# A 2.1 GPA TRIPLE-PHASE SPRING STEEL

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## ABSTRACT

The key way of achieving sustainability of a product is to design a manufacturing process that increases the mechanical properties of traditional materials, e.g. steel, whilst also increasing processing efficiency, and diminishing energy consumption. A novel process has been developed that allows for a traditional spring steel (60Si2Mn) to be produced with a high level of strength (tensile strength is over 2100 MPa, bending strength is 4100 MPa, yield strength is 1700 MPa as well as hardness of 59 HRC), also retaining reasonable ductility on an industrial scale. It is shown that a triple-phase microstructure comprising lenticular prior martensite, nano-scaled needle/lath-like bainitic ferrite and film retained austenite, is obtained. The excellent combination of strength and ductility is attributed to a synergistic multi-phase strengthening effect. The nano-scaled structure exhibits a good balance between strength and toughness. The presence of prior martensite provides the kinetics of subsequent nano-scaled bainitic transformation by bainitic laths nucleating at the martensite–austenite interfaces. This design methodology potentially broadens the application of spring steel to components that experience more demanding service environments, such as heavy loads.

*Keywords: triple-phase microstructure, prior martensite, high strength, nano-scaled bainitic ferrite and retained austenite.*

## 1 INTRODUCTION

In the rapid developing industry, steel still plays a leading role among industrial materials, not only depending on developing new high performance steels, but also tapping the mechanical potentials of conventional steels. Among traditional steels, medium-carbon steels behave in an intermediate manner between high and low carbon steels. They have been widely used for large parts, forging and automotive components due to their good balance of strength and ductility, and wear resistance coupled with relatively low cost [1], [2].

The properties of steels depend in a complex way on their microstructure and heat treatment. Concerning the strength of steel, one promising way is the development of processes suitable to manufacturing multi-phase microstructure [3], [4]. It is possible to tailor the mechanical properties to the respective application by adjusting the volume fraction, size and distribution of the different phases. For example, the highest strength obtainable is about 2.5 GPa with a fracture toughness around 30 Mpa $m^{1/2}$ in the case of bulk high carbon high silicon steel. This is attributed to the combined behavior of the phases comprising nano-scaled bainitic ferrite (BF) and carbon-enriched film austenite [5]. A strength of 2000 MPa has been developed in a medium carbon alloyed triple-phase steel by Mandal et al. [6], with a mixture of lath martensite (M), lower bainite (LB) and retained austenite (RA). They have found that with respect to fine LB, highly dislocated lath martensitic structure in conjunction with some fine micro-alloying precipitates is an important designing factor to reach 2 GPa strength level. We have found that a tensile strength over 1600 MPa with an elongation of 5% can be achieved by controlling the volume fraction of martensite, the RA content, and the amount of BF in an unalloyed ductile iron [7]–[10]. The marteniste obtained through initially rapid quenching is found to greatly accelerate nanobainite transformation [7], [10].

However, inferior mechanical properties have also been reported for multi-phase steels compared with those having conventional microstructures [11], [12]. Namely, it is clear that

doi:10.2495/HPSM180011

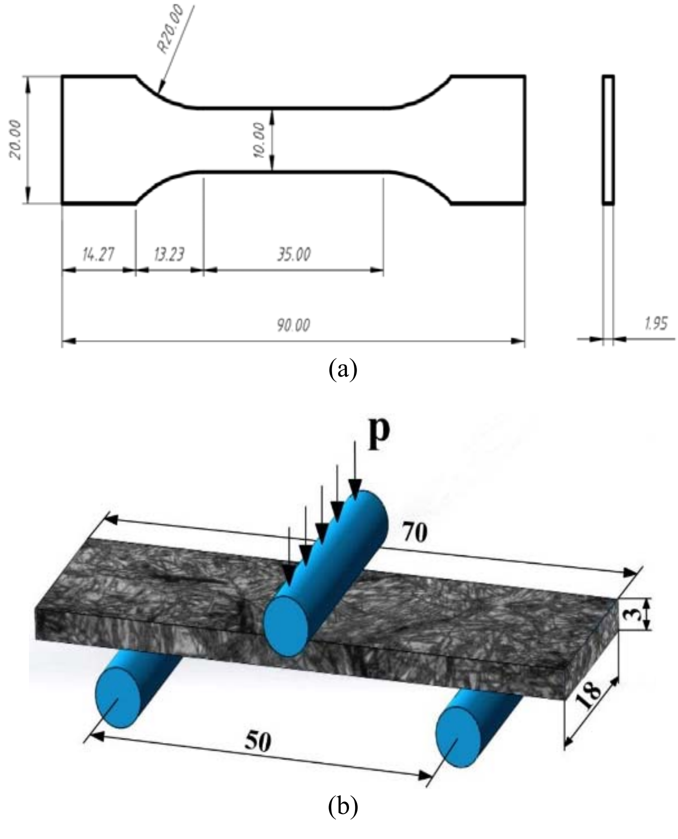
the role of each phase and the interaction between different phases on the mechanical behavior in the multiphase steels are still to be determined.

In this work, an attempt was made to design a high performance medium carbon spring steel with triple-phase microstructure by a novel process based on the multiple phase concept. A possible transformation mechanism and synergistic strengthening effect are discussed.

## 2 EXPERIMENTAL PROCEDURE

The examined steel was produced commercially by hot and cold rolling and continuous final heat treatment. The chemical composition was 0.64C-1.73Si-0.77Mn-0.19Cr-0.05Mo-0.03Ni-0.01P (wt. %). A multiple-step quenching and isothermal holding process (MSTI) was developed as follows: after austenitizing at 900°C for 30 min, the samples were rapidly quenched to 210°C with a cooling rate of approximately 60°C/s for preventing the formation of non-martensite microstructure such as pearlite and ferrite, then held at 180°C for 5 min, and up heated to 250°C for 240 min, finally air cooled to room temperature.

The tensile test with a 100kN load at a crosshead speed of 0.05 mm·min$^{-1}$ and the three-point bending test were carried out on a DNS100 universal testing machine respectively. The sample geometries and dimensions are shown in Fig 1. Hardness was tested on a HR-150A Rockwell hardness tester with a load of 150 kg. For each sample condition, three readings were taken and averaged to represent all testing values.



(a)

(b)

Figure 1: Geometry and dimensions (unit: mm) of (a) tensile and (b) bending samples.

After being ground, polished and etched in 2% nital solution, the microstructure was observed by scanning electron microscopy (SEM, XL30-ESEM). Thin disc samples were subsequently observed in a transmission electron microscope (TEM, *Talos* F200) at 200 kV operating voltage.

## 3 RESULTS AND DISCUSSION

A typical SEM micrograph of the as-received 60Si2Mn steel, Fig. 2(a), shows granular pearlite with globular cementite (Cem) in a ferrite (F) matrix. Fig. 2(b) shows a SEM micrograph taken from the heat treated sample. A triple-phase microstructure comprised of prior martensite (PM), bainitic ferrite (BF) and retained austenite (RA) is obtained after the designed heat treatment. The RA has two main morphologies: very thin films and coarser blocks. It demonstrates that most amounts of RA exist in the manner of film rather than block type. The morphology of PM is observed to have lenticular type with small dot-like features surrounded by the fine needle/lath BF interwoven with film RA.

The results of the mechanical properties for as-received and heat-treated samples are compared in Fig. 3. The tensile strength increases from 1247 to 2103 MPa and the yield strength increases from 1176 to 1712 MPa. The elongation of the heat-treated sample is 5.47%, slightly lower than that of as-received sample (see Fig. 3(a)). However, it retains reasonable ductility on an industrial scale. Fig. 3(b) shows that the hardness has the same trend of change with strength through the comparative analysis of two samples. The hardness achieved by heat treatment is more than 3 times that of the as-received hardness. Table 1

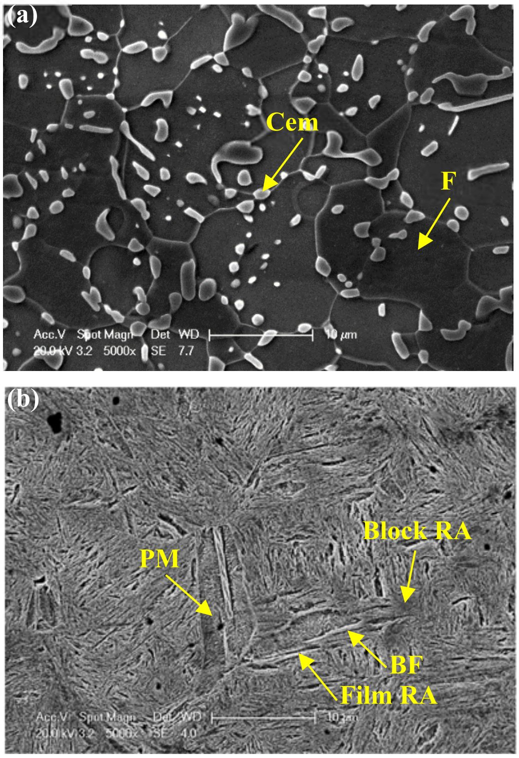
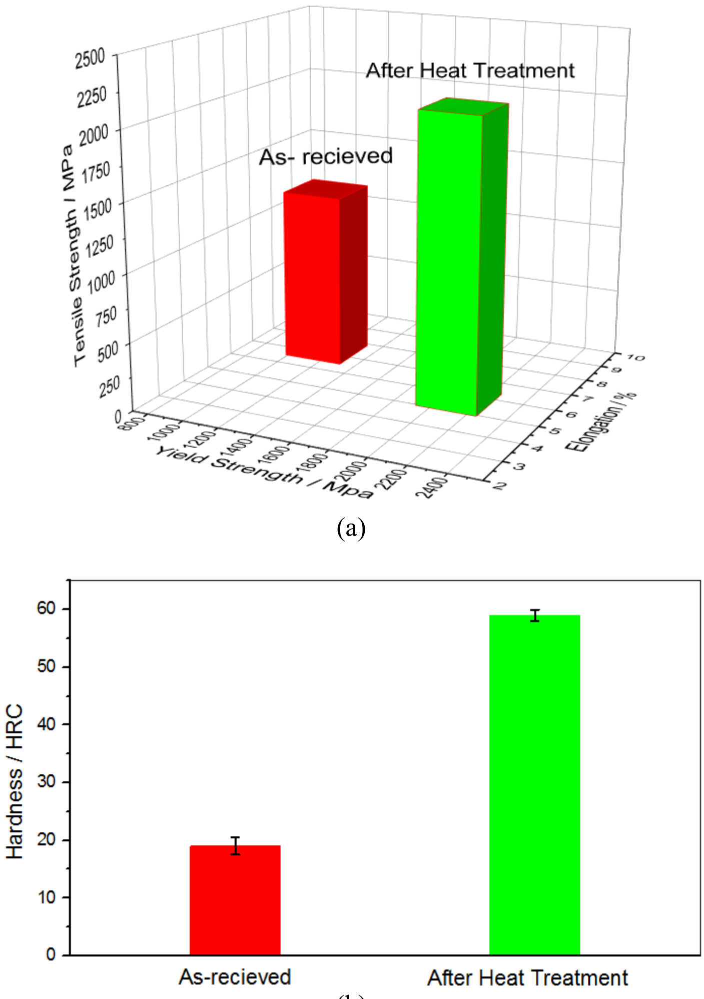


Figure 2: SEM micrographs of (a) as-received sample and (b) sample after heat treatment.



(a)

(b)

Figure 3: Tensile properties (a) and hardness results (b) of two samples.

Table 1: Bending properties of sample after the designed heat treatment.

| Bending strength (MPa) | Bending deflection (mm) |
|---|---|
| 4100±150 | 3.2±0.3 |

shows that a high bending strength of 4100 MPa with a deflection of 3.2mm can be obtained after the designed heat treatment.

The designed MSTI process consists of three steps including initially rapid quenching, secondly holding at 180°C for 5 min and thirdly isothermal holding at 250°C for 240 min and air cooling to room temperature. The first process step is to hinder austenite from transforming to pearlite or ferrite, which is demonstrated in Fig. 2(b). It is not surprising that a certain amount of PM is formed during quenching to 180°C for 5 min in the second process since the start temperature of the martensite formation (Ms) is approximately 240°C based on the calculation formula given in [13] and the austenizing temperature in the designed process. Fig. 4 is a schematic diagram illustrating the influence of PM on nucleation site and morphology of BF and RA during the third process step. On isothermal holding at 250°C, the PM is tempered with carbide formation within martensitic lath by some carbon atom migration (also can be seen in Fig. 2(b)). However, only some carbon atoms can migrate to form carbides inside the PM, the others will partition into the adjacent austenite due to high Si content which is considered to delay carbide precipitation strongly in this steel [14], [15]. Some researchers [16], [17] have found that both the migration and the partition processes of carbon atoms can happen simultaneously, and will influence each other. Since the carbide formation within PM is inhomogeneous, thus the transferring of carbon atoms from PM to austenite is uneven along the PM/austenite interface. The different regions with various carbon contents can be achieved along the interface during the partitioning process. In the regions where there are less carbon atoms, BFs tend to nucleate and grow to the interior of the austenite grains. In the regions with high carbon content, the austenite can be formed. The film RA distributes mainly between BF laths, and it more easily enriched by carbon atoms from either PM or BF and may remain until the room temperature (RA(+C)), which is different from the block RA nearby the PM region without carbide partition (yellow part). Therefore, a triple-phase microstructure of BF and RA adjacent to PM is produced (see Fig. 4).

It can be clearly seen from the TEM micrograph in Fig. 5 that an alternating nano-scaled mixture of fine needle/lath BF with width ranging from 20 to 40 nm and ultrafine film austenite of less than 10 nm in width ((BF+RA)nano) is formed along the interface between PM and austenite (also see black dash circle in Fig. 4). This indicates that the existence of PM results in a nano-scaled microstructure of (BF+RA)(nano) in this spring steel. According to previous work [17], [18], the formation of (BF+RA)nano is mainly due to the finely distributed carbides within PM laths and the corresponding partition of carbon atoms during isothermal holding at 250°C. Also, Toji et al. [16] have suggested that the high density dislocations in the austenite near PM lath can be introduced during quenching to increase the BF nucleation, and thus refine the microstructure.

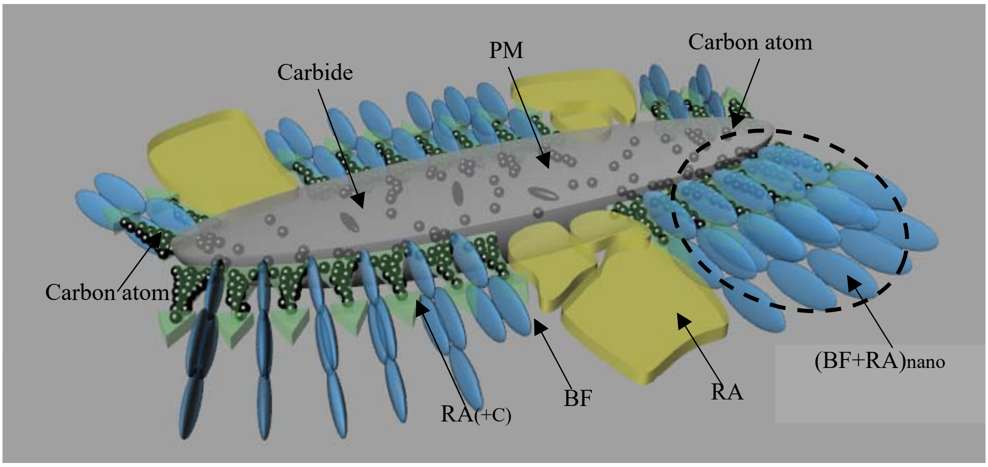


Figure 4: Schematic of evolution of triple-phase transformation during heat treatment.

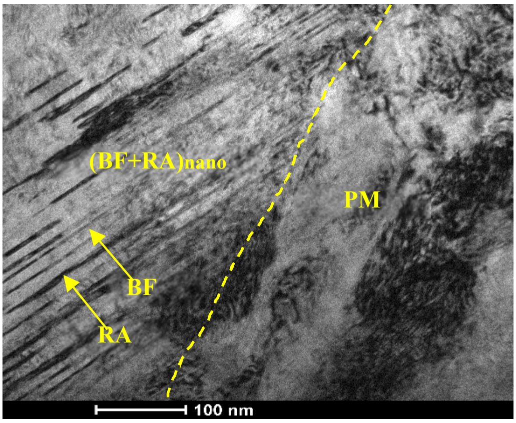


Figure 5: TEM micrograph of sample treated by the designed process.

It is well known that the microstructure is of importance in determining the specific properties of steels. The excellent combination of high strength and acceptable ductility (see Fig. 3 and Table 1) is attributed to a synergistic triple-phase strengthening effect in the spring steel. The (BF+RA)nano phase in triple-phase microstructure plays a significant role in greatly improving mechanical properties. The higher strength and the hardness are obtained mainly due to nano-scaled needle/lath BFs. The nano-scaled film RA(+C) is more stable than the block one and can inhibit the micro-crack initiation and propagation in a wide range of loading and absorb the strain from neighboring PM and BF during plastic deformation [18], [19]. Compared with (BF+RA)nano, the PM is also a contribution to the hardness improvement. However, not only that, the point is to highlight that the PM is indispensable in the triple-phase microstructure since the super high strength with acceptable ductility can bot be achieved without (BF+RA)nano nucleated around PM.

## 4 CONCLUSIONS

A triple-phase microstructure characterized by a nano-scaled lath/needle bainitic ferrite (BF) and carbon-enriched film retained austenite (RA) nucleated around the prior marteniste (PM) is developed by a multiple-step quenching and isothermal holding process (MSTI) in a commercial spring steel. A tensile strength over 2100 MPa, a yield strength more than1700 MPa, a bending strength of 4100 MP, a hardness of 59 HRC as well as an acceptable ductility, can be achieved. This is attributed to a synergistic multi-phase strengthening effect of PM and nano-scaled BF and RA.

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