Integrated Production Technologies for Ultra-fine Grained Steel Sheets

Manabu KIUCHI

Professor Emeritus, University of Tokyo, Japan Research and Development Center for Metals (JRCM), 5-30-1 Shiba, Minato-ku, Tokyo 108-0014 Japan.

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A national project was conducted by NEDO and executed by a consortium organized by JRCM with aims to develop integrated production technologies necessary for manufacturing ultra-fine grained steel (UFGS) sheets. In the project, the diverse technologies were concurrently developed relating with (1) high-speed large-reduction semi-continuous hot forging, (2) high-speed short-interval hot tandem rolling, (3) multi-cycle hot bending for strain accumulation, (4) high-strength anti-wear rolls, (5) multi-functional lubricants, (6) mathematical modeling and simulation of ultra-fine grain generation and (7) joining of UFGS sheets. The project succeeded in building up the integration of advanced technologies available for overall steel sheets manufacturing as well as production of UFGS sheets. Utilizing the developed technologies, UFGS sheets of plain low carbon steel having 1.0–2.0 mm thickness, 300 mm width, 1.0 μm grain diameter and 600–700 MPa tensile strength were successfully manufactured and found assuredly formable to practical products.

KEY WORDS: forging; rolling; multi-cycle bending; ultra-fine grain; steel sheet; roll; lubricant.

1. Introduction

Steel sheets possessing high strength, flexible deformability, quality surface and stable long life are strongly demanded by automobile, electric appliance, machine, shipbuilding and architecture industries. Ultra-fine grained steel (UFGS) sheets are recognized to be one of the most effective solutions to reply to those demands. For instance, the most urgent and serious issue for car manufacturers is to make their products environmentally compatible. Due to such situation, they need to take powerful countermeasures to obtain new mother materials far more appropriate and superior for their car manufacturing than before. Figure 1 shows mechanical properties of high strength steel sheets currently being used for cars.

UFGS sheets are capable of coping well with such demands and playing vitally important roles for the inevitable evolution of cars. Similarly, in coming future, advanced products and systems such as extremely energy saving industrial machines, highly functional home electric appliances, high speed light weight working robots, reliable long life houses and diverse clean and efficient infrastructures as well as environmentally harmonized passenger cars will certainly be manufactured and built up based on superior steel sheets. UFGS sheets will contribute to the development of such products and systems owing to their economical production cost, excellent recycle-ability and superior mechanical properties as well.

This paper is going to explain the outcomes of a national project named “PROTEUS”, that aimed to develop production technologies for manufacturing UFGS sheets. The project was conducted by NEDO, managed by JRCM and executed by a consortium of industry and university. The research and development works were carried out since 2002 and finished in March, 2007.

2. Process Design for Manufacturing of UFGS Sheets

Low carbon UFGS sheets are considered as one of the most valuable mother sheets for diverse industries. Their strength is enhanced only by ferrite grain refinement without utilizing any rare micro-alloying elements. The sheets have excellent properties, flexible usability and economical competitiveness comparing with other steel sheets. They also have good adaptability to re-cycling, re-using and re-sourcing. They are capable of saving energy and working as
an environmentally compatible mother material. However, the generation of ultra-fine grains of 1.0 \( \mu \text{m} \) diameter level in plain carbon steel sheets is extremely difficult. The process principle to generate ultra-fine grains in steel sheets was suggested by the preceding national project, named “Super Metal Project”.\(^1,2\) The research works in project clarified the fact that, in order to manufacture UFGS sheets through hot rolling, large amount of strain energy should be added to the sheets by means of high thickness reduction rolling at comparatively low temperature. Large strain energy would activate re-crystallization and low temperature would constrain grain growth, as the result, ferrite grains might be refined to ultra-fine. The principal conditions necessary to generate ultra-fine ferrite grains looks rather simple, however, it is not easy to satisfy these conditions in practical hot rolling. The preceding project suggested that the thickness reduction per one-pass should be 50–80\%, the accumulated total reduction should be around 90\% and the sheet temperature should be lower than 750\(^\circ\)C. Actually, these values exceed far from the possible limit of the present hot rolling technology.

Hot rolling is the most productive process for manufacturing steel sheets. If it is feasible, the commercial production of low cost UFGS sheets becomes real. However, the conventional hot rolling technologies are unable to cope with the conditions suggested by “Super Metal Project”. The rolling force becomes extremely large as 3 times of the available limit of the conventional hot rolling. The rolling mills that are capable of supporting such a big force have never been built. There are no rolls and no lubricants that can bear such high rolling pressure (see Fig. 2).

In order to realize the hot rolling of UFGS sheets, a new framework of sheet rolling technologies, that is capable of reducing roll-separating force, achieve high level of thickness reduction and enhance strain energy accumulation, should be built up.

Taking such situation and technological obstacles into account, for efficient promotion of the project, the four working groups were organized to deal with the following subjects.

(1) High-speed large-strain hot rolling technologies,
(2) Highly functional roll and lubricant technologies,
(3) Mathematical modeling and simulation of ultra-fine grain generation,
(4) Joining technologies for UFGS sheets.

Every group was consisted of several sub-groups. For example, the group (1) included 3 sub-groups engaged into different process technologies, such as 1) high-speed large-reduction semi-continuous hot forging, 2) high-speed short-interval hot tandem rolling and 3) multi-cycle strain accumulation hot bending. Figure 3 shows a schematic framework of manufacturing process of UFGS sheets investigated in this project.

The technologies aimed by this project were expected to be usable for not only manufacturing UFGS sheets, but also overall steel sheet production. For instance, the semi-continuous large-reduction hot forging was considered to be capable of taking the place of conventional hot rough rolling for plate manufacturing. High-speed short-interval tandem rolling technology was also expected to be available for diverse finishing strip rolling.

3. High-speed Large-reduction Semi-continuous Hot Forging

Generally, hot sheet rolling consists of rough rolling and finish rolling. In hot rough rolling, the thickness of c/c (continuously cast) slab is reduced to the required value through multi-pass rolling. If large thickness reduction could be obtained by using small number of mills and rolls, the productivity might be remarkably improved. More importantly, the large thickness reduction effectively refines grains in rolled plates and/or sheets. In actual cases, however, in order to give such large thickness reduction to slabs, extra-ordinarily big mills and rolls are necessary. Slabs usually have 250–350 mm thickness, therefore, the large reduction rough rolling needs very big rolls with 2 000 mm diameter or more, as the result, the rolling force becomes unrealistically large.

Due to the situation like this, in this project, instead of rough rolling, a new high-speed large-reduction semi-continuous forging technology was introduced to realize effective large thickness reduction of slabs.\(^3\) A forging machine with novel structure and driving mechanism was designed and a test machine was built for the experimental investigation. The machine was capable of giving 90\% thickness reduction to work-pieces through single-pass forging. It worked with high forging speed of 100 cycle/min and 30–60 mm feeding stroke for one cycle (see Fig. 4).
The test machine has one-tenth dimension of the designed practical forging machine. If it is scaled up, one forging machine actually has the working ability same as those of 2–3 conventional rough rolling mills at least.

The crank mechanism driven by an electric motor enables horizontal motion as well as vertical motion of forging dies. The work-piece is fed horizontally by two pairs of pinch-rolls installed at the inlet and the outlet of the forging machine. Their intermittent motion is synchronized with the rotation of the crank mechanism for the dies. A three-step water-cooling devices installed in adjacent to the outlet is capable of fixing the forged internal structure and prevent the growth of austenite grains.

By using the test machine, a series of forging tests were carried out with respect to a plain carbon steel of 440 MPa grade having a simple chemical composition of 0.136mass%C–0.64mass%Mn–0.02mass%Si. The mean austenite (γ) grain size of the heated work-piece before forging was found roughly 250 μm. The work-piece temperature just before forging was 1273 K. The thickness reduction was changed in the range from 43 to 82%. After forging, the work-piece was rapidly cooled by water and its microstructure was observed.

As the result, the homogeneous microstructure consisting of austenite grains, of which diameter was less than 30 μm, were obtained at the exit of the forging machine in cases when the thickness reduction was larger than 70% and the temperature of the work-piece was 1273 K (see Fig. 5).

The reverse transformation of the forged work-pieces under re-heating was also investigated. It was found that the austenite grain size was further refined and became roughly 10 μm (see Fig. 6).

It was confirmed that the refinement of austenite grains in hot sheet bars could be achieved by the large-reduction semi-continuous forging. Such austenite grain refinement before hot finish rolling is essentially effective for ferrite grain refinement to the level of 1.0 μm.

4. Super Short Interval Multi-pass Rolling (SSMR)

The preceding research works suggested that the hot finish rolling conditions necessary for manufacturing UFGS sheets were (1) large thickness reduction and (2) comparatively low sheet temperature. The thickness reduction was recommended to be higher than 90% per one rolling pass and the sheet temperature to be lower than 973 K. However, it is quite difficult to satisfy these conditions on the ground of conventional sheet rolling technologies, because the rolling force becomes extraordinarily large and roll-sheet contact pressure rises to extremely high. Therefore, in order to realize the hot finish rolling for UFGS sheets, the rolling process should be reformed to reduce the rolling force and roll-sheet contact pressure down to the acceptable level. At the same time, the strain accumulation in rolled sheet should be enhanced as large as possible.

In this project, for the finish rolling that satisfies such requirements, the super short interval multi-pass rolling technology was introduced instead of one-pass heavy duty rolling. So as to achieve the strain accumulation effectively, the interval of the passes must be shorter than so-called strain/stress relaxation time. The interval, that is the time necessary for a sheet to move from one roll-stand to the next, must be short enough so that the deformation energy generated in the sheet does not dissipate before all rolling passes finish.

The interval of rolling-passes can be made short by increasing the rolling speed and/or decreasing the inter-stand distance. It should be noticed that the high-speed rolling accelerate heat generation rate in the sheet and causes temperature rise. The temperature rise promotes the strain relaxation and decreases the effect of strain energy accumulation. Therefore, the generated heat must be removed from
the sheet immediately at the exit of roll-gap. Taking those matters into consideration, the super short interval multi-pass rolling mill was designed for the manufacturing test of UFGS sheets. The process was named as “SSMR (Super Short Interval Multi-Pass Rolling)”. The features of SSMR mill are summarized as follows. (1) At the downstream stage of hot finish rolling, at least two roll-stands including the final one are installed at extremely short intervals comparing with those of conventional hot tandem mills. (2) In those roll-stands, the high speed and large thickness reduction rolling, such as 40–50% reduction per pass, is carried out. (3) The interval time is shorter than 0.3 s. (4) The temperature of sheet is kept around Ae3 by inter-pass cooling, (4) After rolling, the sheet is cooled down immediately. If the sheet temperature is too low, the rolling force exceeds the mill capability. In addition, the microstructure of rolled sheet contains irregularly deformed grains. On the contrary, if the rolling temperature is too high, the effective strain accumulation cannot be achieved and, as the result, the effective grain refining is not attained.

In SSMR process, the sheet temperature is kept higher than the value recommended by the preceding research works because of the aim to reduce the rolling force. Therefore, the immediate cooling of sheet just after rolling is indispensable for completing the rapid ferrite transformation and suppressing grain growth.

SSMR is based on the following technologies and equipments. 1: Tandem rolling mill with extremely short interval of roll-stands, 2: Highly functional control system to carry out high speed and large reduction rolling, 3: Strongly effective inter-stand cooling system for immediate heat removal from sheet, 4: Highly powerful rapid cooling technology to prevent ferrite grain growth. A test mill system was built for research works. It was a 3-roll-stands hot tandem mill and its scale was roughly 1/4 of actual mills. Figure 7 shows a schematic illustration of the test mill system. The interval of F2 and F3 stands was about 1.0 m. Test-strips were heated up to 1 273 K and subjected to 3-pass finish rolling. They were rolled down to thin sheets with 1.0–2.0 mm thickness. The thickness reduction at each pass was in the range from 40 to 50% and the accumulated total reduction was around 100%. The minimum inter-pass (interval) time was 0.17 s. The sheet temperature was controlled to be around Ae3 by means of the inter-stand cooling systems. After rolling, sheets were immediately cooled down to 923 K by the specially designed rapid cooling system. Then they were cooled in the air down to room temperature.

Figure 8 shows the microstructures of manufactured plain carbon steel sheets. The ferrite grain size is 0.9 μm in surface layer and 1.2 μm as average through the thickness. Figure 9 shows the internal structures of three kinds of
steel sheets manufactured by different processes. A steel sheet made by a conventional hot strip mill has ferrite grain size of about 5 μm. A steel sheet by a specifically built compact mill (in Japan), that is able to achieve high 50% thickness reduction in commercial production, has ferrite grains of 2.5 μm. It is clear that a UFGS sheet manufactured through SSMR process has ferrite grains much smaller than those of two other sheets.

Through the investigation, the following facts are confirmed.

1. Plain carbon UFGS hot strips with composition of 0.15mass%C–0.74mass%Mn–0.01mass%Si can be manufactured by SSMR process.
2. The ferrite grain size of rolled strips is 0.9 μm in surface layers and 1.2 μm on the average.
3. The rolling force is suppressed to be within the acceptable range by introducing multi-pass and relatively high temperature rolling.
4. Actually, SSMR technology can reduce the rolling force down to half of that estimated on the suggestion made by “Super Metal Project”.
5. Owing to the multiple innovations, SSMR technology has become usable for overall steel sheet rolling as well as rolling of UFGS sheets.

5. Multi-cycle Hot Bending

The strain accumulation could be attained in steel sheets by multi-cycle plastic bending. Standing upon this principle, a strain accumulation multi-cycle hot bending technology was developed. For effective performance of multi-cycle bending, the specially designed multi-roller benders were built. Each bender was composed of upper and lower vertical loaders and a group of upper and lower horizontal flat rolls.

Effects of hot multi-cycle bending on strain accumulation and grain refinement were investigated with respect to Fe–0.13mass%C–0.01mass%Si–0.75mass%Mn sheets under various thermo-mechanical conditions. Through the tests, the best specifications of the bender and the best operation conditions were clarified. It was found that the multi-cycle hot bending was capable of making ferrite grain size after bending into almost half of that before bending. At the same time, it was noticed that the sheet temperature should be kept in an appropriate range for effective grain refining.

6. Functional Roll and Lubricant

In the conventional hot sheet rolling, the thickness reduction is usually less than 40%, the rolling force (roll-separating force) per unit width is less than 15–20 kN/mm and the total rolling force acting to one work roll is less than 40 000 kN. For hot rolling of UFGS sheets, as mentioned above, the rolling force increases tremendously. If it is carried out without any countermeasures, the estimated rolling force per unit width exceeds 45 kN/mm and the total rolling force becomes 120 000 kN at maximum. Needless to say, the conventional rolling mills, rolls and lubricants are not able to support such high level of rolling force and roll-sheet contact pressure.

By introducing SSMR technology, the target value of the unit rolling force was reduced to 30 kN/mm and the total rolling force was lowered to 60 000 kN. Even though the target values were drastically reduced by SSMR technology, they are still much higher than the level that the conventional hot rolling technology can bear. For an instance, as for the unit rolling force, the target value 30 kN/mm is still roughly twice of the present possible limit.

Therefore, in order to utilize SSMR technology for practical rolling, high functional rolls that can bear large rolling force and high contact pressure were needed. For SSMR technology, rolls having high surface hardness, anti-adhesion resistance and anti-wear strength are indispensable. In addition, effective lubricants that can support high speed and large reduction rolling are necessary.

The lubricants are requested to have two important functions, one is to introduce steel sheets smoothly and stably into roll-gap and another is to reduce roll-sheet contact pressure and total rolling force as well. The lubricant that is effective for the smooth and stable introducing needs rather high friction coefficient. On the contrary, the lubricant that reduces the sheet-roll contact pressure and the rolling force needs rather low friction coefficient. Two functions are contrary to each other, however, high-speed large-reduction rolling as like as SSMR needs such lubricants (see Fig. 10).

6.1. Super Cermet-roll

Figure 11 shows the mechanical properties of rolls required for heavy duty hot rolling such as SSMR. The dras-
tic improvement of roll surface strength and hardness should be achieved to bear the required high contact pressure and preserve high anti-wear resistance.

The cermet (ceramics–metal) roll is composed of a steel alloy core and a WC sleeve. The WC sleeve has extremely high hardness, strength, elastic modulus and anti-wear resistance. It is an excellent material for surface layers of rolls. However, WC is a brittle material and has not satisfactory toughness, therefore, the WC sleeve needs to be reinforced through combining with the appropriate tough steel alloy core. However, it is not easy to obtain high enough bonding strength between steel alloy core and WC sleeve. Before this project, the attainable bonding strength between them was roughly 600 MPa. From basic study and empirical knowledge, it was predicted that high bonding strength of 1000 MPa would be necessary for WC-sleeve cermet rolls in order to bear the heavy load for SSMR process.

In the project, the effects of bonding process parameters were systematically investigated. Consequently, the best process was found. The bonding strength reached to higher than 1000 MPa that was high enough for the required heavy duty rolling. Thus highly functional cermet rolls were developed and named as “Super Cermet Roll” (see Fig. 12). Super cermet rolls have excellent functions and abilities for all kind of hot and cold rolling as well as high-speed high-reduction hot rolling. They will be used widely for overall steel sheet rolling and have high potential to innovate hot and cold strips.

6.2. Fine Carbide Reinforced Roll

Rolls reinforced by precipitated fine carbides have high anti-wear resistance even under heavy duty rolling. They are sometimes called as “HSS Rolls”. Mechanical properties of these rolls are depending upon the size and spacing of dispersed carbides. It is expected that, when the volumetric fraction of carbide is unchanged, smaller particle size and narrower spacing provide better anti-wear resistance. Before the project, the lowest level of carbides spacing was about 50 μm. The basic studies and knowledge based on in-line utilization predicted that the anti-wear resistance would become 5 times as high as that of the conventional HSS rolls if the carbides spacing was reduced to 10 μm.

In this project, by increasing the solidification speed up to the upper limit in casting of the mother material and forging the cast billet under the selected conditions, the fine dispersion of precipitated carbides were obtained (see Fig. 13). The spacing of carbides became less than 10 μm. It was confirmed that the anti-wear resistance of new roll became 5 times high comparing with the conventional HSS rolls, where the total volumetric fraction of carbides was about 13%. The developed rolls were named as “Super HSS Roll”. The rolls could be utilized for various types of heavy duty rolling and contribute to the extension of sheet rolling technologies.

6.3. Liquid-colloidal Lubricant

A liquid-colloidal-type lubricant, that is a mixture of water glass, calcium stearate and potassium tri-poly phosphate, has been developed. It has specific characteristics of high friction coefficient at low temperature and low friction coefficient at high temperature. These characteristics are the results of combination of frictional properties of solid lubricants and inorganic compounds. Through stabilization, the improvement of anti-adhesion ability and anti-seize performance is achieved. The excellent gripping performance and capability of reducing rolling force has been confirmed (see Fig. 14).

Figure 15 shows the drop of rolling force occurred in ac-
7. Numerical Simulation of Grain Generation

7.1. Micro-scale Model of Nucleation and Grain Growth

In this project, a micro-scale model to simulate the nucleation of ferrite and austenite grains was proposed standing upon the cluster dynamics. In addition, a simulation model and method to predict the ferrite transformation from dislocation cells in heavily deformed austenite grains was formulated. The simulation method was combined with the ferrite nucleation and grain growth model.

The material parameters included in the proposed formulations were measured experimentally by using a high-speed hot compression tests (see Fig. 16). The propriety of those formulations was confirmed by comparing experimental measurements with analytical results. The theoretically predicted ferrite grain size after heavy deformation showed fairly good agreement with the measured values.

The developed micro-scale model was combined with the process simulation models of forging, rolling and bending. A series of simulations were carried out in order to obtain the technical data for the optimal design of processes, machines and devices for efficient production of UFGS sheets. In order to perform the exact simulation, the material constants in high strain rate range were obtained, as mentioned above, by the high-speed compression test system. The system was able to perform the compression test under the strain rate up to 300/s.

7.2. Nano-scale Model of Micro-band Formation

A nano-scale model to simulate micro-band formation in austenite grains was formulated by taking account of diffusion terms. The model is able to simulate the formation of micro-bands that consist of dense accumulation of dislocations.

It has been confirmed by TEM observation that micro-bands are formed in parallel with (111)-plane. Through heating a specimen in TEM, it is directly observed that nuclei for re-crystallization are generated among micro-bands. It is also observed that the nuclei do not grow beyond the bands and the maximum size of newly generated grains do not exceed the space between them.

7.3. High-speed Large-reduction Working Process Model

For prediction of the microstructure change in steel sheet through high-speed and large-reduction hot forging, rolling and/or multi-cycle bending, each macro-scale process model was coupled with the micro-scale metallurgical model. By utilizing the coupled model, not only deformation features of work-pieces, but also the grain generation and refinement behavior were analyzed (see Fig. 17).

Through a series of simulations, the influences of process parameters, such as steel sheet temperature, thickness reduction, die and roll dimension, strain history and strain rate, on the microstructure evolution and the improvement of their mechanical properties were systematically investigated. The results were used for the design of processes, machines, rolls, cooling devices and others for practical production of UFGS sheets. The simulation technologies have become indispensable for the development of new steel sheets and manufacturing processes.

8. Mechanical Properties and Formability of UFGS Sheet

In this project, a certain number of UFGS sheets were manufactured and subjected to the tensile test and some other forming tests. The results were summarized in the following figures. Figure 18 shows outlook of a UFGS sheet. It shows good shape and surface quality. Figure 19 shows some results of the tensile test. Two important facts are noticed. 1) The tensile strength of UFGS sheets increases almost following to Pickering’s equation, 2) UFGS sheets have high enough local elongation. Figure 20 shows the result of bending test. It is clear that UFGS sheets have ability to bear 180-degree bending. No cracks and any other defects caused by bending are observed. Figure 21 shows the result of deep drawing test. It is found that the drawing ratio reaches up to 1.95. Figure 22 shows an example of practical die forming of structural part. The result shows that UFGS sheets are formable to practical parts for cars, machines and structures.
9. Conclusion

In this paper, the result obtained through “National Project on Production Technologies for UFGS Sheets” have been explained. Through the collaborated research works conducted by NEDO, managed by JRCM and executed by the consortium of industries and universities, the advanced
technologies relating with 1) high-speed large-reduction semi-continuous hot forging, 2) high-speed super short-interval hot tandem rolling, 3) multi-cycle hot bending, 4) high functional rolls, 5) multi-functional lubricants, 6) simulation and prediction of grain generation and 7) other issues were systematically investigated and diverse new technologies were developed. The developed technologies are widely usable to overall production of steel sheets as well as UFGS sheets. They are expected to play leading roles for the innovation of steel sheet manufacturing.

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