RESEARCH ACTIVITIES ON ADVANCED STEELS IN NERCAST

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ABSTRACT National Engineering Research Center of Advanced Steel Technology (abbreviated as NERCAST) is a share-hold company promoted by the Chinese Administration. Its target is to research and develop steel products with characteristics of high performance, long duration, resources saving, low cost and environment benign. Before and after its establishment, some of the major steel research programs, funding by both the government and steel companies, have been undertaking. An overview on the recent steel research activities in NERCAST will be made in the paper.
KEYWORDS advanced steel, research activity, performance improvement

INTRODUCTION

Energy saving, resources saving and environment protection are now strongly demanded against the rapid development of steel production and consumption in China in recent years. According to the statistics published by IISI on January 19, 2005, 272.5 million tonnes of crude steel were produced in Chinese steel plants in the year of 2004, which increased 23.19% over the year of 2003. At mean time, the total crude steel production of the world was of 1054.6 million tonnes and increased 8.8% over the year of 2003. The crude steel produced in China was approximately in the portion of 1/4 of total crude steel produced in the world (25.8%). Data from Chinese Iron and Steel Association indicated that the domestic market for apparent steel consumption was 312.5 million tonnes in the year of 2004. It should be noted that there have been supply shortage of iron ore and other metallic ores, shortage of transportation capacity for raw materials, shortage of energy consumed for steel processing, and the pollution problem due to production gas and dust emission. These problems could become more severe if only the steel production capacity be expanded to meet the market requirement. To develop advanced steel with the characteristics of high performance, energy saving, resources saving, near-net shape and low cost will be one of the potential ways to meet the above requirements. High strength, high toughness and long duration of steel products could result in the reduction of steel consumption. There are rooms for steel production and fabrication to reduce energy consumption, especially for new steel to be produced with energy effective production line. Raw materials can be saved through the new design for alloying and processing. There is steel saving and high efficiency due to near-net steel products in the fabrication of steel parts. The development of advanced steel will bring about low cost of steel products.

The modern steel age as we know it was born in the period 1850-1856 with the discoveries of Kelly and Bessemer of the pneumatic process. In 1856, Bessemer claimed “The Manufacture of Malleable Iron and Steel without Fuel” from hematite pig iron at the Cheltenham meeting of the British Association, which is the origin of modern BOF and changed wrought iron to mild steel [1]. The yield strength of wrought iron was doubled from 100MPa to 200MPa of mild steel. Over the past 150 years, there are indeed many innovations in steels, only a few of the important steel progresses I could mention here: the beginning of alloy steel production by the development of Robert Mushet's self-hardening steel (8-10%W, 1.2%Mn and 1.1-1.68%C) in 1868, notable contributions by Robert Hadfield's development of manganese and silicon steels, high speed steel invented by Taylor and White in 1900, Harry Brearley's discovery in 1912 of stainless properties of high chromium steel, the maraging steel introduced in 1961 by the International Nickel Co. of Canada, microalloyed steel and TMCP developed since 1960's to the present [2], etc. From the end of 19th century to the end of 20th century, almost all of the steel grades we used today have been developed by alloying base on the processing development. What is going on with the steel in this century: is there any room to develop an new steel? It is no doubt that steel has always been changed with our understandings and steel processing to meet requirements from both end user and environment.

Since the end of last century, steel people all around the world have been showing strong interest at grain refinement into microns or sub-microns in scale to seek a potential way to increase strength without any loss in ductility and toughness. The administrations of Japan, Korea, EU and China funded the nationwide or international research projects for grain refinement in steels, Ultra Steel and Super Metals in Japan, HIPERS' 21 in Korea, Ultrafine Grained Steels in EU and NG Steel in China. Based on these research projects, a large amount of research results were published. The steel research activity has been stimulating since then, and two successive international conferences are held every two years to exchange newly developed ideas and results: ISUGS 2001 in Japan, ISUGS 2003 in Australia, ICASS 2002 in Japan and ICASS 2004 in China. There are, of course, many other important conferences (including 1st International Conference on Super-High Strength Steels) concerning with the steel research and development all over the world.

Share Holders of NERCAST
Central Iron and Steel Research Institute
Shanghai Baosteel Group Corporation
Anshan Iron and Steel Group Corporation
Wuhan Iron and Steel (Group) Corp.
Dongbei Special Steel Group Co., LTD
Taiyuan Iron and Steel (Group) Co., LTD
Shougang Group
Panzhihua Iron and Steel Group Corporation
Jiangsu Shagang Group
Xinye Hi-Tech Company
University of Science and Technology of Beijing
Shanghai University
Northeast University

Figure 1 Share Holders of National Engineering Research Center of Advanced Steel Technology

The steel history proved a truth that steel is the advanced material which can be produced and applied in large quantity, low cost, high performance, and environment benign. Under the authority of the National Development and Reform Commission of China, eight major steel plants, three steel metallurgy oriented universities, one steel metallurgical engineering company and one steel

HOME

research institute raised a share hold R&D center based on the steel research and development works in Central Iron and Steel Research Institute in June of 2004, **Figure 1**. CISRI owns 45.45% shares of NERCAST and each of other 12 shareholders owns 4.545% shares respectively. The target of NERCAST is to research and develop advanced steels instead of conventional steels to meet demands for energy saving, resources saving and environment benign in the steel processing and applications. The aim of the paper is to introduce the recent steel research activities in NERCAST.

1. HIGH PERFORMANCE PLAIN LOW CARBON STEEL

The traditional methods for plain carbon steel to increase the ultimate tensile strength of plain carbon steel were to increase of the carbon and/or manganese content. But such steels obviously reduced weldability and were prone to weld cracking. Along with the designing code changed from ultimate tensile strength to yield strength, microalloyed steels were developed to meet higher strength demand over 295MPa. There are five plain carbon steels listed in GB/T 700 – 1988 varying from yield strength of 195MPa to 275MPa with a step of 20MPa. Is it available to develop a new plain low carbon steel of yield strength over 355MPa without any addition of alloy elements? The results show that the yield strength of plain low carbon steel can be over 355MPa or even 400MPa if ferrite grains are refined into micron scale. The ideas to develop new plain low carbon steel were to be promoted in the both rebar and strip production in some of Chinese steel plants. Steel rebar was developed to replace grade III microalloyed steel rebar of minimum yield strength of 400MPa. Hot rolled strips are used to replace conventional truck chassis made of microalloyed steel with minimum yield strength of 355MPa.

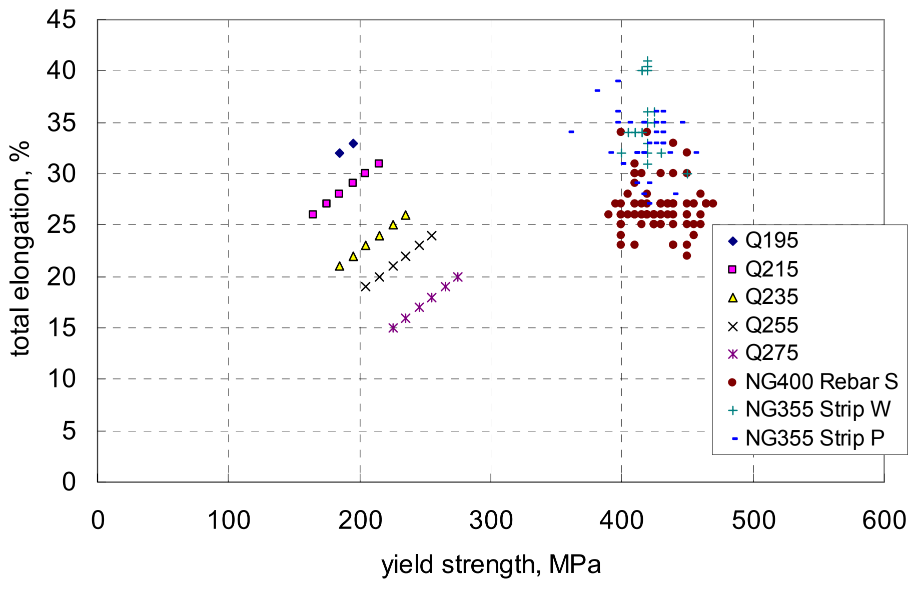

Figure 2 Strength and ductility of advanced plain low carbon steel rebar and strip.

The chemical compositions of plain low carbon steel strips produced in WISCO are as follows: 0.12-0.16%C, 0.10-0.30%Si, 0.70-0.90%Mn, P≤0.025%, S≤0.008%. The thickness of the strip is from 2.75mm to 5.0mm. The similar chemical compositions of plain low carbon steel strips produced in PanSteel are: 0.13-0.18%C, 0.20-0.25%Si, 0.47-0.66%Mn, 0.012-0.019%P, 0.005-0.009%S. The thickness of the strip is from 3.0mm to 7.0mm. The typical mean ferrite grain

HOME

in steel strips produced in tandem rolling lines ranged from 4 microns to 8 microns. A good combination of strength and ductility is presented in the advanced plain low carbon steel rebar and strip produced in steel plants, **Figure 2**.

Plain low carbon steel, as the major portion of total steel products, is enhanced to higher strength grade than ever before through ferrite grain refinement into microns for the applications of rebar and truck chassis. Higher strength and toughness could be achieved in hot rolled steel rebar and strip through microstructure control by the addition of microalloying elements for building and container respectively.

2. HIGH STRENGTH MICROALLOYED STEEL

Microalloyed steel has been recognized as the major progress of steel grades over past 40 years. The origin of microalloyed steel was to meet the demand for both higher strength and better weldability other than by the increase of carbon and manganese [3]. There are five conventional microalloyed steels listed in National Standard GB/T 1591 – 1994, Q295, Q345, Q390, Q420 and Q460. The yield strength of five conventional microalloyed steels ranges from 295MPa to 460MPa for the thin gauge steel products (thickness or diameter no more than 16mm). If the steel products gauge increases to 50 – 100mm in thickness or diameter, the yield strength goes down to the range of 235MPa to 400MPa. The chemical compositions in the National Standard GB/T 1591 – 1994 are as follows: ≤0.20%C, 0.80 – 1.70%Mn, ≤0.55%Si, ≤0.025 – 0.045%P, ≤0.025 – 0.045%S, 0.02 – 0.20%V, 0.015 – 0.060%Nb, 0.02 – 0.20%Ti. Microalloying elements play an important role in grain refinement and precipitation, which bring about strength increase and toughness improvement. Through grain refinement to about two microns, the yield strength can be over 600MPa, which is the target we develop a new microalloyed steel, **Figure 3**.

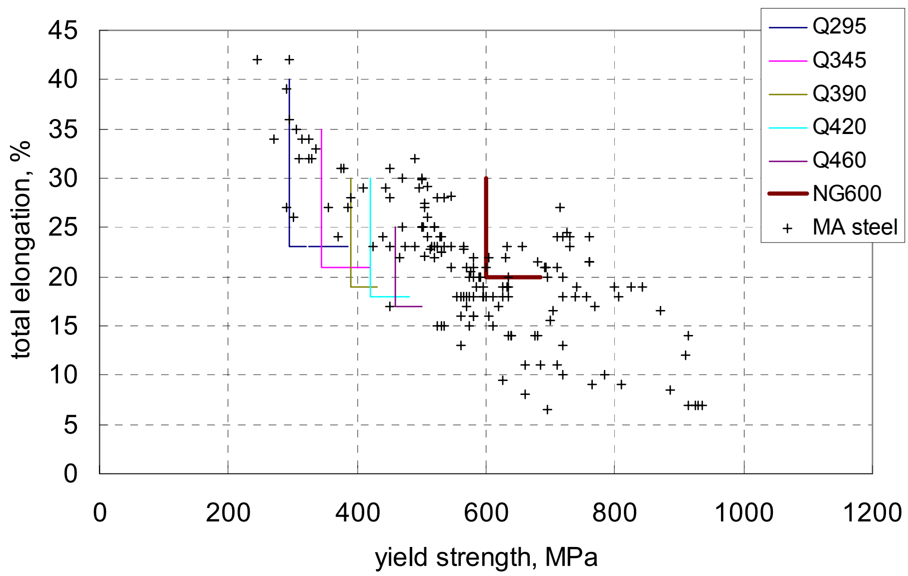

Figure 3 The higher strength microalloyed steel to be developed.

It is believed that Deformation Induced Ferrite Transformation (abbreviated as DIFT) is the effective mechanism to form ultrafine grains in microalloyed steels. In microalloyed low carbon steel (conventional X65 steel), the volume fraction of ferrite induced by deformation increases with the increase of total reduction, **Table 1**. When total reduction near 90 percent, the volume fraction of transformed ferrite induced by deformation approaches to 98 percent. Ferrite grains of less than 2μm in size could be obtained through DIFT. With the increase of total reduction, no remarkable increase on grain size has been observed. It should be noted that grain of induced ferrite keeps almost unchanged, and successive deformation has little effect on ferrite grain growth. Through DIFT rolling, ferrite grain in hot rolled strip can be refined to about 1μm in size.

Table 1 Deformation induced transformed ferrite in low carbon microalloyed steel (conventional X65 steel) subject to hot rolling at various reduction

Total reduction, %	69	73	77	79	82	88
Volume fraction of ferrite induced, %	71	85	96	94	90	98
Mean size of ferrite grain, μm	1.22	1.04	1.16	1.12	0.99	0.92

The effect of microalloying elements on DIFT is still ambiguous. Yada et al thought that niobium had little effect on grain refinement. The research of Hickson and Hodgson showed that transformation temperature was lowed by the addition of niobium, and the driving force for nucleation was increased. Lee et al thought that the addition of niobium can enhance grain refinement for ferrite transformed by strain induction. We investigated the effect of niobium on DIFT in ultra low carbon steels microalloyed with niobium, 0.003%C-0.22%Si-1.12%Mn-0.052%Nb (No.296) and 0.003%C-0.19%Si-1.10%Mn-0.110%Nb (No.298), which were soaked at 1453K for niobium resolved in austenite. Polygonal ferrite and finer equiaxed ferrite can be found in No.296 steel specimens water cooled after deformation. The lower the deformation temperature is, the higher the volume fraction of finer equiaxed ferrite becomes. The finer equiaxed ferrite is the result of DIFT in the steel. But in the steel microalloyed with higher niobium (No.298), no equiaxed ferrite was found. There are only larger elongated grains transformed from deformed austenite grains or deforming bands, which were formed during cooling not during deformation. It is shown that the addition of niobium inhibits DIFT in ultra low carbon steels soaked at high temperature and the addition of 0.11%Nb could depress DIFT in the wider range of deformation temperature and strain. That is the story for the steels microalloyed with niobium totally resolved. If niobium precipitates during deformation, which depresses recrystallization and increases accumulative deformation energy, DIFT will be promoted through the addition of niobium. It is important to let niobium precipitation happen before potential ferrite induced from austenite to realize DIFT rolling in steels microalloyed with niobium.

3. DELAYED FRACTURE RESISTANCE STEEL

In general, machine parts made of steel are demanded to subject to more severe working conditions, especially higher and cyclic load. One typical example is the bolt subject to delayed fracture accompanied with higher strength than ever before. Although the highest ultimate tensile strength of bolt steel in the National Standard is of 1200MPa, there are some reports from customers that delayed fracture occurred. Delayed fracture resistance and fatigue resistance are required for high strength steel with ultimate tensile strength over 1200MPa. 1300MPa grade and 1400 grade steels for delayed fracture resistance bolt have been developed to be used in automobile engine and suspension.

The demand for high strength steel bolt with high delayed fracture resistance attracts people to

HOME

develop new steels. There are certainly several effective means to improve delayed fracture resistance: hydrogen trap by vanadium precipitates, grain boundary chemistry to avoid hydrogen segregation, the existence of retained austenite, to make grain boundary free of carbides, etc. Another potential method to improve delayed fracture resistance could be grain refinement, especially austenite grain refinement. The growth of austenite grain follows Beck's equation. It is shown by the results that activation energies of grain boundary migration for 42CrMo steel and microalloyed Cr-Mo steel are 425kJ/mol and 525kJ/mol respectively. Therefore, the drag force for grain boundary migration is larger in Cr-Mo steel microalloyed with niobium and vanadium. Because microalloy precipitates bring about drag effect for grain boundary migration, finer austenite grain in microalloyed Cr-Mo steel could be obtained.

Another method for austenite grain refinement in structural alloy steel is the cycle heat treatment. To adopt cycle $\gamma \leftrightarrow \alpha$ transformation refinement, the prior austenite grains in 42CrMo steel and microalloyed Cr-Mo steel become finer. The prior austenite grains of 42CrMo steel and microalloyed Cr-Mo steel are of 4.66μm and 2.07μm in size respectively when they are subject to cycle transformation of four times. It is also demonstrated that the addition of niobium and vanadium in Cr-Mo steel brings about grain refining in cycle heat treatment. To change austenitizing temperature and apply cycle heat treatment, specimens with austenite grain size from 4.7μm to 120.0μm could be obtained in 42CrMo steel. At strength level of 1150MPa, critical notch tension stress of the steel with grain size of 4.7μm is 1490MPa. But for the steel with prior austenite grain size of 13.0μm, critical notch tension stress is only 1135MPa. It is shown that K_{ISCC} increases as prior austenite grain is refined.

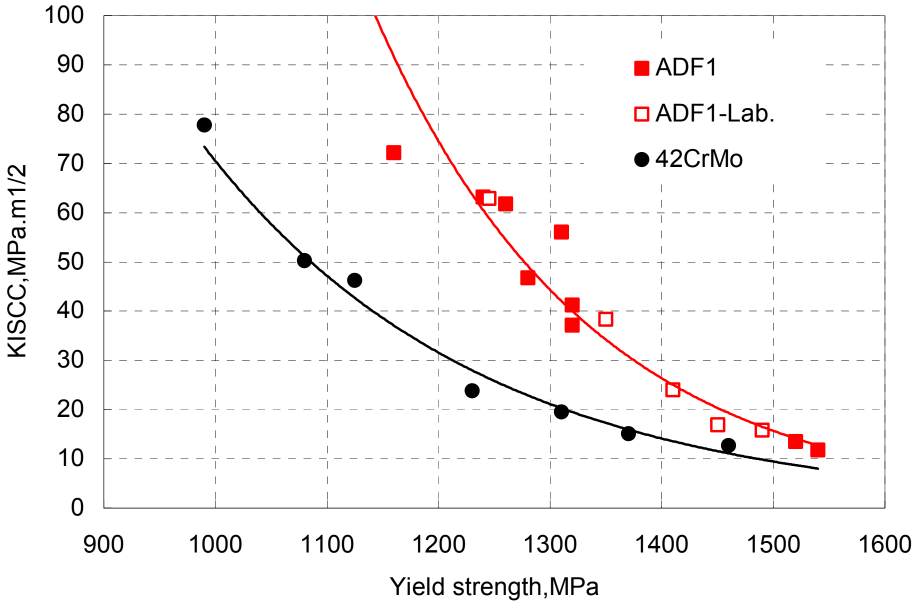

Figure 4 K_{ISCC} and $R_{p0.2}$ of 42CrMo steel and ADF1 steel.

Industrial trials for new delayed fracture resistance steels (medium carbon Cr-Mo-V-Nb steels) were performed in Northeast Specialty Steel Co. The steels were melted in EAF and refined in LF/VD. Commercial steel 42CrMo is chosen as comparison with the new steel. Prior austenite grains are of 20 microns in 42CrMo steel and 8 microns in the new steel after quenching and tempering. It is well known that K_{ISCC} decreases as yield strength increases. Both 42CrMo steel and the new steels present the same tendency, **Figure 4**. For 42CrMo steel, K_{ISCC} can be expressed with yield strength as: $K_{ISCC} = 3.91\times10^3 \exp(-4.0\times10^{-3} R_{p0.2})$. At the same strength level, it is obvious that K_{ISCC} of the new steel is higher than that of 42CrMo steel.

The typical characteristic of delayed fracture in steels is of intergranular fracture. Therefore, the change of fracture mechanism from intergranular to transgranular is an indication of the improvement for delayed fracture resistance. The new steel could subject to higher tempering temperature while remaining higher strength. At the same strength level, higher K_{ISCC} for the new Steel is partly due to grain refinement. At strength level of 1100MPa in proof yield strength, intergranular fracture occurred in 42CrMo steel, while transgranular fracture was present in the new steel. The steel we developed can meet the requirements from the end users, and is now applied to manufacture high strength bolts for automobiles.

4. Ultrahigh Strength Steel with Improved Toughness

Ultrahigh strength steels are widely applied in the airplane and the space equipment, in which high specific strength is demanded to save weight of the parts. There are indeed many ultrahigh strength steels to be as the candidate for this application. But there is still a demand for better combination of both higher strength and higher toughness. Through the purification steelmaking, the 2000MPa grade ultrahigh strength steel with fracture toughness, K_{IC}, over 100MPam$^{1/2}$ has been developed, **Figure 5**. Comparing with AF1410 steel, the new steel presents higher strength to 2000MPa. It also has higher toughness than 300M steel. The new steel is the secondary hardening steel of super cleanliness with the sum of sulfur, phosphorous, oxygen, nitrogen and hydrogen less than 50ppm.

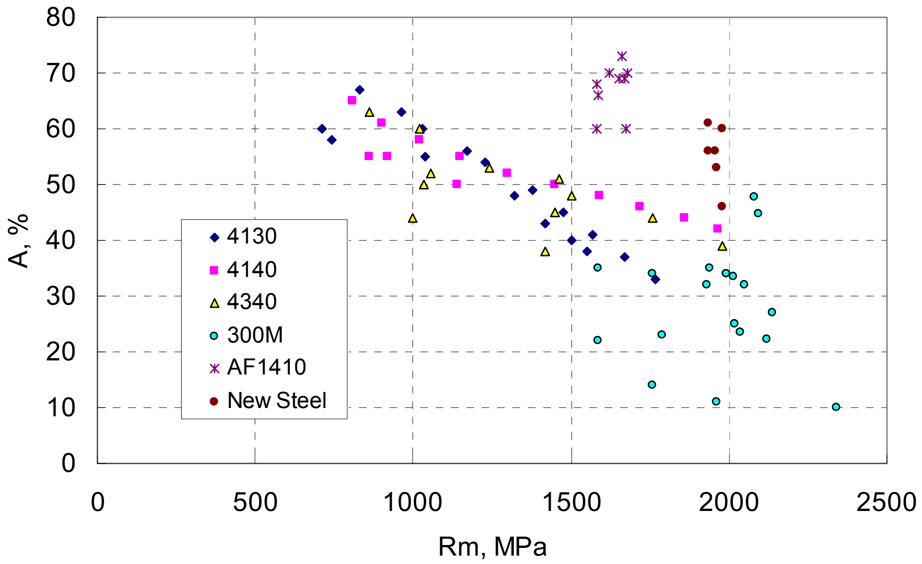

Figure 5 A new ultrahigh strength steel developed in NERCAST.

5. Nickel Saving Stainless Steel

Due to its high performance, the attention has been paid on high nitrogen steel (HNS) more than 60 years. With the development of the melting technology, the nitrogen content in steel could be

HOME

enormously enhanced. The advantages of HNS over conventional stainless steels could be realized. It attracts many people to the steel alloyed with nitrogen.

In China, there has been a rapid growth of stainless steel consumption in recent years. The domestic production of stainless steel could not meet the market. Imported stainless steel is now still to be the major part of the market. Since 1999, stainless steel apparent consumption in China has been increasing steadily to reach at 4.2 million metric tons in 2003. Stainless steel has been widely used in almost all aspects in accordance with rapid economic development. The large amount of stainless steel consumption in China could bring about recourse shortage worldwide. There is really a strong requirement for stainless steel to be nickel saving, high performance, low cost and environment benign. HNS could be used as a candidate to meet the demand, especially HNS rebar for infrastructure.

Base on ideas to get high nitrogen contents into melts and keep them in solution during solidification, a 0.10%C-22% Cr-17%Mn alloy system was selected as base metal for nitrogen alloying from 0.35% to 0.68%. The 0.68%N Steel presents not only higher strength but also good ductility and toughness, **Figure 6**. Strength of 0.68%N steel slightly decreases when solution soaking temperature increases. When soaking at 1200□, yield strength decreases to 532 MPa and ultimate tensile strength is 892MPa. Mechanical property of 0.68%N steel can meet requirement for Grade IV steel rebar for construction. Compared with AISI 316 steel of typical yield strength level of 260MPa, yield strength of 0.68%N steel is over twice the former. It is also distinctly higher than that of duplex stainless steel, AISI 2205. Both AISI 316 and AISI 2205 steels are popularly used as steel rebar for construction and bridge.

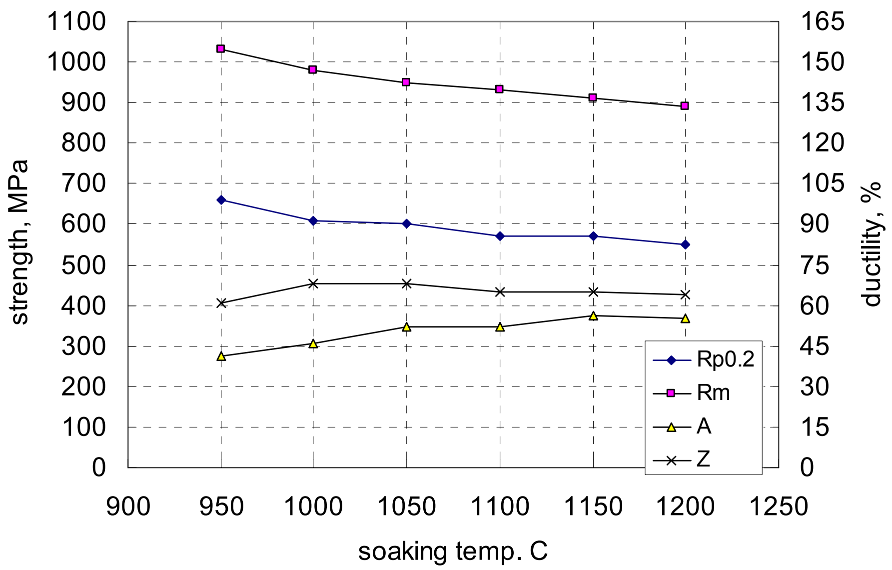

Figure 6 Tensile properties of 0.68% nitrogen steel.

Five heats of Cr-Mn-N high nitrogen steel with nitrogen content from 0.35 to 0.68% were prepared in the induction furnace in atmosphere. Nitrogen significantly enhances the stability of austenite. The more nitrogen is added into the steel, the more amount of austenite in the steel is. Cr-Mn-N high nitrogen stainless steel with 0.68% nitrogen content possesses comprehensive properties of strength and ductility. It could meet specifications for grade IV steel rebar. It is affordable for steelmakers to roll Cr-Mn-N high nitrogen stainless steel at their hot mills. The recommended temperature for hot working is in the range of 1000 – 1200□.

6. SUMMARY

The academic exchange is one of the means for NERCAST to promote technology transfer. In the year of 2005, NERCAST sponsored and will sponsored a series conferences and seminars in China: Sino-Italian Seminar on High Grade Pipeline Steels during April 7-8, International Seminar on Heat Resistance Steels during April 12-13, Domestic Seminar on TSCR Technology during April 13-14. In July12-14, we held a Domestic Seminar on Specialty Steels. During November 8-10, 2005, we will cooperate with Chinese Society for Metals to hold HSLA Steel 2005 and ISUGS 2005 in Hainan Island. In the early of July, NERCAST held the training course to the steel people on the production and application of ultrafine grained steels. In September of 2006, we will hold the International Conference on High Nitrogen Steels to enhance the production of this nickel saving steel. Any idea and attendance from steel people on these academic activities will be warmly appreciated.

Steel is one of the advanced materials. Due to its high performance, environment benign, rich in resource, mass in production and low price. Nobody could image what happens without steel in our daily life. But there is indeed a question asked by our steel societies: is it still possible to improve steel performance remarkably without any loss of its characteristics stated above?

Steel is not a single product. There are currently more than 3,500 different grades of steel with many different properties – physical, chemical and mechanical, most of which have been developed in the last 30 years. Steel is an extremely complicated material with an amazingly large number of variants, especially phases presented in steels, and new discoveries are still being made. You have been shown why products made with steel are safer, stronger and a better value. That is why people in steel society always show strong interest at the research on advanced steels.

In the near future, more and more efforts will be involved in the research of advanced steel in NERCAST to meet the requirement from steel producers and customers.

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HOME