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Effect of quenching temperature on microstructure and properties of 50CrMnVA spring steel for piano tuning pins

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Abstract: Spring steel has excellent elasticity, strength, and toughness. 50CrMnVA spring steel is a high-strength spring steel with excellent mechanical properties and process performance, so it is widely used in piano tuning pins. This paper investigates the effect of quenching temperature on the mechanical properties of 50CrMnVA spring steel, including the microstructure, hardness, and tensile properties of the experimental steel after treatment at different quenching temperatures, and clarifies the effect of aging time on the alloy's microstructure, hardness, strength, elongation, and reduction of area. The results show that the mechanical properties are optimal when the quenching temperature is 860 °C.

Keywords: piano string axle; 50CrMnVA spring steel; microstructure; mechanical properties

1. Introduction

The piano tuning pin is a key functional component in the piano sound source system, with both mechanical accuracy and acoustic sensitivity. Its essential role is to reliably anchor the end of the string on the cast iron frame and achieve precise fine-tuning of tension increments or decrements through reversible rotational motion, so that the fundamental frequency and harmonic structure of the string accurately correspond to the twelve-tone equal temperament system. he friction pair formed by the interference fit between the tuning pin and the pin block must resist continuous axial tension and periodic impact loads of up to 900 N during a service cycle of several decades, while maintaining the torque attenuation rate under temperature and humidity cycles. A rate of less than ±1.5 cents/year can ensure that the overall pitch drift of the piano remains within the acceptable threshold of the human ear. From the perspective of acoustics, the mechanical impedance characteristics of the string–pin coupling node directly determine the vibration energy transfer efficiency: when the torsional stiffness and damping of the pin system are mismatched, nonlinear bifurcation phenomena will be induced, resulting in beat frequencies and false overtones, thus degrading the purity of the timbre. Therefore, the tuning pin material needs to achieve a balance between multiple properties such as elastic limit, fretting wear resistance, stress relaxation resistance, and chemical stability. 50CrMnVA spring steel is a high-performance solution that has emerged through the collaborative optimization of alloying and heat treatment under these stringent constraints. This steel introduces Cr and V microalloying elements on the basis of traditional carbon–manganese spring steel, which significantly improves the service reliability of the material under complex stress conditions and provides a key material with both process adaptability and economy for the modern piano manufacturing industry.

From the perspective of materials science, the chemical composition design of 50CrMnVA spring steel follows the composite strengthening concept of *solid solution strengthening + carbide dispersion strengthening + grain boundary purification*. Specifically, the carbon content of 0.50 wt.% ensures that the martensitic matrix has sufficiently high dislocation density after quenching [1–6], thus providing high yield strength. The Cr content of about 1.0 wt.% not only enters into solid solution in the ferrite matrix to cause lattice distortion, but also precipitates M7C3 alloy cementite during the tempering process, which effectively pins dislocations and improves tempering softening resistance. By forming VC/V(C,N) nanoscale precipitates, the 0.10 wt.% V addition refines the original austenite grains (ASTM grain size can reach above 11) on the one hand, and reduces the grain boundary migration rate on the other, thereby inhibiting abnormal grain growth during quenching and minimizing overheating sensitivity [7–11]. In addition, the self-corrosion potential E_{corr} of the steel in 3.5% NaCl solution is about 120 mV more positive than that of conventional 60Si2Mn steel, and the pitting potential E_b is increased by nearly 200 mV, indicating that the dense passivation film formed by the addition of Cr significantly improves the corrosion resistance of the material in a humid environment, which is particularly critical for the long-term stable service of pianos in subtropical high-humidity climates [12–15].

Spring steel has excellent elasticity, strength, and toughness. It is typically used in quenched and tempered conditions, and its elastic deformation ability enables it to withstand a certain load without permanent deformation after the load is removed [16–17]. 50CrMnVA spring steel is a high-strength spring steel with excellent mechanical and processing properties [18–21]. Therefore, it is widely used in piano tuning pins, heavy-duty mold springs, and other applications. The hardenability of this steel is high, and the added vanadium element can refine the grain structure, reduce overheating sensitivity, and improve strength and toughness. It also has high fatigue strength and a high yield ratio. Quenching treatments of 50CrMnVA spring steel at different temperatures were carried out, and the mechanical properties, such as microstructure, tensile properties, and hardness, under different heat treatment conditions were studied, providing a reference for the formulation of the heat treatment process of 50CrMnVA spring steel in the production of piano tuning pins.

2. Materials and Methods

The experimental specimens of 50CrMnVA spring steel were prepared by melting in a medium-frequency furnace, followed by sand casting. The chemical composition of the steel, expressed in mass fractions, is as follows: carbon (C) 0.54 %, silicon (Si) 0.251 %, manganese (Mn) 0.93 %, chromium (Cr) 1.14 %, copper (Cu) 0.058 %, nickel (Ni) 0.041 %, with iron (Fe) making up the remainder.

The heat treatment process employed for 50CrMnVA spring steel involved high-temperature quenching followed by medium-temperature tempering, which is a widely used treatment for spring steel. This process aims to produce a microstructure composed of ferrite and finely dispersed carbides, which is conducive to achieving a balance of strength, hardness, plasticity, and toughness, thereby meeting the required comprehensive mechanical properties. The quenching of the experimental steel was conducted in a box-type resistance furnace at temperatures of 780 °C, 820 °C, 860 °C, 900 °C, and 940 °C, each for a duration of 40 minutes, with oil serving as the quenching medium. Subsequently, the steel was tempered at 490 °C for 90 minutes and then water-cooled. The microstructure of the experimental steel was examined using a metallographic microscope, with a 3 % nitric acid alcohol solution used as the etchant. The mechanical properties of the steel in various states were assessed using a 5105 microcomputer-controlled electronic universal testing machine.

3. Results

The microstructural observations of the 50CrMnVA experimental steel following quenching at various temperatures and subsequent tempering at 490 °C are shown in Figure 1. Within the temperature range of 780 °C to 940 °C, the martensitic morphology of the 50CrMnVA steel progressively transitions from an acicular to a lath-like structure as the temperature increases. This evolution is indicative of the martensitic transformation behavior typical of medium-carbon steels. The martensitic microstructure predominantly consists of dislocations, twins, and lath structures, which significantly influence the mechanical properties of martensite. Dislocation-rich martensite exhibits enhanced toughness due to its capacity for substantial plastic deformation,

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whereas twin-rich martensite is typically characterized by increased hardness and brittleness, attributable to its limited plastic deformation capacity. In 50CrMnVA steel, the martensitic microstructure transitions from a twin-dominated to a dislocation-dominated state with increasing quenching temperature, thereby enhancing the material's toughness.

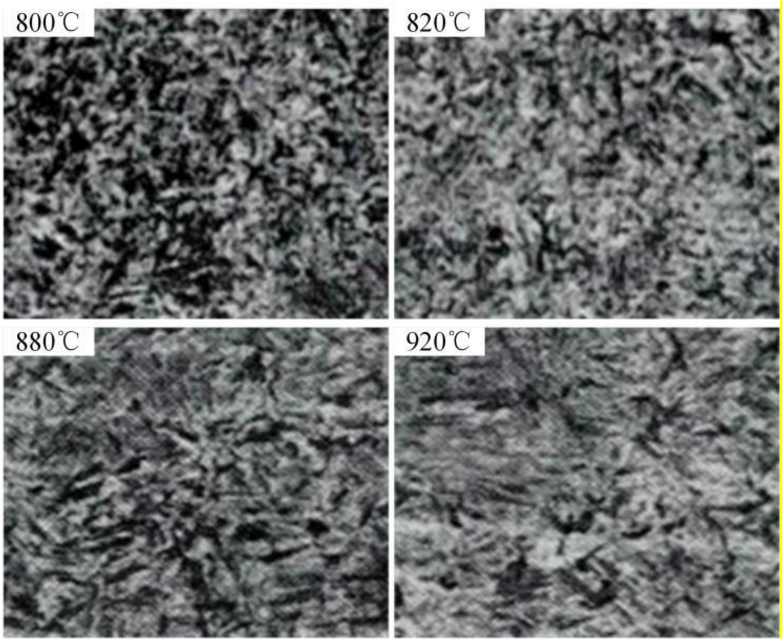

Figure 1. Microstructure of 50CrMnVA experimental steel after quenching at different temperatures and tempering at 490 °C, 200x

The influence of quenching duration and temperature on the material's mechanical properties was systematically investigated. The experimental steel was quenched after a dwell period at temperatures ranging from 780 °C to 940 °C for 40 minutes, followed by tempering at 490 °C for 90 minutes. Subsequently, the steel was evaluated for its mechanical properties. It is generally acknowledged that an optimal balance of material properties can be achieved through precise control of these processing parameters. The data presented in Table 1 show the mechanical properties of the experimental steel subjected to various quenching temperatures, with a constant tempering temperature of 490 °C. This dataset provides a comprehensive overview of how the quenching regime influences the mechanical behavior of the steel.

Table 1. Effect of quenching temperature on the mechanical properties of 50CrMnVA experimental steel

Number	Quenching temperature / ℃	Yield strength MPa	Tensile strength MPa	Hardness HV	Section shrinkage / %	Elongation %
1	780	1289	1347	627	50.14	12.52
2	820	1310	1369	653	47.56	12.94
3	860	1324	1408	678	46.99	14.24
4	900	1309	1427	663	46.10	13.18
5	940	1305	1432	658	40.73	12.63

The steel hardness test is a method used to evaluate the hardness of a material, which can help determine differences in chemical composition, microstructure, and processing. Hardness tests reflect the strength properties of materials and are an important tool in the development and quality control of metallic materials. Through these tests, the wear resistance, indentation resistance, and resistance to plastic deformation of a material can be evaluated. The Vickers hardness test was used in this experiment. From the curve, it can be seen

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that the hardness of 50CrMnVA experimental steel increases and then decreases with increasing quenching temperature. At 860 °C, the hardness reaches its maximum value.

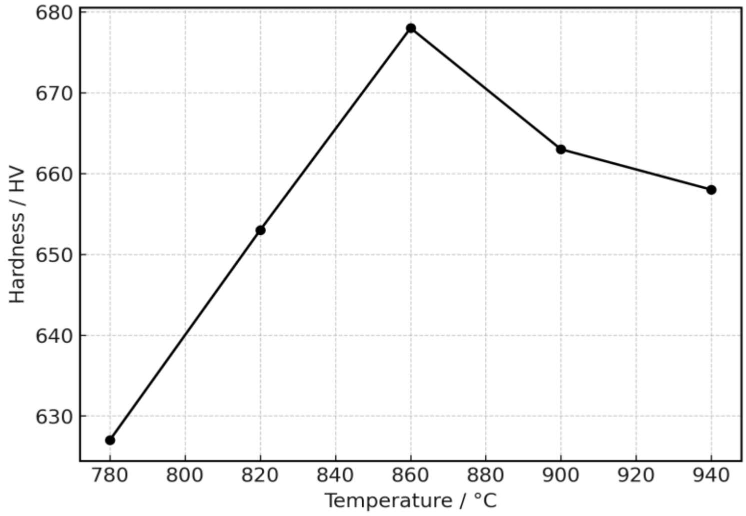

Figure 2. Effect of quenching temperature on hardness of experimental steel

Yield strength is the critical stress that describes the transition of a material from an elastic to a plastic state when subjected to an external force. It marks the point at which permanent deformation of the material begins to occur. The determination of yield strength is usually carried out by tensile testing. Yield strength is not only an important index of material properties but also an approximate measure of certain mechanical behaviors and processing characteristics of materials in engineering. Figure 3 shows the effect of quenching temperature on the yield strength of the experimental steel. It can be seen from the curve that the yield strength of 50CrMnVA experimental steel increases at first and then decreases with increasing quenching temperature. At 860 °C, the yield strength reaches its maximum value

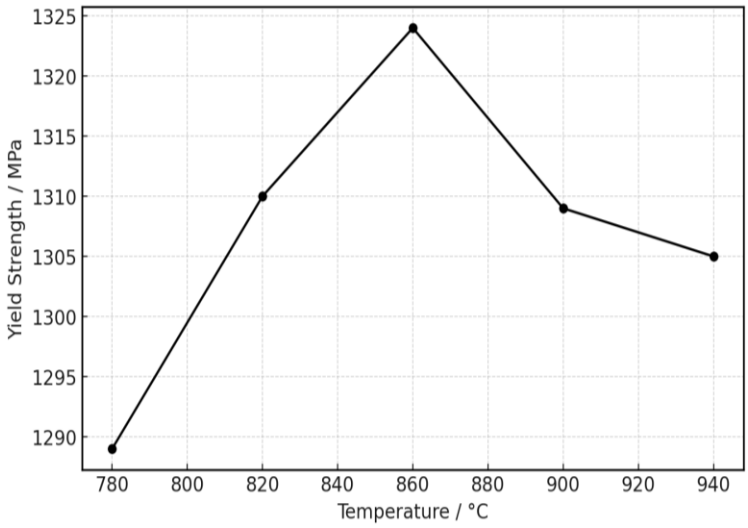

Figure 3. Effect of quenching temperature on the yield strength of experimental steel

Tensile strength is a critical mechanical property that quantifies a material's capacity to withstand tensile forces without fracturing. It is determined by measuring the maximum stress a material can endure before fracture. This parameter is a significant indicator of both the strength and ductility of a material under tensile loading conditions. Figure 4 illustrates the effect of quenching temperature on the tensile strength of 50CrMnVA experimental steel. The results show that an increase in quenching temperature correlates with a progressive

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increase in tensile strength. Notably, at a quenching temperature of 940 °C, the steel exhibits its maximum tensile strength, signifying the optimal heat treatment condition for achieving superior tensile properties in this material.

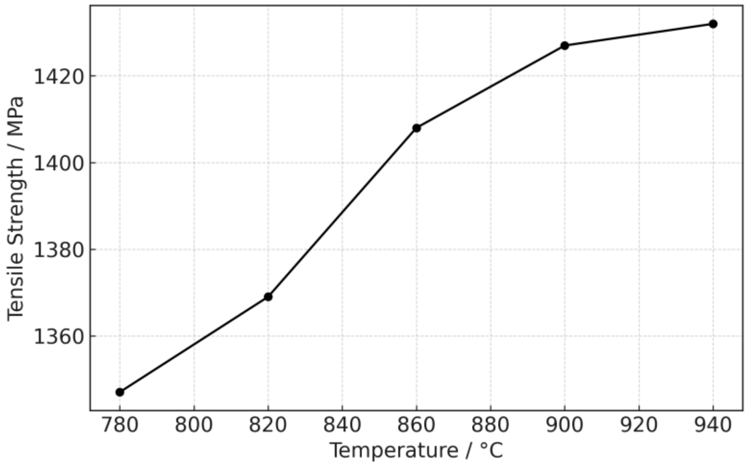

Figure 4. Effect of quenching temperature on the tensile strength of experimental steel

Section shrinkage, a key metric in tensile testing, is defined as the percentage reduction in the cross-sectional area of a specimen at the point of fracture relative to its original cross-sectional area. This parameter indicates the extent of plastic deformation that a material undergoes during the tensile process and serves as a measure of its ductility and strength. Figure 5 illustrates the effect of quenching temperature on the section shrinkage of 50CrMnVA experimental steel. The data in the graph indicate that, as the quenching temperature increases, the section shrinkage of 50CrMnVA steel shows a decreasing trend. Specifically, at a quenching temperature of 940 °C, the steel exhibits its minimum section shrinkage value, suggesting reduced ductility at this temperature.

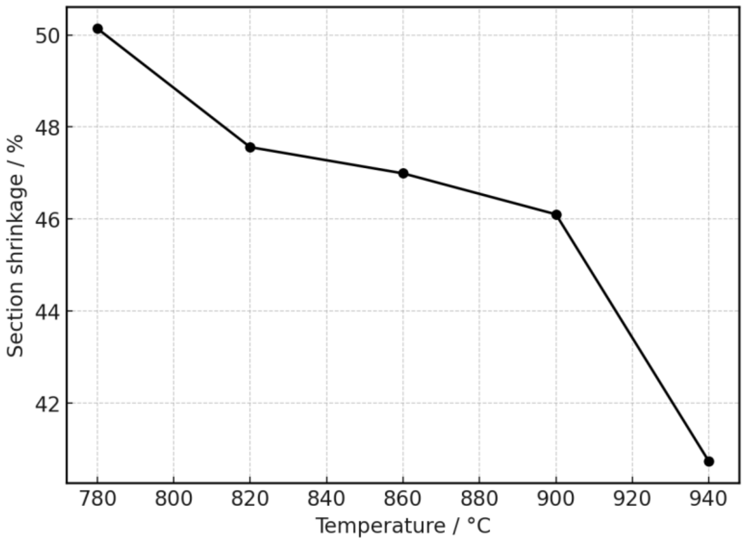

Figure 5. Effect of quenching temperature on the elongation of experimental spring steel

Elongation is one of the most important indicators of material plasticity, describing the degree of deformation a material undergoes when subjected to tensile forces. Figure 6 shows the effect of quenching temperature on the elongation of experimental steel. The curve shows that, as the quenching temperature increases, the elongation of 50CrMnVA experimental steel first increases and then decreases. At 870 °C, the elongation reaches its maximum value.

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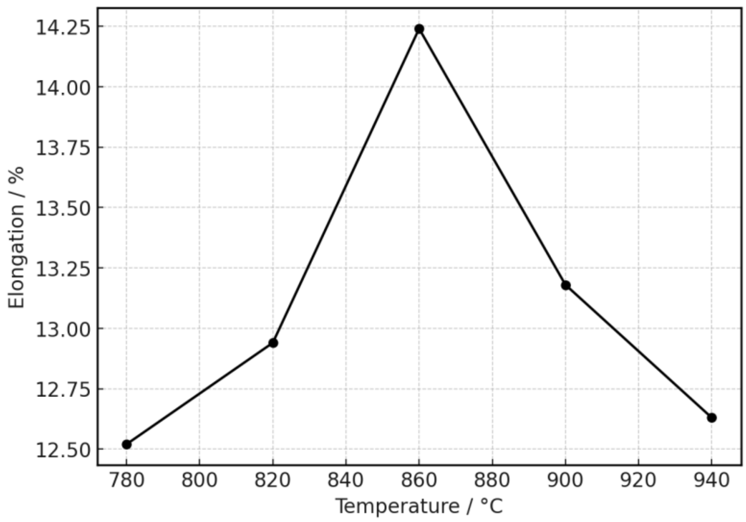

Figure 6. Effect of quenching temperature on the elongation of experimental steel

4. Discussion

The experimental results reveal a pronounced nonlinear coupling interaction between quenching temperature and the microstructural and mechanical characteristics of 50CrMnVA spring steel. The optimal performance window is localized around 860 °C. At quenching temperatures below the critical threshold, the austenite grains do not undergo complete refinement, and carbides are not fully dissolved, leading to the formation of coarse martensite laths and a significant presence of internal twin structures. This results in insufficient dislocation slip resistance. While hardness and yield strength increase incrementally with rising temperature, the reserve of plastic toughness remains inadequate, as evidenced by the low reduction of area and elongation index, and there is a tendency toward early brittle fracture under cyclic impact loads. This makes the material unsuitable for meeting the long-term requirements of anti-relaxation and resistance to fretting wear in piano tuning pins.

Conversely, when the quenching temperature surpasses 860 °C and approaches 900 °C, abnormal grain growth occurs, accompanied by an increase in grain boundary energy. The VC/V(C,N) precipitated phase becomes coarser and is distributed in a chain-like pattern along the original austenite grain boundaries, causing local stress concentrations and the formation of quenching microcracks. Additionally, excessively high temperatures promote an increase in residual austenite content, which can transform into brittle upper bainite or coarse carbides during subsequent medium-temperature tempering, significantly reducing the material's fatigue life. In these cases, although hardness and yield strength remain high, there is a sharp decrease in the plasticity index, with the reduction of area dropping from 46.99 % at 860 °C to 40.73 % at 940 °C, while elongation also shows a declining trend, indicating that the material has reached a critical state of toughness exhaustion.

Only within the precise quenching window at 860 °C is the thermal activation energy sufficient to promote the complete solid solution of Cr and V microalloying elements, thereby inhibiting grain boundary migration. The martensite lath structure is refined to the submicron scale, and the dislocation cell structure is dense and uniformly distributed. The M7C3 and VC nanoscale carbides precipitated during tempering are uniformly dispersed, producing a significant synergistic effect of precipitation strengthening and grain boundary purification. At this temperature, hardness peaks at 678 HV, yield strength at 1324 MPa, tensile strength at 1408 MPa, elongation at 14.24 %, and reduction of area at 46.99 %. The optimal balance of strength, plasticity, and toughness is achieved. This study therefore provides a robust material solution for the long-term service life of piano tuning pins under conditions of 900 N axial tension, periodic impact, and coupled temperature and humidity environments.

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5. Conclusions

This study systematically elucidates the nonlinear coupling between quenching temperature and the microstructure–mechanical property relationship of 50CrMnVA spring steel used for piano tuning pins. Within the quenching range of (780–940) °C, hardness, yield strength, tensile strength, elongation, and reduction of area all exhibit a pronounced rise–then–fall trend, demonstrating the steel's extreme sensitivity to the thermal processing window. When the quenching temperature is precisely set at 860 °C, the prior austenite grains are refined to the submicron scale through synergistic pinning by V(C,N) and M7C3 nanoprecipitates; the martensite laths transform from twinned to high–dislocation-density types, markedly improving microstructural homogeneity. After tempering at 490 °C, uniformly dispersed alloy carbides further purify grain boundaries and strengthen the matrix, achieving an optimal balance of strength, ductility, and toughness. Under these conditions, the material reaches a peak hardness of 678 HV, a yield strength of 1324 MPa, a tensile strength of 1408 MPa, an elongation of 14.24 %, and a reduction of area of 46.99 %, all substantially superior to the values obtained at other temperatures.

Quenching below 860 °C leads to incomplete carbide dissolution, grain coarsening, and an excessive fraction of twinned martensite, increasing susceptibility to early brittle fracture. Conversely, when the temperature exceeds 860 °C and approaches 940 °C, abnormal grain growth occurs; chain-like VC/V(C,N) precipitates induce stress concentrations, and retained austenite transforms into brittle upper bainite, causing a sharp drop in ductility and toughness. Hence, 860 °C is identified as the optimal quenching window for 50CrMnVA spring steel in piano tuning-pin applications. These findings not only provide reliable heat-treatment parameters for the industrial production of high-load, long-life piano pins, but also lay a solid theoretical and experimental foundation for the domestic substitution of high-performance spring steels in premium musical instruments, offering significant engineering value and broad prospects for commercial adoption.

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