Research on a new process of the non-quenched and tempered steel with high strength and high toughness

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Abstract

The controlled-forging and controlled-cooling has become the main process of the non-quenched and tempered steels now. However, there is a problem that the unstable toughness and its lower values restrict the expanded application and the development of the steels. In this study, the process of the non-quenched and tempered steels was optimized through the micro-alloying and the controlled-forging and controlled-cooling technology. The simulated rapid cooling followed by self tempering after forging was tried to control the microstructure and mechanical properties of the steels. A new process of the non-quenched and tempered steels was proposed to ensure high strength and high toughness for the studied steels. The toughening and strengthening mechanism of the steels processed by the new process was discussed and evaluated, which could provide the fundamental theory, technical support and process parameters for the industrialized production of the high strength and high toughness non-quenched and tempered steels.

Keywords: Non-quenched and tempered steels; Self tempering processes; High strength and toughness; Introduction

1. Introduction

Recently, with the rapid development of the transport industry and machinery equipment industry, the requirement of the non-quenched and tempered steels with high performance and high quality increases accordingly.

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During the 11th 5 year plan organized by Chinese government, there are some preliminary progresses that both the strength and toughness of the non-quenched and tempered steel have been improved. However, facing to the rocket development of the modern transport industry and the light-weight requirement, the current domestic non-quenched and tempered steels cannot meet the requirements in variety, quality and quantity completely. Thus, most of that needed to be imported now (such as Cylinder Crankshaft, Steering Knuckle, Radius Arm, Connecting Rod). This situation can be ascribed to the unstable toughness and its lower values which restrict the expanded application and the development of the steels. In order to upgrade these steels for take place of the imports and even export of them, it is necessary to carry out of a new process of the high strength and high toughness non-quenching and tempering steels which are used for the machinery and equipment industry and automobile industry. It was demonstrated that quenched and self-tempering (QST) technique could be applied to improve not only the strength but also the toughness of the high strength low alloyed steel in an economical way [xx]. Thus, in this study the QST-technology was applied to the non-quenched and tempered steels, aiming at improving both strength and toughness of the non-quenching and tempering steels. The toughening and strengthening mechanism of the steel processed by QST-techniques was discussed and evaluated, which could provide the fundamental theory, technical support and process parameters for the industrialized production of the high strength and high toughness non-quenched and tempered steels.

2. Experimental Procedures

2.1. Chemical composition and CCT diagram

The chemical composition of the non-quenched and tempered steel applied in this study is given in Table 1. The obtained ingot was hot-rolled to 85mm in thickness. Samples for thermal cycle tests and hot-rolling tests were taken from the 85mm-thick plate. Fig.1 shows the continuous cooling transformation (CCT) diagram of the studied steel. It can be seen that the bainitic transformation starting temperature (Bs) ranges from about 350 to 520 ºC with a cooling rate from 16 ºC/s to 1.6ºC/s. Fig.2 shows the microstructure revolution in the self tempering treatment for dual phase microstructural control.

| C  | Si  | Mn  | S  | P  | V  | Cr  | Ni  | Ti  |
|----|-----|-----|----|----|----|-----|-----|-----|
| 0.42 | 0.76 | 1.33 | 0.011 | 0.013 | 0.10 | 0.13 | 0.017 | 0.020 |

Table 1 Chemical composition of tested steel 38MnVS6 (wt%)
3. Experimental reference and method

For the production of HSLA steel plates, different process schedules have been developed to improve the strength of the steels (A. Streisselberger, J. Bauer, P. Fluss, H.G. Hillenbrand and P. Cordon, 2008; J. Bauer, P. Fluss, E. Amoris and V. Schwinn, 2005). Such as (i) the hot rolling in austenite region + air cooling + normalizing (N) (CEN, 2004), (ii) hot rolling in austenite unrecrystallisation region or in dual-phase (austenite + ferrite) region + air cooling (TM) (CEN, 2004), (iii) hot rolling in austenite unrecrystallisation region or in dual-phase (austenite + ferrite) region + accelerated cooling (TM + AC) (CEN, 2004) and (iv) the quenching and self-tempering technology (QST). Among these processes, QST could produce fine-grained steel by the combination of chemical composition design and process, therefore, the specified mechanical properties also could be achieved in the required product thickness (QST).

So we expect to use this new process in the production of the non-quenching and tempering steels to get high strength and high toughness. Thus, the quenching and tempering process were conducted in the controlled forging process, which was named as controlled forging + quenched and self-tempered technology (CF + QST).

Tensile tests and Charpy impact tests were performed to investigate the relationships between microstructure and properties in non-quenched and tempered steels. The tensile specimens were machined to the size with 65 mm in length and 10 mm in diameter, and the impact specimens were prepared with 55 mm in length, 10 mm in width and 10 mm in height. Both the specimens above were heated to 1200°C for 10 minutes and air cooled to 1050°C/950°C, and then the specimens were directly quenched in oil to various temperature ranging from 300°C to 900°C, and finally air cooled to the room temperature.

4. Results and Discussion

4.1. Optical Microscopy

Fig. 4 shows the optical micrographs of samples with different quenching processes which include quenching temperature (1050°C/950°C) and different holding time. It can be seen that the microstructure is mainly the ferrite phase and pearlite phase after quenching process with 8/6 seconds, but some martensite phase could be observed in the microstructure as shown in Fig. 4a1, 4b1. After quenching with 16/10 seconds, the microstructure consists of mainly martensite and small volume of granular bainite and lower bainite (Fig. 4a2, 4b2). Furthermore, as the
quenching time increase to 28/14s, the microstructure consists of granular bainite, small fraction of lower bainite and blocky martensite as shown in Fig4a3, 4b3.

The formation of the microstructure shown in Fig.2 could be explained by the processing design. Because the austenized specimens were quenched to the temperature just below the Bs temperature, thus the microstructure consists of bainite and untransformed austenite. During the holding process of the quenching, the carbon concentrates into the untransformed austenite, which stabilizes the untransformed austenite. In the followed air cooling process, the untransformed austenite phase would transform to M-A. Finally the bainitic microstructure with dispersed M-A islands can be obtained in the CF+QST process.

Fig. 4. Optical microscopy and scanning electron microscopy

Fig.4 The microstructure evolution of the studied steel during CF+QST process examined by optical microscopy. (a1) sample quenched at 950°C for 6s, (a2) sample quenched at 950°C for 10s, (a3) sample quenched at 950°C for 14s, (b1) sample quenched at 1050°C for 12s, (b2) sample quenched at 1050°C for 16s, (b3) sample quenched at 1050°C for 28s.

4.2. Mechanical Properties

The mechanical properties of the studied steel processed by CF+QST 1050°C/950°C were given in Fig.5,6. For comparison, the mechanical properties of the studied steels processed by conventional technique (i.e., controlled forging and controlled cooling (CF&C)) were also given in Table 2. It can be seen that all the tensile strength, total elongation and toughness of the studied steels processed by CF+QST were improved comparing to those of the studied steel processed by conventional technique. For example, the tensile strength ranges from 974MPa to 1077MPa, which is significantly higher than the tensile strength (970MPa) of the steel processed by conventional CF&C techniques. It is also very interesting that the toughness of the studied steel ranges from 19J to 45J, which is higher than that of the studied steel (about 10-25J) processed by conventional CF&C technique (Yoo J, Choo W, Park T, 1995; Ghosh S K, Haldar A, Chattopadhyay P P, 2008; Dhua S K , Mukerjee D, Sarma D S, 2003; Ghosh S K, Haldar A, Chattopadhyay P P, 2007; Thompson, S W, Colvin D J, Krauss G, 1996; S.K.Dhua, D.Mukerjee and D.S.Sarma, 2001; S.K.Ghosh, A.Haldar and P.P.Chattopadhyay, 2007).
At present time, the improved mechanical properties of the 38MnVS6 processed by CF+QST technique could be attributed to the fine ferrite-pearlite structure and multiphase, such as the combination of bainite and the M-A island. Further experiments, such as the detailed microstructure examination, need to be done to study the relationship between processing parameters, microstructure and the final properties. However, the results given in Fig.5,6. indicates that the new processing technique (CF+QST) is a promising technique to fabricate the non-quenching and tempering steel with high strength and high toughness(Yoo J Y, Choo W Y, Park T W,1995;Ghosh S K, Haldar A, Chattopadhyay P P ,2008;Dhua S K , Mukerjee D, Sarma D S,2003;Ghosh S K, Haldar A, Chattopadhyay P P,2007;Thompson, S W, Colvin D J, Krauss G,1996;S.K.Dhua, D.Mukerjee and D.S.Sarma,2001;S.K.Ghosh, A.Haldar and P.P.Chattopadhyay,2007).

Table 2 Mechanical properties for CF&C

| CF&C(controlled-forging and controlled-cooling) | Begin forging :1150, Finish forging:850,60%(Total amount of deformation for multiple passes forging), Controlled cooling 1.5°C/S; ferrite-pearlite structure |
|-----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Rp0.2/MPa | Rm/MPa | A/% | Z/% | Ak/J |
| 971  | 647  | 12.5 | 35  | 20.6 |
| 934  | 618  | 14  | 39  | 6.4  |
| 905  | 615  | 11  | 42.5 | 14   |
| 945  | 630  | 10.5 | 40  | 24   |
| 940  | 625  | 12  | 38.5 | 14   |
| 955  | 635  | 12.5 | 36.25 | 11.5 |
| 970  | 645  | 13  | 34  | 14   |

Fig. 5. The ferrite-pearlite structure mechanical properties of the studied steel processed by CF+QST 1050°C/950°C
From the experiment results as indicated in Fig. 5,6 it can be seen that CF+QST technique can improve both strength and toughness of non-quenched and tempered steels. Because of the improved strength, the amount of the alloying elements, such as V, Nb and Cr, can be reduced in the steelmaking process, which could further reduce the steel production cost. Through the comparison of the mechanical properties as given in Fig. 5,6, the multiphase bainitic non-quenched and tempered steels are much better on all aspects of the mechanical properties. However, it is noted worthy that such as after the oil quenching at 950°C for 8s, the combination microstructure of bainite and M-A island, the best mechanical properties for Rm1016MPa, Rp0.2639 MPa, A 27%, AKU2 44J experienced CF+QST technology can be only successfully fulfilled in the laboratory. If it can be applied in steel industry in the future, it will further reduce the production costs, energy consumption and improve the productivity.

Using stronger vanadium steel is equivalent to lighten the component. It not only potentially reduces the steel consumption but also accords with the national automobile lightweight requirements. It was shown in our previous study that the fatigue strength of 38MnVS6 processed by CF&C technique was about 423MPa. It could be predicted that the CF+QST technique could improve fatigue strength about 116MPa, i.e., a high fatigue strength about 539MPa could be obtained by CF+QST technique in the studied steels(Y. Murakmi, T. Nomoto, 1999; C. Bathias, Fatigue Fract, 1999; Z.G. Yang, S.X. Li, J.M. Zhang, G.Y. Li, Z.B. Li, W.J. Hui, Y.Q. Weng, 2004; Z.G. Yang, J.M. Zhang, S.X. Li, G.Y. Li, W.J. Hui, Y.Q. Weng, 2006). which could improve the safety of steel parts, service life and service performance of Cylinder Crankshaft, Steering Knuckle, Radius Arm and Connecting Rod, et al.

![Figure 6](image1.png)

**Fig. 6. The multiphase structure mechanical properties of the studied steel processed by CF+QST 1050°C/950°C**

![Figure 7](image2.png)

**Fig. 7. Prediction of fatigue strength**
5. Conclusions

The mechanical properties of 38MnVS6 processed by CF+QST technique were improved significantly comparing to the conventional processing technique (CF&C). The tensile strength of the steel with ferrite-pearlite structure could be increased to 1077MPa with the toughness about 45J and total elongation about 15%. Furthermore, the tensile strength of the steel with multiphase structure could be increased to 1770MPa with the toughness about 52J.

The new processing technique, i.e. CF+QST, could be applied to fabricate the non-quenching and tempering steel with high strength and high toughness, it has many advantages and potential comparing to the conventional technique (CF&C). However, it also needs to be explored further in the near future.

Comparing to the conventional technique (i.e., controlled forging and controlled cooling (CF&C)), the CF+QST process at 1050°C can obtain the good combination mechanical properties with ferrite-pearlite structure which could greatly improve the service life of the non-quenching and tempering steel. In another aspect, without considering the structure transformation, the CF+QST process at 950°C and oil quenching for 8 seconds can obtain the better combination mechanical properties with bainitic structure embedded with little M-A islands, such as Rm1016MPa, Rp0.2639 MPa, A 27%,AKU2 44J.

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