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Study of Cold Coiling Spring Steel on Microstructure and Cold Forming Performance

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Abstract. Medium-carbon cold-coiling locomotive spring steels were treated by a novel Q-P-T (quenching-partitioning-tempering) process. Scanning electron microscopy (SEM), transmission electron microscope (TEM) and X-ray diffraction (XRD) were used to characterize the relevant parameters of the steel. Results show that the microstructure of tested steel treated by Q-P-T process is a complex microstructures composed of martensite, bainite and retained austenite. The volume fraction of retained austenite (wt.%) is up to 31%. After pre-deforming and tempering again at 310℃, the plasticity of samples treated by Q-P-T process is still well. Fracture images show that the Q-P-T samples are ductile fracture. It is attributed to the higher volume fraction of the retained austenite and the interactions between the multi-phases in Q-P-T processed sample.

1. Introduction
Numerous researches have been performed to develop new advanced high strength steels for the application in lightweight automotive structures and heavy load, high speed railways. From dual phase (DP) steel, transformation induced plasticity (TRIP) steel in 1990s[1-3] to quenching-partitioning (Q-P) steel[4-7] and quenching-partitioning-tempering (Q-P-T)[8-10] steel in recent years, the comprehensive properties of steels have promoted greatly in contrast with traditional steels. For example, steels treated by Q-P process show good mechanical properties which are obtained through controlling the percentage of stable retained austenite at room temperature. But one of its strengthening preconditions is to prevent the carbide precipitation which is not corresponding with the actual experimental status in some cases[11, 12]. Based on this, Xu[9] proposed a new process called Q-P-T process which not only ensures the stability of retained austenite but also makes fine carbide precipitation in the matrix by adding carbide forming elements like silicon. Following this, the product of strength and elongation of steels with 0.4 wt.% carbon content reaches to 31627 MPa•% which meet the requirements of new generation high strength steel’s strength and elongation product≥3×104 MPa•% predicted by Matlock and Speer[9, 13]. The high value of the product of strength and ductility suggests that steels treated by Q-P-T process also have good comprehensive properties. The processes
aforementioned are usually used in steels with carbon content lower than 0.5 wt.%. While spring steels used in high speed locomotives usually contain more than 0.5 wt.% carbon content. It has been confirmed that spring steels treated by Q-P-T process possess better comprehensive properties compared with that of the traditional Q-T process[14]. But studies mentioned above are mainly for hot coiling spring steel with the diameter larger than 20 mm which needs heating during coiling process. Study on cold coiled spring steels treated by Q-P-T process is rarely reported. The diameter of the cold coiled spring steel is smaller than 20 mm which does not need any heating during coiling process. So it has increasingly wide utilization for its higher precision and less energy conservation than hot ones. But the heat treatment parameters may have differences for its size effects and application differences comparing with hot ones. In this paper, the novel process used in medium-carbon cold-coiling spring steel is discussed to find suitable parameters for actual production in which the hardness is between 42-46 HRC. On the basis of this, the strengthening mechanism of the spring steel treated by Q-P-T process compared with the traditional Q-T process are discussed by setting up the pre-strain and tempering treatment after deformation, which simulate the actual production process.

2. Experimental procedures
Commercial hot-rolled spring steel with Φ12mm diameter bar was used in the investigation (chemical compositions, wt. %: 0.59C, 1.61Si, 1.15Cr, 0.66Mn, 0.16V, Fe). And the phase transformation temperatures were measured by DIL 805A/D dilatometer, as shown in Table 1.

| NO. | AC₁ | AC₃ | Mₛ | Mₐ |
|-----|-----|-----|-----|-----|
| Temperature (℃) | 780 | 865 | 262 | -27 |

The Q-P-T process was performed as shown in figure 1. Firstly, the sample of the test steel was austenitized at 880℃ for 18min; then it was quickly cooled with -80℃/s to 210℃ for 12s, followed by held at different isothermal temperatures (300℃, 350℃, 380℃, 400℃) for 90min. after that, the sample was tempered at 310℃ for 90min. Secondly, samples treated by the optimal parameters of Q-P-T with enough strength and good plasticity and suitable hardness were pre-strained and then tempered at 310℃ for 90min to simulate the productive process of the cold coiling spring.

Figure 1. schematic diagram of Q-P-T process(a) and Q-T process(b)
Uniaxial tensile tests were conducted as standard dog-bone tensile test samples on MTS testing machine at room temperature at 2mm/min, and the hardness was tested on the micro hardness tester (HVS-1000). Meanwhile, the microstructure of the steel was characterized by OM (PMG3-OLYMPUS), SEM (SUPPA40), TEM (Tecnai G2F20S-TWIN, 200KV) and the fraction of the retained austenite was detected by XRD (350 X-ray, Cu Ka radiation), respectively.
3. Results

3.1 Microstructure
As shown in figure 2, the typical microstructure of Q-P-T process is composed of martensite (M), bainite (B) and retained austenite (R) in which the size of the initial martensite (IM) is about 0.5μm while the size of the fresh martensite (FM) is 0.2–0.3μm which is consistent with researches in literature [15] and there are small steps in bainite which is a typical characteristic for lower bainite.

Figure 2. Microstructure composed of M(a), B(b) and R(c) with isothermal temperature at 380℃ in spring steel treated by Q-P-T

Corresponding to figure 2, the SEM microstructure (figure 3) of the tested steel is composed of dark gray martensite (IM), blocky martensite/retained austenite island (M/A) and bainite (B) which is present in the form of long, thin sheaves with a dominant crystallographic orientation within a single plate. At the same time, the white film or sheet structural retained austenite dispersed on the matrix.

Figure 3. SEM image of samples isothermal at different temperature
Typical residual austenite microstructure was shown in figure 4 lots of film like and some bulk retained austenite can be seen in the DF image. And as shown in figure 3, the volume fraction of the retained austenite (wt.%) increased at first and then decreased with the increasing of the isothermal temperature. The maximum value appears at 380 °C which is correspond with the variation tendency of the volume fraction of M/A island. It is a result of competition between carbon partition and the decomposition of retained austenite. On the one hand, with the increasing of the isothermal temperature, more and more carbon distributed from initial martensite to retained austenite which makes the austenite more and more stable; on the other hand, with the increasing of the isothermal temperature, the thermal stability of the retained austenite become more and more worse. Before 380 °C, the partition mechanism plays main role of the process, while after 380 °C, the thermal stability is a leading role.

### 3.3 Mechanical Properties

#### 3.3.1 Mechanical Properties before Pre-strain Deformation

The variation tendency of mechanical properties (Rm, Rp0.2, hardness, reduction of area and elongation) for the samples treated by Q-P-T process in table 2. For Q-P-T process, it can be seen that the strength (Rm and Rp0.2), the hardness and the reduction of area are decreased with the increasing of the isothermal temperature while the elongation of the tested steel increased at first and then decreased a little when the temperature exceeds 380 °C. It is inconsistent with the change rule of the retained austenite. In addition, the product of strength and ductility changed from 1.86×10^4 MPa▪% at 300 °C to 3.49×10^4 MPa▪% at 380 °C and decreased to 1.56×10^4 MPa▪% at 400 °C. The higher the value, the more energy of the tested steel absorbed during the deformation process or more work done by tensile force. Over all consideration, 380 °C is the isothermal temperature that is best suited for cold coiling process for Q-P-T process.

| Temperature (°C) | Z (%) | A (%) | Rp0.2 (MPa) | Rm (MPa) | Hardness (HRC) |
|------------------|-------|-------|-------------|----------|----------------|
| 300              | 47.7  | 10.2  | 1527.66     | 1822.7   | 54             |

Table 2. Mechanical properties and the volume fraction of retained austenite in the tested steels treated by Q-P-T.
3.3.2 Mechanical Properties after Pre-strain Deformation. After pre-strain and tempering treatment mentioned above for Q-P-T process, the samples isothermal at 380°C was clamped on the MTS again for concurrent tensile test. The change of the ultimate mechanical properties are shown in Figure 5 there is substantial improvement in yield strength and the ultimate tensile strength exceed 1700 MPa.

|        | 350  | 380  | 400  |
|--------|------|------|------|
| Stress | 45.8 | 45.5 | 43.3 |
| %      | 8    | 8    | 1    |
| YS     | 10.7 | 23.3 | 13.6 |
| %      |      | 2    | 7    |
| UTS    | 1331.08 | 1207.93 | 1174.38 |
| MPa    | 1589.4 | 1493.5 | 1443.2 |
|        | 2    | 1    | 5    |
|        |      |      |      |
|        | 48   | 43   | 42   |

3.4 Fracture Image
Figure 6 shows images of the tensile fracture of the processes after pre-strain treatment. The depth of dimples is deeper and the sizes are uniform (~0.6μm) in fibrous area. And there are few micro-cracks in fibrous area. There are holes connection characteristics in radiated area.

Figure 5. Stress-strain curves treated by Q-T and Q-P-T process

Figure 6. SEM images of tensile fracture surface: (a) fibrous and (b) radiated area of Q-P-T process.
4. Discussion
After pre-strain treatment, tensile strength and the yield strength is significantly improved concurrently. This is the result of Bauschinger effect[15]. The plasticity after pre-strain is still good which is due to the existence of the large amount of the retained austenite. It has been proved that the residual austenite can significantly improve the plasticity of steels. Firstly, residual austenite can split martensite area space, reduce the effective grain size, stop the crack expansion[16]. Secondly, residual austenite can transform to martensite during tensile deformation and produces TRIP effect which effectively alleviate the local stress concentration and delay the formation of cracks, which delays the onset of necking [17, 18]. Lastly, it is pointed out that the average dislocation density in martensite decreases during uniform deformation which is lower than the value before deformation while the dislocation density in the retained austenite increases rapidly. It has been observed in TEM that dislocations in martensite moved to the adjacent residual austenite which makes martensite in an ‘undeformed’ state and greatly enhances the deformation capacity of hard phase, which was called dislocation absorption by retained austenite (DARA) effect [19]. So there is interaction between each phase and under the triple action, i.e. Bauschinger effect, TRIP effect and DARA effect, the plastic deformation capacity of the novel process shows significant enhancement compared with traditional ones which means materials treated by Q-P-T process is more suitable for cold forming.

5. Conclusions
The main conclusions of the present work are as follows:
(1) Muti-phase microstructure composed of martensite, bainite, retained austenite is obtained for the tested steel treated by Q-P-T process.
(2) Comprehensively considering the factors suitable for cold coiling as mentioned above, samples treated by Q-P-T process have lower yield strength, approximate tensile strength, good plasticity, higher contents of residual austenite and suitable hardness. So the optimal partitioning temperature is 380℃.

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