Production Technologies for High-Quality SAE-9254 Spring Steel

MING-LUN CAI

Metallurgical Department
China Steel Corporation

SAE 9254 is commonly used for automotive suspension springs, requiring strict surface quality to ensure fatigue performance. In collaboration with downstream customers, slip-marks between rings and rust-induced pitting were identified as the primary causes of Eddy Current Testing (ET) alarms. Slip-marks, caused by ring-to-ring contact during strapping, were reduced by increasing lubricant concentration and optimizing strapping pressure. Rust, resulting from thin and FeO-rich scale, was mitigated by raising the laying temperature and slowing conveyor speed, increasing scale thickness from 4 μm to 10 μm and improving the FeO/Fe_3O_4 ratio from 3.0 to 2.3. Above improvements raised the ET pass rate from 51% to 85%, exceeding competitor levels and improving the customer's wire drawing efficiency by 13.6%.

Keywords: SAE 9254 suspension springs steel, Eddy Current Testing, Strapping parameters, Stelmor cooling

1. INTRODUCTION

1.1 Current Status

SAE 9254 steel is characterized by high tensile strength and excellent fatigue life, making it a widely used material for automotive suspension springs, as illustrated in Figure 1. Since surface defects on the material can significantly reduce fatigue strength and service life, stringent surface quality requirements are imposed. After wire drawing, customers perform 100% surface inspection using Eddy Current Testing (ET). Any detected defect triggers an alarm and halts wire feeding until the flaw is manually removed. A high frequency of ET alarms not only increases the labor burden but also adversely affects production efficiency. Therefore, minimizing surface defects on wire rod materials is crucial for reducing quality risks and maintaining customer productivity.

1.2 Problem Description

Automotive suspension springs operate under cyclic loading conditions. Surface defects can act as initiation points for fatigue cracks, significantly shortening fatigue life and potentially leading to spring fracture during vehicle operation, posing serious safety hazards. Moreover, the spring wire undergoes Induction Treated Wire (ITW) heat treatment, reaching a tensile strength of 1800–2000 MPa. Severe residual defects may propagate under static conditions, leading to premature fracture even before spring forming, which can endanger personnel and equipment.[1]

CSC's Customers use the frequency of ET alarms as

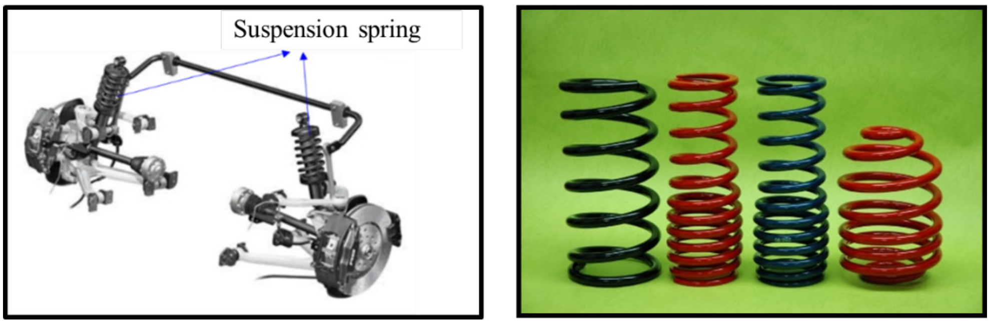


Fig.1. Schematic Diagram of an Automotive Suspension Spring.

a key quality indicator. However, as wire drawing lengths vary depending on rod size, using absolute ET alarm counts leads to imprecision in quality evaluation. To standardize assessment, the critical quality index is defined as the number of ET alarms per 100 meters of wire rod, with ≤6 as the acceptance criterion. Feedback indicates that in 2023, only 51% of coils met this criterion, as shown in Figure 2, which significantly impacted customer productivity. Continuous improvement efforts are thus necessary to meet customer expectations.

This project aims to identify the correlation between ET-detected surface defects and upstream manufacturing processes. By investigating and optimizing current process parameters, the goal is to improve surface quality and increase customer yield. Based on an average ET pass rate of 51% during January to August 2023, the target is to exceed P-Company's level of 76%.

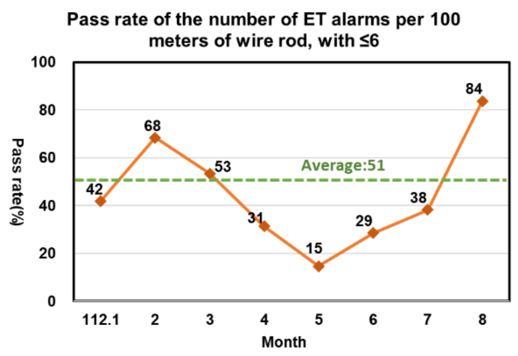


Fig.2. Monthly Trend of ET Pass Rate from Jan. to Aug. 2023.

2. EXPERIMENTAL METHOD

2.1 On-Site Observation

The customer's Eddy Current Testing (ET) is conducted offline. Before inspection, the system is calibrated using a standard reference rod notched axially to a depth of 0.07 mm. During inspection, any defect signal exceeding the threshold value (>0.07 mm) triggers an alarm and automatically stops the wire feeding. Operators then identify and manually grind the defect at the indicated location.

On-site investigation revealed that ET alarms primarily result from two defect types: slip-marks between rings and rust, as summarized in Table 1. The most common between-rings slip-mark defect appears as a transverse mark approximately 3–5 cm in length. In addition, the customer noted that prolonged storage of CSC's SAE 9254 wire rods often leads to minor rust formation, which increases ET alarm counts.

2.2 Data Collection

To better understand the relative proportions of each defect type, the customer agreed to classify and rank the ET alarms observed for each coil. The analysis results, shown in Figure 3, indicate that slip-marks between rings account for the highest proportion at 73%, followed by pits due to rust at 11%.

Based on the above findings, four major root causes of ET alarms were identified. The two primary defect types will be further analyzed in the subsequent sections.

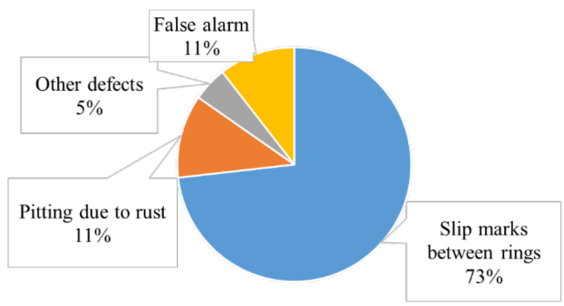


Fig.3. Proportion of Defect Types Triggering ET Alarms

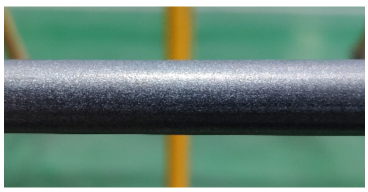
3. ANALYSIS

3.1 Slip-marks Between Rings

3.1.1 Cause Analysis

Slip marks between rings are primarily caused during the coil strapping process. When coils are pressed by clamping plates, lateral slippage and friction may occur between adjacent rings, leading to surface damage(2). As this process takes place during cold strapping of coil rods, the resulting microstructure exhibits evident plastic deformation, as shown in Figure 4.

Table 1 Classification and Visual Characteristics of ET Alarm Defects.

Defect Type	Slip-marks between rings	Pitting due to rust
Appearance		

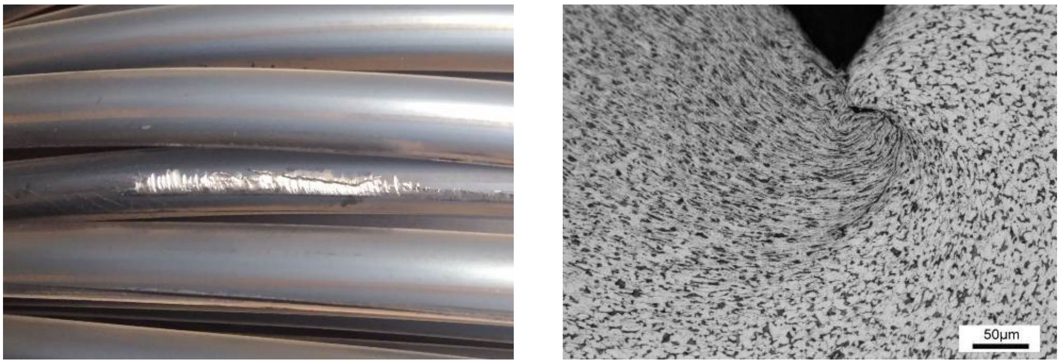


Fig.4. Surface Appearance and Metallographic Analysis of Slip-marks Between Rings.

3.1.2 Evaluation of Strapping Parameters

To further evaluate the influence of strapping parameters on slip marks between rings, a Taguchi design of experiments was conducted using three factors at two levels each, as shown in Table 2. The severity of slip marks between rings was assessed through visual inspection by uncoiling, and the rating served as the basis for evaluating the improvement effect.

Main effects analysis revealed that increasing the lubricant concentration significantly reduced severity, as shown in Figure 5. In contrast, changes in strapping pressure had only a marginal effect, and extending the lubrication sprinkling time showed no noticeable improvement.

Table 2 Experimental Factors and Level Settings.

Factor	Process Parameter	Level 1	Level 2
A	Strapping Pressure (t)	Lower	Standard
B	Lubrication Sprinkling Time (s)	Standard	Longer
C	Lubricant Concentration (%)	Standard	More viscous

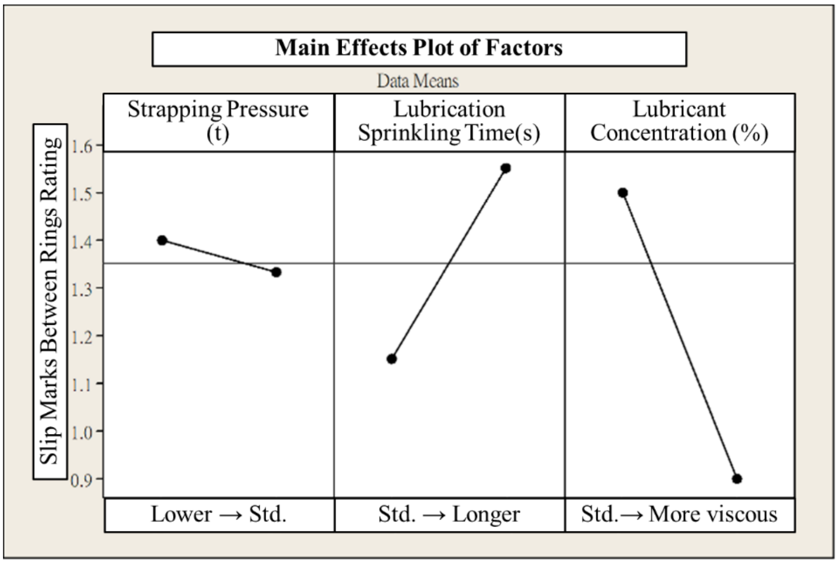


Fig.5. Main Effects Plot of Factors on Slip-marks Between Rings Rating.
(*Lower rating values indicate better surface quality.)

3.2 Rust

3.2.1 Cause Investigation

SAE 9254 also has stringent requirements regarding ferrite decarburization. Historically, decarburization-reducing strategies have included lowering the laying temperature, applying a cooling fan in the front section of the Stelmor cooling conveyor, and increasing conveyor roller speed[3]. These measures aim to allow the wire rods to quickly pass through the critical ferrite decarburization temperature range (740–830°C) during cooling. While effective in minimizing decarburization, these practices result in a lower initial laying temperature after final rolling (approximately 810°C), which limits the residence time in the high-temperature range. Consequently, only a thin scale (~4 μm) is formed, as shown in Figure 6.

3.2.2 Metallurgical Mechanism of Scale Formation

According to the Fe–O phase diagram as shown in Figure 7, FeO, Fe_3O_4, and Fe_2O_3 are all stable phases at temperatures above 570°C. However, FeO becomes unstable below 570°C and decomposes into Fe_3O_4 and α-Fe according to the following reactions[4]:

$$(1-4y)Fe_{1-x}O \rightarrow (1-4x)Fe_{1-y}O + (x-y)Fe_3O_4 \quad \text{.......} (1)$$

$$4F_{1-y}O \rightarrow Fe_3O_4 + (1-4y)\alpha - Fe \quad \text{.......} (2)$$

Since Fe_3O_4 has a denser structure and superior corrosion resistance compared to FeO, increasing its thickness is critical for improving the overall protective effect. Therefore, in addition to increasing total scale thickness, promoting the formation of Fe_3O_4 is key to enhancing corrosion resistance.

3.2.3 Optimization of Cooling Parameters

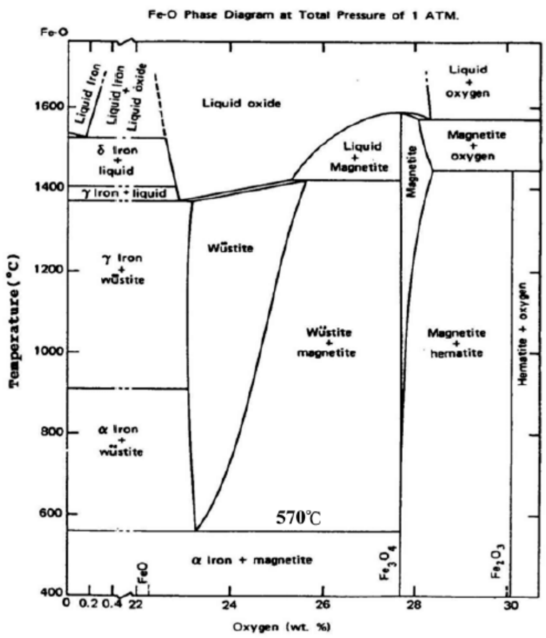


Fig.7. Fe–O Phase Diagram.

To evaluate the influence of cooling parameters on scale growth, a Taguchi design of experiments was implemented using three factors at two levels each, as outlined in Table 3. Scale thickness was measured via metallographic analysis and used to evaluate improvements.

Figure 8 shows that the main effects analysis revealed that increasing the laying temperature and reducing conveyor speed (i.e., slower cooling) effectively increased scale thickness. This is attributed to the longer residence time at elevated temperatures, which promotes oxidation. While increasing cooling fan intensity had a lesser effect on scale thickness, it helped accelerate the material's passage through the critical ferrite decarburization temperature range, potentially reducing decarburization risk.

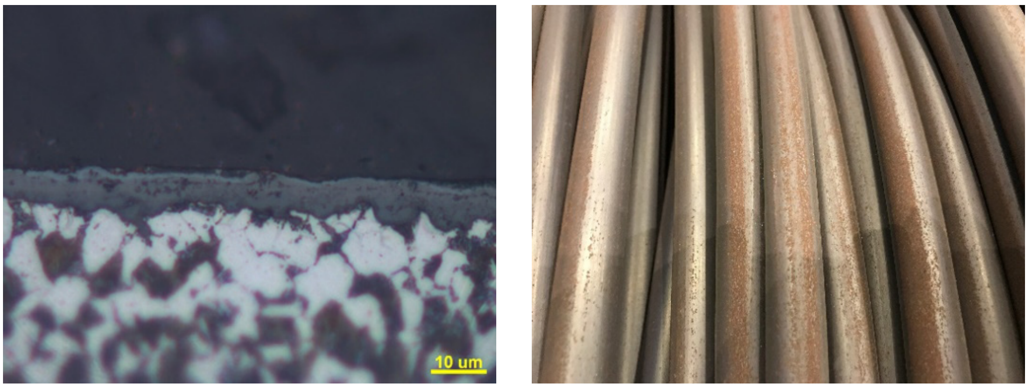


Fig.6. Current scale thickness of SAE 9254 and surface rust after long-term storage.

Table 3 Experimental Factors and Level Settings.

Factor	Cooling Parameter	Level 1	Level 2
A	Laying Temperature	Low	High
B	Cooling Fan Rotation Intensity	Weak	Strong
C	Conveyor Speed	Fast	Slow

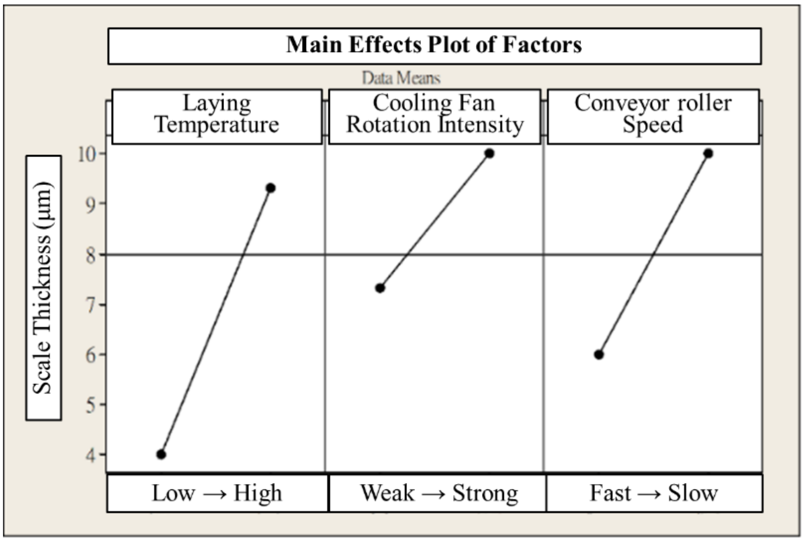


Fig.8. Main Effects Plot of Factors on Scale Thickness.

4. RESULTS AND DISCUSSION

4.1 Optimization of Strapping Parameters

Based on the previously discussed analysis, the following optimized strapping parameters were adopted. The lubricant concentration was increased, which effectively reduced slip marks. Since further reductions in strapping pressure did not yield significant improvement, higher strapping pressure was maintained in consideration of the risk of coil collapse during storage and transportation. As extended lubrication time showed no benefit, the original spray time was retained to avoid production delays.

Visual inspection of the wire rod coils revealed that most observed slip-marks between rings were classified as slight and non-critical defects, as shown in Figure 9, indicating that surface quality has been effectively controlled.

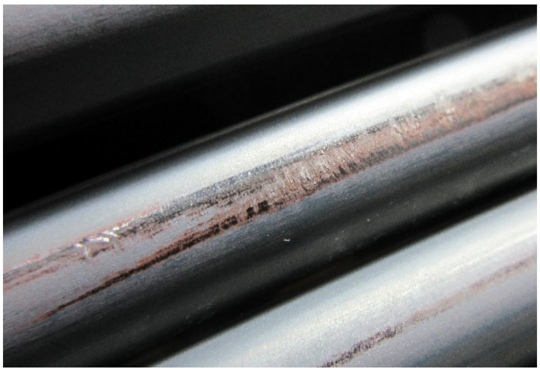


Fig.9. The appearance of slight and non-critical slip-mark Defects.

4.2 Cooling Process Optimization to Enhance Scale Thickness

The wire rod was controlled at a higher laying temperature immediately after final rolling. This approach not only promotes scale growth but also avoids the ferrite decarburization-sensitive temperature range. In the first and second zones of the Stelmor cooling bed, enhanced cooling fan speed was applied for rapid cooling to allow the wire rod to quickly pass through the 740–830°C decarburization range. Subsequently, in the third zone, the insulation cover was closed, and the conveyor speed was reduced to enable slow cooling and extend the holding time near 570°C, which facilitates the formation of protective oxide layers.

As shown in Figure 10, after implementing the revised cooling parameters, the average scale thickness increased from 4 μm (FeO/ Fe_3O_4 ratio ≈ 3:1) to 10 μm (FeO/Fe_3O_4 ratio ≈ 7:3). This indicates not only a thicker overall scale but also a significant increase in Fe_3O_4 content. Additionally, no evidence of ferrite decarburization was found across the full cross-section

To verify the actual impact of increased scale thickness on corrosion resistance, a humidity resistance test was conducted under 50°C / 95% RH conditions for 240 hours. As shown in Figure 11, the rust resistance rating improved from Grade 1 to 5 after improvement. Almost no corrosion was observed, confirming a significant enhancement in corrosion resistance.

4.3 Effectiveness Verification

After applying the improvement measures, the ET inspection pass rate increased from 51% to 85%, as shown in Figure 12. Moreover, the pass rate exceeded the target level of 76% equivalent to competitor P's benchmark. These results confirm the effectiveness of the countermeasures and demonstrate a stable and significant enhancement in product quality.

5. CONCLUSIONS

This study investigated the root causes of Eddy Current Testing (ET) alarms in SAE 9254 wire rods, identifying slip-marks between rings and rust as primary contributors. By optimizing strapping lubrication parameters and modifying Stelmor cooling conditions to promote thicker Fe_3O_4 oxide scale formation, surface defect occurrence was significantly reduced. These improvements enhanced corrosion resistance and increased the ET pass rate from 51% to 85%, exceeding

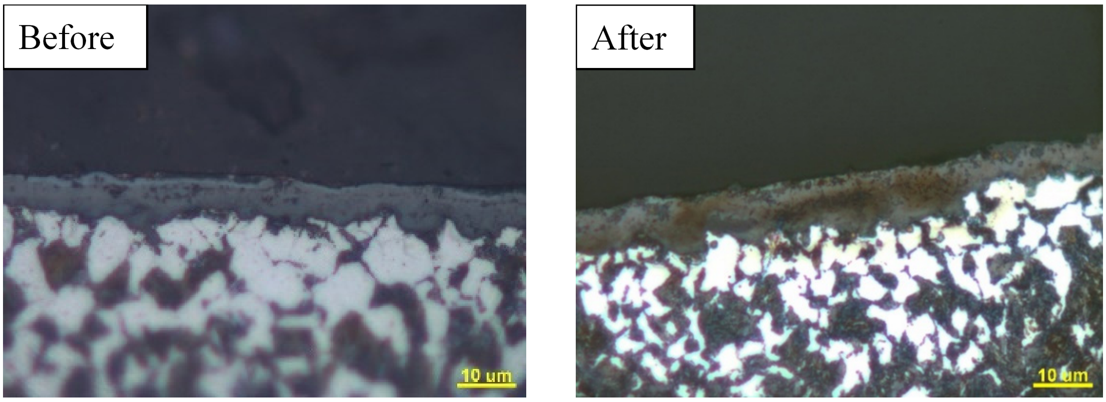


Fig.10. Comparison of Scale Before and After Stelmor Cooling Optimization.

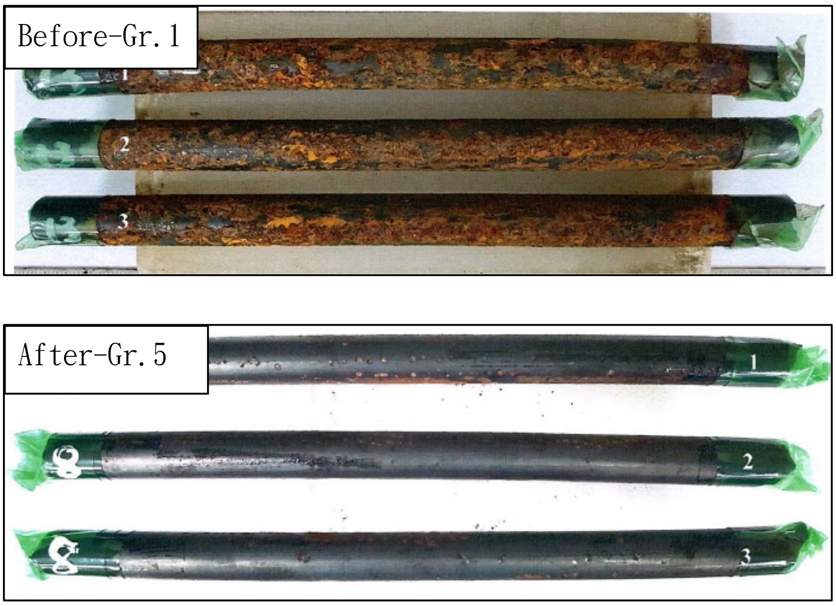


Fig.11. Humidity Resistance Test Results Before and After Improvement.

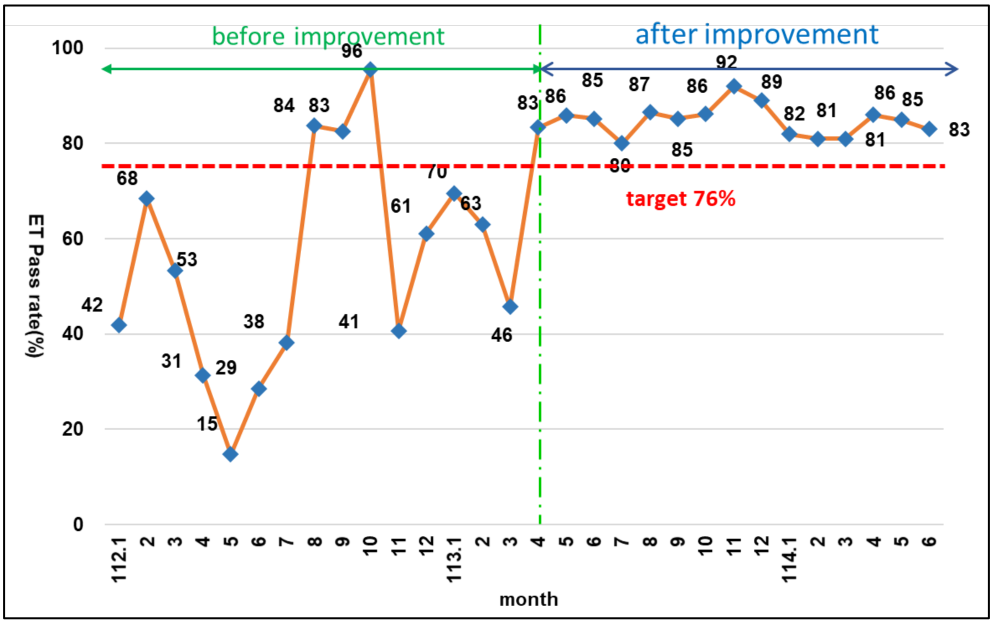


Fig.12. Improvement Trend of ET Pass Rate for SAE 9254.

the target benchmark. The results demonstrate the effectiveness of integrated process control in improving surface quality and product reliability for high-performance spring applications.

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