied by F1$\rightarrow$F5 hot-rolling process. Oxides as dispersive

| C   | P   | S    | Al$_t$ | Al$_s$ | O   | Al$_{O_3}$ |
|-----|-----|------|--------|--------|-----|------------|
| 0.056 | 0.014 | 0.0052 | 0.028  | 0.027  | $\leq 30$ ppm | 0.0015 |

Table 2. Chemical composition average in 63 heats with Jan. 2002.
precipitates in the dislocation line and grain boundaries, and oxide size of precipitates is about 5–20 nm with spinel (Fe₃O₄) structure. Therefore, it is considered that soluble [S] and [O] precipitates or deformation induced precipitation, at direct-rolling process, and ultra-fine sulfides and oxides act as γ-DRX grain-growth prohibit. The finer α-grain size distribution is shown in Fig. 8, which varies with rolling pass and final sheet thickness. The mechanical properties are shown in Table 3. According to Chinese Criterion (GB 700-88) plain carbon steel with 0.06–0.12 % C should have yielding strength (σy) reaching 195 MPa and tensile strength (σb) reaching 315–390 MPa. From Table 3, the average strength level of tested strip (total output is 18 000 tons) has been doubled, compared with Chinese Criterion (GB 700-88).

2. Microstructure Refinement in Low-carbon Bainite Steels

The microstructure with ultra-fine ferrite and pearlite is not a unique choice for all applications in microalloyed steels. As being studied in comparison between (UFG F-P) and acicular ferrite (AF) microstructure in the same composition of ultra-low carbon bainite steel, which is
shown in Fig. 9 and Table 4. AF microstructure has better resistance to stress corrosion cracking (SCC) in H2S environment for line pipe application even UFG grain size refines to about 1 μm.4) From one of our study5) it shows that hot deformation has strong effect on microstructure refinement for line pipe LCB/ULCB steels. Investigation on CCT and DCT diagrams has been carried out which demonstrates that hot deformation can accelerate transformation, depress the formation of lath ferrite and bainite, and refine the island structure, so that it promotes the formation of acicular ferrite microstructure.

One way to refine the microstructure in LCB/ULCB steels is to develop Deformation Induced Precipitation (DIP) and combination of DIP with subsequent phase transformation controlling in middle-temperature region. An example is called as “Relaxing-precipitation-Control (RPC)” technology, as shown in Fig. 10. DIP would occur after final rolling immediately in Nb-containing microalloyed steel. If certain period (a few seconds to tens seconds) can be kept at suitable temperature region (or after TMCP it followed by reheating at suitable temperature region), dislocation structure for rolling-state will be relaxed to some more stable state, due to dislocation redistribution and DIP process control, these cause mechanical properties improved and yield strength raised to about 800 MPa ($\sigma_y = 150$ MPa) as shown in Fig. 11, or both $\sigma_y$ and SCC resistance rose to higher level under lower cost condition (save micro alloying element spending).

### 3. Microstructure Refinement in Alloy Structural Steels

Quench-Tempered Martensite (QTM) structure is popular microstructure in alloy structural steels. Since final process for their application is that all production process should be done in machinery workshop or factory, the final microstructure refinement would be performed beyond metallurgical process. Considering this situation, fast heat-treatment technology (in our study, D.C. electric touching heating with heating velocity up to 200°C/s), $\gamma$-grain size
can be refined up to \(-2 \mu m\). **Figure 12** is the variation of mechanical properties with \(\gamma\) grain size in 42CrMo/ISO683–1/ASTM A340, A322/AISI 4140/SCM 440 steel, it demonstrates that all mechanical properties have been much improved using this method. The more important fact is that delayed fracture resistance is also much improved by \(\gamma\)-refinement if \(\gamma\) G.S. downs to 2–5 \(\mu\)m, as shown in **Fig. 13**.

In order to increase delayed fracture resistance in alloy structural steel, the principles for alloy-design should be re-
vised or added. In order to increase the cohesive energy for interfaces, such as grain boundaries, interface between carbides and matrix, the Mo content in 42CrMo should be changed. In order to increase hydrogen trap sites and disperse hydrogen trap more uniform distribution in the QTM matrix, some benefit-alloying element, such as vanadium should be added.  

Another way to develop high resistance to delayed fracture steel is to investigate the carbide-free bainite/martensite multiphase steel (CFB/M). In a 0.20%C-2%Si-2%Mn-0.5%Cr steel, the multiphase steel with 18–25% carbide-free bainite, about 8% carbon-enriched austenite film which locates at lath/sub-lath boundaries, and martensite microstructure have been studied, as shown in Fig. 14.7,8) B/M microstructure has higher strength while austenite film is good hydrogen trap site. Their mechanical properties are as following: \( \sigma_s = 1600\, \text{MPa}, \sigma_{0.2} = 1335\, \text{MPa}, \delta_s = 13.5\%, \psi = 56.2, A_k = 81\, \text{J} \). By testing of susceptibility to [H] embrittlement, which shows in Table 5, the new developed steel (U20Si) has much better delayed fracture resistance than 42CrMo has.

4. Summary

From physical metallurgy point of view, 5 ways to get microstructure refinement of structural steel in China have been reported in this paper. From chemical metallurgy point of view, the purified steel-making technology and solidification technology to have fully equiaxed crystal mi-

Fig. 12. Effect of \( \gamma \)-grain refinement on mechanical properties in 42CrMo steel.

Fig. 13. Effect of prior \( \gamma \) grain size on delayed fracture resistance in 42CrMo.

42CrMo/ISO683-1/ASTM A340.A322/AISI 4140/SCM 440/42XM

Fig. 14. TEM micrographs of CFB/M (U20Si).

| Materials | Electricity density for change \( \lambda \) (A/cm²) | Time for [H] charge (hr) | Mechanical properties | \( E_{\text{AI}} \) |
|-----------|----------------|------------------|-----------------|----------|
| U20Si     | 0              | 0                | 1210 1520 18.1 | 58.0 0   |
|           | 0.5            | 4                | 1190 1490 12.6 | 47.6 18  |
| 42CrMo    | 0              | 0                | 1410 1510 14.8 | 49.6 0   |
|           | 0.5            | 4                | / 1460 1.5     | 3.1 94   |

\( E_{\text{AI}} \) — Embrittling Index, \( E_{\text{AI}} = (\psi - \psi_0) / \psi_0 \times 100\% \)
rostructure are two key processes, which support ultra-fine grain steels to perform and apply for the customs. In order to develop and finally form new production route, the following 3 aspects should be emphasized:

1) On-line system for quality control, quality prediction, mechanical properties and microstructure prediction.
2) Welding and joining technology for applying ultra-fine grain steels.
3) Advanced technology to analyze and inspect ultra-fine microstructure, especially when $\alpha$ grain size downs to about 1 $\mu$m and second phase size downs to nanometer.

The last 3 aspects are not included in this paper. Up to now, about 50,000 tons of tested steel have been produced, these products are on trial application, including beams and parts for vehicle and truck, rebar for building industry, steel for container and weathering steels for communication and railway industry, microalloyed plate for line pipe and engineering construction, high strength ($\sigma_b/H11005 \geq 1,500$ MPa) bolts for car and engine. About 20 steel companies in China, whose capacity is more than 50% of total capacity in whole country, are joining this program.

Acknowledgments
The author is chief-scientist for the reported R & D program, but many works have been performed by participators who come from R & D sector, total people are 182, and participators who come from industry, the numbers are more than 100. The author is grateful to all efforts from my colleagues and participators. We are acknowledged that this project is financially supported by Ministry of Science and Technology in Central Government of China.

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