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Influence of Solid Solution Temperature on the Microstructure Evaluation of 15-5PH Stainless Steel for Pipe Organ Rail Rod Applications

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Abstract: This study investigates the effect of solid solution treatment temperature on the microstructure and mechanical properties of 15-5PH stainless steel, with the aim of optimizing its performance for precision mechanical components. Samples were solution-treated at 975 °C, 1000 °C, 1025 °C, and 1050 °C, followed by aging at 480 °C for 1 h. Microstructural observations revealed progressive grain coarsening with increasing solution temperature. Mechanical testing showed that yield and tensile strengths increased with temperature up to 1025 °C, reaching maximum values of 1390 MPa and 1286 MPa, respectively, due to enhanced dissolution of strengthening phases prior to aging. In contrast, ductility and impact energy decreased consistently with increasing temperature; the highest toughness was obtained at 975 °C (35.5 J), while the lowest values occurred at 1050 °C (6.5 J). The optimal combination of strength and ductility was achieved at 1025 °C, indicating this temperature as the most effective solution-treatment condition for the tested steel. These findings provide a basis for selecting heat-treatment parameters to enhance the performance and reliability of components manufactured from 15-5PH stainless steel.

Keywords: pipe organ rail bar machine; 15-5PH stainless steel; microstructure; mechanical properties

1. Introduction

The rail bar mechanism in pipe organs serves as a critical mechanical interface between the keyboard and the sound-producing pipes. When a key is pressed, motion is transferred through a system of levers, linkages, and sliders to actuate the corresponding valve that regulates airflow into the selected pipe. Because each key is mechanically coupled to an individual valve, the performer receives precise tactile feedback, and small variations in key pressure translate into differences in musical expression.

To ensure the long-term reliability of this mechanism, the rail bar components must provide high dimensional stability, resistance to wear, sufficient strength, and corrosion resistance. These requirements highlight the importance of selecting materials with microstructural stability and mechanical performance suitable for cyclic loading under varying environmental conditions.

Although the general behavior of 15-5PH stainless steel has been studied in various engineering fields [1–3], limited attention has been given to how specific solution treatment parameters affect its suitability for high-precision, long-life mechanical systems such as organ rail-rod mechanisms [4]. Understanding the influence of solution treatment temperature on microstructure and mechanical properties is therefore relevant for improving material performance in such applications.

15-5PH stainless steel is a martensitic precipitation-hardening alloy containing approximately 15 % chromium, 5 % nickel, and alloying elements such as copper and niobium [8–11]. It is used in aerospace components, medical devices, marine structures, and precision machinery due to its favorable combination of strength, toughness, and corrosion resistance. In aerospace applications [12–15], it is employed in landing gear components and engine parts subjected to high stresses. In medical engineering, it is used for instruments and implants requiring biocompatibility and corrosion resistance. In marine environments, it is applied in components exposed to saltwater where long-term corrosion resistance is essential [16–17].

For organ rail-rod mechanisms, 15-5PH stainless steel is of interest because its mechanical properties can be tailored through heat treatment, typically involving solution treatment followed by aging. Solution treatment promotes homogenization of alloying elements, while aging induces the formation of strengthening precipitates, allowing mechanical properties to be adjusted for specific operational requirements [19–21].

In this study, the effect of different solution treatment temperatures on the microstructure and mechanical properties of 15-5PH stainless steel is examined. The aim is to provide experimental data that may assist in selecting heat-treatment parameters for precision mechanical components, including those used in pipe-organ rail-rod systems.

2. Materials and Methods

The 15-5PH stainless steel specimens used in this study were produced via sand casting using an intermediate-frequency induction melting furnace. The chemical composition (mass fraction, %) of the steel is as follows: 0.005 C, 0.45 Si, 0.55 Mn, 0.004 S, 0.005 P, 15.45 Cr, 5.40 Ni, 0.40 Nb, 0.40 Mo, 3.80 Cu, and balance Fe.

Solution treatment was conducted using a box-type resistance furnace at four different temperatures: 975 °C, 1000 °C, 1025 °C, and 1050 °C, with a holding time of 1 hour for each condition. Three specimens were prepared for each solution treatment condition to ensure statistical reliability of the test results. Subsequently, all specimens were subjected to aging treatment at 480 °C for 1 hour in a controlled heating furnace.

Microstructural characterization was performed using an optical metallographic microscope (e.g., Olympus BX53M). The specimens were etched with a 3 % nital solution to reveal the microstructure. Mechanical properties, including tensile strength, yield strength, elongation, section shrinkage, and impact energy, were measured using a microcomputer-controlled electronic universal testing machine (e.g., Instron 5105), ensuring compliance with standard testing protocols. All mechanical tests were performed in triplicate for each condition to ensure data reproducibility.

3. Results

The microstructural characteristics of ultra-low-carbon 15-5PH stainless steel after solution treatment at different temperatures are shown in Figure 1 (40× magnification). The micrographs indicate that the solution temperature has a pronounced effect on grain size and grain-boundary morphology. As the temperature increases, the prior-austenite grains become progressively coarser, accompanied by a noticeable increase in the effective grain size. After solution treatment, the matrix exhibits a typical lath-martensitic structure, with martensite laths of various orientations confined within the boundaries of the original austenite grains. A clear relationship was observed between microstructure and mechanical properties. Finer grains were associated with improved toughness and ductility, whereas coarser grains corresponded to decreased impact resistance and reduced plastic deformation capacity. These findings confirm that microstructural refinement through optimized solution temperature plays a key role in improving the performance of 15-5PH stainless steel.

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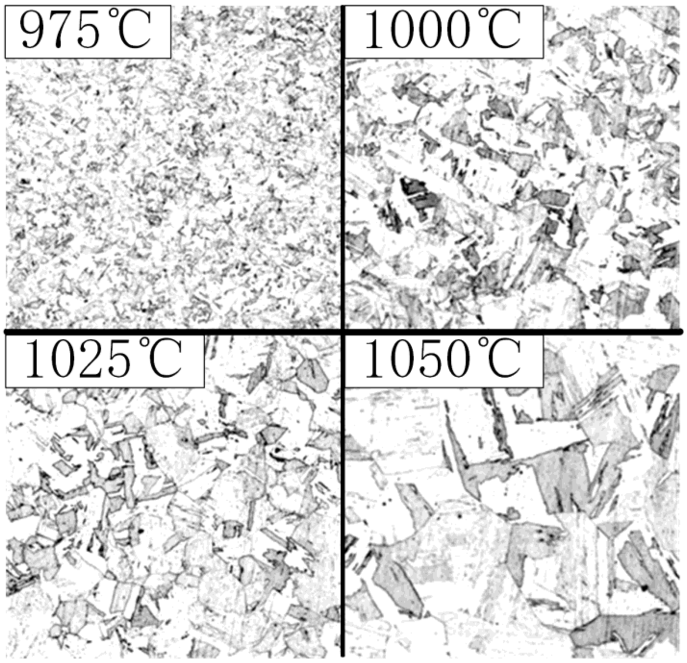

Figure 1. Effect of solid solution temperature on the microstructure of the experimental steel (40× magnification)

Mechanical properties were evaluated after solution treatment at 975 °C, 1000 °C, 1025 °C, and 1050 °C, followed by aging at 480 °C for 1 h. Each condition was tested three times, and the individual measurements are summarized in Table 1.

Table 1. Mechanical properties of samples at different solid solution temperatures

Temperature °C	Number	Yield strength MPa	Tensile strength MPa	Impact energy / J	Section shrinkage / %	Elongation %
975	1	1272	1275	35.3	14.3	53.8
	2	1275	1280	35.4	14.5	41.1
	3	1275	1279	35.8	14.4	54.1
1000	1	1380	1279	16.6	11.6	47.1
	2	1384	1282	16.9	11.8	47.2
	3	1382	1279	16.9	12.0	49.7
1025	1	1391	1285	11.1	11.5	36.8
	2	1388	1287	11.3	11.5	37.0
	3	1391	1286	11.2	11.7	37.2
1050	1	1360	1276	6.3	8.4	33.2
	2	1362	1273	6.5	8.6	32.8
	3	1361	1273	6.7	8.5	33.0

To assess the variability of the measurements, standard deviations were calculated using Equation (1).

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \quad (1)$$

where
SD—standard deviation
x_i—individual measurement
$\bar{x}$—arithmetic mean
n—number of repeated tests.

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The averaged values and corresponding standard deviations are presented in Table 2. The results show good repeatability, with the largest variation observed in elongation at 975 °C, likely due to microstructural heterogeneity at lower solution temperatures.

Table 2. The averaged values and their corresponding standard deviations of mechanical properties of experimental steel at different solid solution temperatures

Temperature ℃	Yield strength MPa	SD MPa	Tensile strength MPa	SD MPa	Impact energy J	SD J	Section shrinkage %	SD %	Elongation %	SD %
975	1274	1.7	1278	2.6	35.5	0.26	14.4	0.10	49.7	7.42
1000	1382	2.0	1280	1.7	16.8	0.17	11.8	0.20	48.0	1.47
1025	1390	1.7	1286	1.0	11.3	0.10	11.6	0.12	37.0	0.20
1050	1361	1.0	1274	1.7	6.5	0.20	8.5	0.10	33.0	0.20

The combined influence of solution temperature on yield and tensile strength is shown in Figure 2. Yield strength increases significantly between 975 °C and 1025 °C, reaching a maximum of 1390 MPa at 1025 °C, after which it decreases slightly at 1050 °C. Tensile strength shows comparatively minor variation but also peaks at 1025 °C (1286 MPa). This demonstrates that insufficient solution temperature leads to incomplete dissolution of strengthening elements, while overheating above 1025 °C promotes grain coarsening and a reduction in strength.

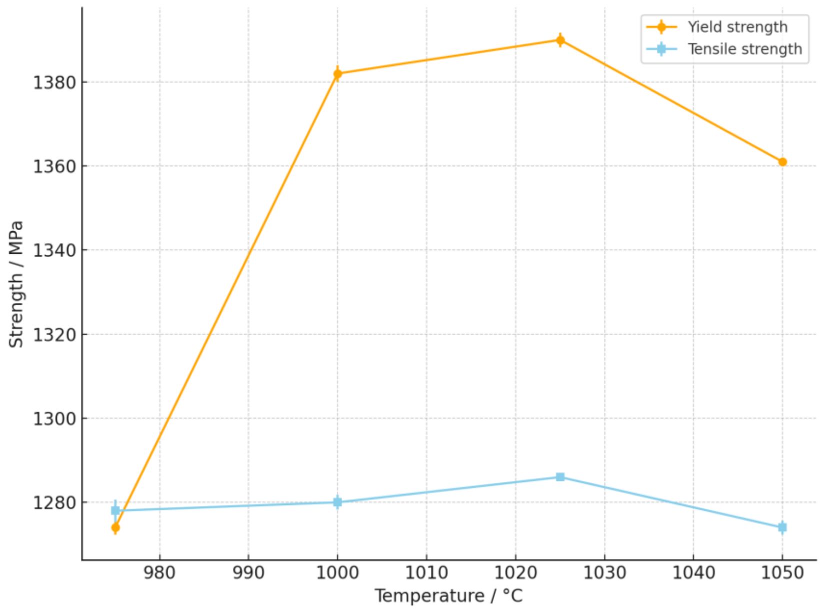

Figure 2. Effect of solid solution temperature on the yield strength and tensile strength of 15-5PH stainless steel

Figure 3 presents the variation of ductility-related properties—impact energy, elongation, and section shrinkage. All three parameters show a consistent decline with increasing solution temperature. The highest toughness and ductility occur at 975 °C, where the impact energy reaches 35.5 J and elongation 49.7 %, while the lowest values appear at 1050 °C (6.5 J and 33.0 %, respectively). This deterioration is attributed to grain coarsening and reduced resistance to crack initiation and propagation at higher temperatures.

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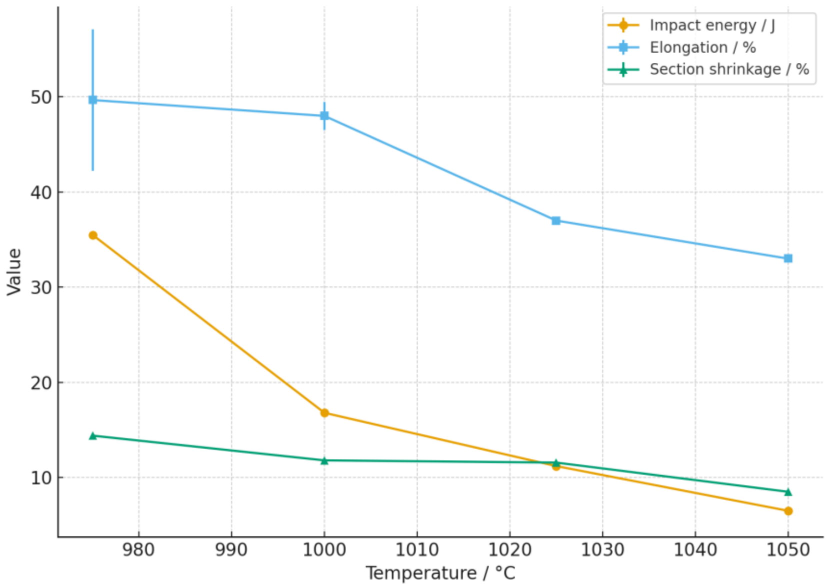

Figure 3. Effect of solid solution temperature on impact energy, elongation, and section shrinkage.

Overall, the results indicate that 1025 °C provides the most favorable balance of mechanical properties, combining maximum yield and tensile strength with acceptable levels of toughness and ductility. Therefore, 1025 °C is identified as the optimal solution treatment temperature for the studied 15-5PH stainless steel.

4. Discussion

The results of this study clearly demonstrate that the solid solution temperature plays a decisive role in determining the microstructure and mechanical properties of 15-5PH stainless steel. The microstructural observations confirm that increasing the solution temperature promotes progressive grain growth and modification of the martensitic morphology, which in turn strongly influences strength, toughness, and ductility.

At the lowest solution temperature (975 °C), the steel exhibits the highest impact energy and elongation, which is consistent with the presence of relatively finer prior-austenite grains and a dense network of grain boundaries capable of absorbing deformation energy. As the temperature increases to 1000 °C–1025 °C, more precipitates dissolve into the matrix, providing an optimal supersaturation level for subsequent aging. This leads to the formation of fine, uniformly distributed strengthening precipitates and results in the highest yield and tensile strengths observed at 1025 °C. Although the grain size is larger at this temperature, precipitation hardening dominates the strengthening effect, producing an advantageous combination of strength and acceptable ductility.

Further increasing the solution temperature to 1050 °C causes excessive grain coarsening and a reduction in the density of strengthening precipitates after aging, which explains the pronounced drop in impact energy, elongation, and section shrinkage. These trends are fully consistent with previously reported behavior of precipitation-hardening stainless steels, where an optimal solution temperature maximizes the balance be-tween precipitation strengthening and microstructural stability.

Overall, the optimal treatment identified in this study (1025 °C) yields the most favorable combination of strength, ductility, and toughness, making it suitable for components such as pipe organ rail rod mechanisms that require high mechanical reliability under dynamic service conditions. The findings align well with the literature and provide a strong basis for the refinement of heat-treatment protocols for 15-5PH stainless steel.

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5. Conclusions

This study examined the effect of solid solution temperature on the microstructure and mechanical properties of 15-5PH stainless steel. The results show that solution temperature strongly affects strength, ductility, and impact toughness through its influence on grain size and the dissolution of strengthening phases. The optimal treatment was identified at 1025 °C, where the steel achieved its highest yield strength (1390 MPa) and tensile strength (1286 MPa) while maintaining acceptable ductility and toughness.

These findings highlight the importance of precise heat-treatment control when tailoring 15-5PH stainless steel for demanding applications. Optimizing solution temperature enhances the mechanical reliability and service life of components such as rail rod mechanisms, where both strength and deformation capacity are required. Overall, the study provides a useful basis for selecting heat-treatment parameters to improve the performance of 15-5PH stainless steel in high-precision engineering applications.

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