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Implementation of ANOVA and Regression to Optimize Vibratory Stress Relief Parameters in EN 31 Steel to Reduce Residual Stress and Improve Brinell Hardness

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Abstract

This study examines the impact of Vibratory Stress Relief (VSR) on the stabilization of the Brinell hardness and the reduction of residual stresses in EN 31 steel components. EN 31, renowned for its high hardness and wear resistance, is prone to residual stress accumulation during forceful turning, compromising dimensional stability and fatigue life. To address this, the influence of critical VSR parameters—vibration frequency, amplitude, and treatment time—was analyzed. Regression models and ANOVA results confirmed that VSR effectively reduces residual stress, with the pre-VSR residual stress (BSR) model achieving an R^2 of 91.31% and the post-VSR residual stress (ASR) model achieving 92.61%. The negative coefficient for amplitude in the ASR model highlighted its substantial effect on stress reduction. Brinell hardness improved significantly after VSR, with the pre-VSR hardness (BBH) model showing an R^2 of 99.76% and the post-VSR hardness (ABH) model achieving 93.75%. The research affirms that the optimization of VSR parameters, specifically amplitude and frequency, improves mechanical stability and guarantees consistent performance in precision manufacturing applications.

Major Findings: *The major finding was that optimized VSR parameters significantly reduce residual stresses and improve Brinell hardness in EN 31 steel, achieving up to 92.61% accuracy in stress prediction and 93.75% accuracy in hardness improvement.*

Keywords: *Brinell Hardness, EN 31 Steel, Mechanical Stability, Residual Stress, Vibration Amplitude, Vibratory Stress Relief*

1.0 Introduction

In modern manufacturing industries, achieving high dimensional accuracy and stability is critical, particularly for components subjected to intense operational loads. EN 31 steel, a high-carbon alloy known for its excellent hardness and wear resistance, is commonly used in the production of bearings, dies, and machine tools[1]. However, hard turning, a machining process employed to shape these components, often induces significant residual stresses. These residual stresses can lead to dimensional instability, workpiece deformation, and reduced fatigue life, posing challenges for long-term component performance.

The hard turning process, commonly applied to EN 31 steel components due to its high hardness and wear resistance, generates significant residual stresses during machining. These residual stresses negatively affect the dimensional stability of the components, causing deformation, reduced fatigue life, and unexpected failure during service[1-3]. In applications requiring high precision and stability, such as automotive, aerospace, and industrial tooling, these defects can compromise performance and lead to costly downtimes.

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Traditional stress relief methods, such as heat treatment, have been used to address residual stress issues. However, these methods come with inherent drawbacks, including high energy consumption, long processing times, and the potential to alter the material's microstructure, affecting its mechanical properties[4-6]. In this context, Vibratory Stress Relief (VSR) emerges as a promising non-thermal alternative. VSR works by applying controlled vibrations to components, redistributing internal stresses, and reducing deformation without changing the material's inherent properties. It offers several advantages, including shorter processing time, lower costs, and environmental sustainability.

While VSR is known to enhance the stability of machined components, its effectiveness is highly dependent on process parameters such as amplitude, frequency, and time. The precise impact of these parameters on the dimensional stability and stress relief of hard-turned EN 31 steel remains underexplored[7,8]. Optimization of these parameters is essential to maximize the benefits of VSR, ensuring consistent performance and minimal deformation. Without a systematic approach to optimizing these conditions, manufacturers risk suboptimal stress relief and reduced component reliability. Review studies that examine how residual stresses are introduced during the hard turning of steel components, especially EN 31 steel[9]. This section presents a comprehensive review of existing studies related to residual stress management in hard-turned EN 31 steel components and the application of Vibratory Stress Relief (VSR) as a non-thermal stress relief method. Residual stresses induced during hard turning have been widely recognized as a significant challenge affecting the dimensional stability, fatigue life, and reliability of components used in high-precision applications. Medtronic Metal[10] emphasizes the growing adoption of VSR for non-thermal stress relief in precision engineering, highlighting its use in scenarios where traditional thermal techniques may alter the material microstructure. Zhou *et al.*[11] proposed a study on the effects of vibration amplitude and vibration frequency on the relief of the transverse and longitudinal residual stresses were investigated and compared to existing literature data. The findings indicate that the vibration frequency is the primary factor in tension relief, and the residual stress reduction effect is most pronounced at 1000 Hz. The stress relief in the Al-Mg-Si-Cu alloy has been examined by Wang *et al.*[12], and residual stress measurements have been conducted using XRD. They concluded that the microstructure has been influenced by the cyclic force. He *et al.*[13] have also demonstrated that mechanical properties can be altered by higher levels of vibration. Frequency is a critical factor in vibratory treatments. VSR is also a highly concerned tension relief process. Numerous studies have been conducted on the impact of VSR on the mechanical properties of materials and the relief of stress. Wang *et al.*[14] found that VSR is efficacious in the stress concentration zone of cold-rolled AZ31 Mg alloys, rather than all residual stresses. Lai *et al.*[15] regarded the lattice motion as a type of internal friction that can be employed as an index for the evaluation of VSR and fatigue. They investigated the evolution law of internal friction and the impact of residual stress relief through dynamic mechanical analysis. Chen *et al.*[16] studies compared Thermal Stress Relief (TSR), VSR, and combined Thermal-Vibratory Stress Relief (TVSR) on 2219 aluminium alloy weldments. Results show that VSR effectively reduces residual stress but is less effective than TVSR, which offers better stress homogenization along multiple directions.

Gong *et al.*[17] explored VSR's impact on the dimensional stability of thin-walled 7075 aluminium alloy components. The results revealed that VSR significantly minimized deformation during machining and improved residual stress distribution, proving useful in precision manufacturing contexts. Yazdian *et al.*[18] This paper investigated how VSR can prevent stress accumulation and structural warping in cold-forged high-strength steel components. The findings suggest that VSR is an effective method to stabilize steel components, enhancing fatigue performance and structural integrity. He *et al.*[19] studied a high-frequency VSR applied to quenched Cr12MoV steel, demonstrating effective residual stress relief without compromising surface hardness. The study emphasized that frequency optimization is crucial to maximizing VSR's efficiency in industrial steel applications. Varangini *et al.*[20] This research evaluated the effect of VSR parameters- such as amplitude, frequency, and cycle duration- on the mechanical and metallurgical properties of AISI 1008 steel. It concluded that careful parameter control can significantly enhance mechanical strength while relieving stress.

Current studies lack systematic frameworks for selecting optimal VSR parameters and comparative analyses with conventional thermal treatments, leaving a gap in understanding the full potential of VSR. Additionally, there is a need for statistical modelling using tools like Taguchi ANOVA and regression analysis to quantify the influence of these parameters. The objective of this research is to improve the dimensional stability and performance of hard-turned EN 31 steel components through the application and optimization of Vibratory Stress Relief (VSR), addressing residual stresses that lead to deformation and reduced fatigue life. While VSR offers a non-thermal alternative to traditional stress relief methods, research on its effectiveness for EN 31 steel remains limited, particularly in terms of parameter optimization involving amplitude, frequency, and time.

2.0 Experimental Methodology

2.1 Experimental Test Set Up

The efficacy of a vibratory stress relief system on hard-turned EN 31 components was examined in this study. The vibration frequency, vibration amplitude, and treatment time were the input parameters chosen for this investigation. More specifically, the vibration frequency (F) levels were established at 750, 850, 950, and 1050 Hz. The input parameters selected for this investigation included vibration frequency (F), vibration amplitude (A), and treatment time (T). These factors were chosen based on their critical influence on the VSR process, as identified in prior research and empirical studies. The vibration frequency was varied at levels of 750, 850, 950, and 1050 Hz to cover a wide operational range. Similarly, treatment time was adjusted across 3, 5, 6, and 7 minutes to evaluate its impact on stress relief. The vibration amplitude was studied at 3, 5, 6, and 7 mm to capture its effect on stress dissipation and surface properties. Residual stress and Brinell hardness were the primary output parameters measured in this study. Residual stress, a crucial factor affecting dimensional stability and fatigue life, was quantified using an X-ray diffraction technique. This method allowed for accurate measurement of residual stresses both before and after the VSR process. Brinell hardness, an indicator of surface hardness and wear resistance, was evaluated using a Brinell hardness tester to assess the mechanical improvements achieved through VSR.

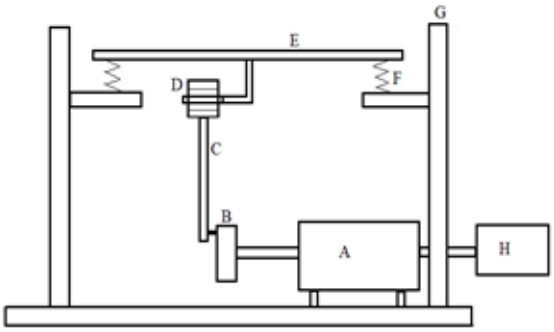


Figure 1. Schematic VSR test set-up.
A = Motor, B = Eccentric Disc, C = Connecting Rod, D = Bearing, E = Exciter table, F = Spring G = Support, H = DC Supply.

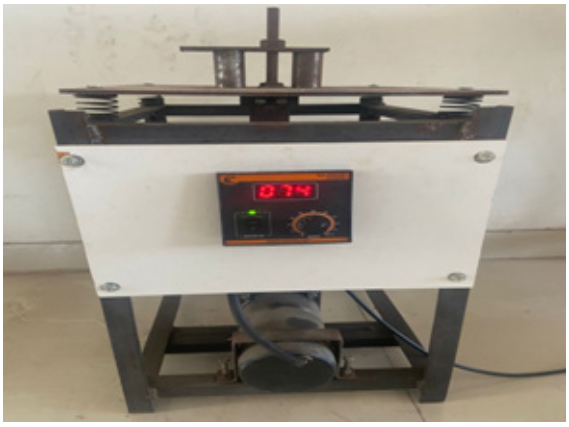


Figure 2. Photograph of the actual test set-up used for VSR.

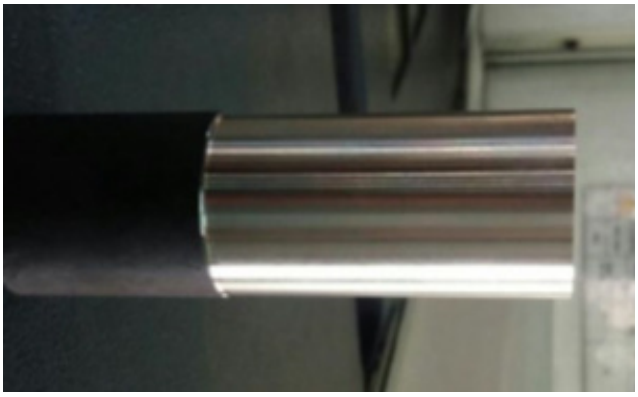


Figure 3. Turned test piece.

The chosen parameters and output measurements were designed to provide a comprehensive understanding of how the VSR process influences the mechanical and surface properties of EN 31 components. By investigating the interactions among vibration frequency, amplitude, and treatment time, this study offers insights into the optimal conditions for enhancing the performance and longevity of precision-manufactured components.

To prevent variations caused by equipment differences, all components were subjected to the same turning machine and parameters. Figure 1 illustrates the experimental VSR configuration utilised in the present investigation. The studied workpiece is a bar of EN 31, which has been toughened to 55 Rockwell Hardness. The test sections were machined on a CNC turning centre to minimise discrepancies in the trials that were conducted. The turned test pieces are illustrated in Figure 3, while the genuine VSR setup is depicted in Figure 2. The experimental apparatus consisted of a frequency controller, an eccentric disc connected to an electric motor, and a mechanically actuated vibration shaker that was used to adjust the amplitude of the vibrations.

3.0 Results and Discussion

3.1 Residual Stress Before and After VSR

3.1.1 Regression Equation

The efficacy of Vibratory Stress Relief (VSR) was evaluated by examining residual stress before (BSR) and after (ASR) treatment. The regression equations, ANOVA findings, and model summaries elucidate the impact of critical parameters- vibration frequency (V), amplitude (f), and treatment duration (d)- on residual stress management. The regression equation for BSR indicates that residual stress before VSR is affected by vibration frequency, amplitude, and treatment duration, as expressed by the following relationship:

$$BRS = 0.054 + 0.000699\ V + 0.234\ f + 0.145\ d - 0.00102\ V*f - 0.00081\ V*d + 0.64\ f*d \quad (1)$$

While each parameter influences the stress level, the interaction terms (such as *V·f* and *V·d*) exhibit lesser effects. This indicates that although interaction effects are incorporated into the model, they may not significantly impact the residual stress before the VSR process. The regression equation for ASR similarly indicates the alterations in residual stress following the VSR therapy.

$$ARS = 0.0666 + 0.000494\ V - 0.182\ f + 0.115\ d - 0.000004\ V*f - 0.000602\ V*d + 1.07\ f*d \quad (2)$$

A significant finding from this equation is the negative coefficient for amplitude (*f*), signifying that increased vibration amplitudes lead to enhanced stress reduction. This corresponds with the principle that increased vibration amplitudes facilitate more effective redistribution of internal stresses, resulting in enhanced stability and lower stress levels.

3.1.2 ANOVA

The ANOVA findings elucidate the relevance of each parameter. The model for BSR attains an R^2 of 91.31% and an adjusted R^2 of 85.51%, signifying that the regression model effectively accounts for a significant percentage of the variability in residual stress before VSR. Nevertheless, certain words such as amplitude (f) and interaction effects (e.g., *V·f*) exhibit elevated p-values, indicating restricted statistical significance. Conversely, the ASR model exhibits an R^2 of 92.61% and an adjusted R^2 of 87.68%, indicating that the selected parameters are superior in forecasting residual stress post-VSR. The BSR model, which describes residual stress levels before the application of VSR, attained an R^2 value of 91.31% and an adjusted R^2 of 85.51%. The high R^2 value indicates that the model successfully explains over 91% of the variability in the residual stress before VSR. This suggests that the selected parameters, particularly vibration frequency and amplitude, play a significant role in determining the initial stress levels in the material. However, further analysis revealed that certain factors, such as amplitude (f) and the interaction effects between vibration frequency and amplitude (V·f), demonstrated elevated p-values. Elevated p-values for these parameters imply that their contributions to the residual stress before VSR are less statistically significant compared to other factors in the model. This suggests that while amplitude and the interaction effects are influential, their impact on residual stress is not as pronounced in the pre-treatment phase as other factors, such as treatment

Table 1. Analysis of variance for residual stress before VSR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	0.024544	0.004091	15.76	0.000
V	1	0.001140	0.001140	4.39	0.066
f	1	0.000030	0.000030	0.11	0.743
d	1	0.000028	0.000028	0.11	0.751
V*f	1	0.000227	0.000227	0.88	0.374
V*d	1	0.000146	0.000146	0.56	0.473
f*d	1	0.000023	0.000023	0.09	0.774
Error	9	0.002337	0.000260		
Total	15	0.026880			

Table 2. Analysis of variance for residual stress after VSR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	0.020254	0.003376	18.79	0.000
V	1	0.000569	0.000569	3.17	0.109
F	1	0.000018	0.000018	0.10	0.758
D	1	0.000018	0.000018	0.10	0.761
V*f	1	0.000000	0.000000	0.00	0.997
V*d	1	0.000080	0.000080	0.44	0.522
f*d	1	0.000063	0.000063	0.35	0.568
Error	9	0.001617	0.000180		
Total	15	0.021871			

time. The enhanced predictive capability underscores the efficacy of VSR in mitigating residual stress when implemented with optimum parameters. Table 1 presents the ANOVA results for residual stress before VSR.

The comparison of BSR and ASR models indicates that VSR significantly reduces stress, with optimum factors such as vibration amplitude being crucial. Despite the interaction terms lacking substantial statistical significance, the individual management of factors like amplitude and frequency directly affects stress reduction. The findings from the ANOVA analysis emphasize the importance of optimizing the VSR parameters for maximum effectiveness. The model for BSR indicates that while vibration frequency and treatment time are highly significant in predicting pre-VSR residual stress, amplitude and its interactions with other factors may require further fine-tuning for improved precision. The negative coefficient of amplitude in the ASR equation indicates that augmenting vibration amplitude during VSR effectively alleviates tension, aiding components in preserving dimensional stability. The table below presents the ANOVA results for residual stress following VSR.

3.2 Brinell Hardness Before and After VSR

3.2.1 Regression Equation

The examination of Brinell hardness before (BBH) and after (ABH) VSR provides quantitative insights into the influence of vibration factors on the mechanical properties of EN 31 steel. The regression models, statistical metrics, and interaction effects among vibration parameters, including frequency (*V*), amplitude (*f*), and treatment time (*d*), furnish critical proof of the impact of VSR on hardness. The regression equation for BBH is articulated as:

$$BBH = 0.29558 + 0.000023\ V + 0.00875\ f - 0.01302\ d - 0.000022\ V*f + 0.000026\ V*d + 0.0423\ f*d \quad (3)$$

This equation demonstrates that although both vibration frequency and amplitude possess positive coefficients, their respective influence on BBH is very little. A value of 0.000023 for frequency indicates negligible gains in hardness with rising vibration frequency. Treatment duration (*d*) exhibits a marginally negative effect, with a coefficient of -0.01302, suggesting that extended treatment may somewhat diminish the Brinell hardness before the VSR process. The minimal coefficients indicate that VSR treatment parameters do not significantly affect BBH, although they nevertheless yield quantifiable alterations. The regression equation for Brinell hardness following VSR (ABH) is:

$$ABH = 0.2312 + 0.000007\ V + 0.112\ f - 0.039\ d + 0.000069\ V*f + 0.000305\ V*d - 0.192\ f*d \quad (4)$$

The analysis indicates a significant impact of amplitude (*f*) on ABH, with a coefficient of 0.112, suggesting that elevated amplitude levels during VSR result in large enhancements in post-treatment hardness. The negative coefficient for treatment duration (-0.039) indicates that excessively prolonged VSR sessions may marginally reduce hardness values. The interplay between frequency and amplitude (*V.f*) yields a minor positive effect, enhancing the potential advantage of concurrently tuning these parameters for superior hardness results.

3.2.2 ANOVA

The ANOVA summary for BBH, as presented in Table 3, indicates that the model accounts for 99.76% of the variation (R^2=99.76%), with an adjusted R^2 of 99.60%, illustrating the model's robust predictive power. Frequency (*V*) demonstrates a highly significant impact, evidenced by a p-value of 0.000, indicating its crucial significance in influencing BBH. The amplitude (*f*) exhibits a statistically insignificant effect (p = 0.324), although treatment duration (*d*) demonstrates a

Table 3. Analysis of variance for Brinell hardness before VSR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	0.000145	0.000024	631.29	0.000
V	1	0.000001	0.000001	31.93	0.000
f	1	0.000000	0.000000	1.09	0.324
d	1	0.000000	0.000000	5.92	0.038
V*f	1	0.000000	0.000000	2.80	0.129
V*d	1	0.000000	0.000000	3.80	0.083
f*d	1	0.000000	0.000000	2.57	0.143
Error	9	0.000000	0.000000		
Total	15	0.000145			

Table 4. Analysis of variance for Brinell hardness after VSR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	0.002320	0.000387	22.50	0.000
V	1	0.000000	0.000000	0.01	0.939
f	1	0.000007	0.000007	0.39	0.546
d	1	0.000002	0.000002	0.12	0.740
V*f	1	0.000001	0.000001	0.06	0.812
V*d	1	0.000020	0.000020	1.19	0.304
f*d	1	0.000002	0.000002	0.12	0.739
Error	9	0.000155	0.000017		
Total	15	0.002474			

considerable influence (p = 0.038), suggesting that while duration affects hardness, it may not be the predominant component.

The ANOVA for ABH presented in Table 4 demonstrates that the model explains 93.75% of the variance, with an adjusted R^2 of 89.58%. Although individual components like frequency and amplitude are statistically insignificant for ABH (p > 0.05), their combination nevertheless demonstrates a significant impact on hardness. The positive coefficient for $V\ dV$ (0.000305) indicates that adjusting vibration frequency alongside suitable treatment duration can yield advantageous hardness results post-VSR.

The transition from BBH to ABH quantitatively illustrates the function of VSR in stabilizing mechanical characteristics. The numerical variation in Brinell hardness values is not significant; however, the technique guarantees uniform material performance by marginally increasing hardness and mitigating unforeseen decreases caused by residual stresses. The model's capacity to forecast ABH outcomes with over 93% accuracy underscores the necessity of VSR parameter tuning for dependable hardness stabilization.

4.0 Conclusion

This research underscores the efficacy of Vibratory Stress Relief (VSR) in diminishing residual stresses and enhancing the mechanical characteristics of EN 31 steel components. The quantitative analysis demonstrates substantial enhancements in residual stress levels and Brinell hardness via the optimal regulation of VSR parameters, such as vibration frequency, amplitude, and treatment duration. The regression model for residual stress Before VSR (BSR) attained an R^2 value of 91.31%, whereas the model for residual stress After VSR (ASR) exhibited superior accuracy with an R^2 of 92.61. The decrease in residual stress following treatment was predominantly affected by vibration amplitude, with increased amplitudes resulting in more efficient stress alleviation, as indicated by the negative coefficient (-0.182) for amplitude in the ASR regression equation. Despite the interaction effects among parameters demonstrating minimal statistical significance, the independent tuning of frequency and amplitude was crucial for stress alleviation.

The examination of Brinell's hardness indicated that VSR contributed to the preservation or enhancement of surface hardness. The regression model for Brinell hardness before VSR (BBH) demonstrated a remarkably high R^2 value of 99.76%, signifying exceptional predicted accuracy. Following treatment, the Brinell hardness of the VSR (ABH) model attained an R^2 value of 93.75%. The amplitude exhibited the most significant influence on hardness, with a coefficient of 0.112 in the ABH regression equation, indicating that increased amplitudes led to enhanced hardness values. In contrast, prolonged

treatment durations adversely affected both stress and hardness, suggesting that excessive vibration may compromise material stability. The elevated prediction accuracy of the regression models highlights the significance of parameter tuning, particularly amplitude and frequency, to attain the necessary stress alleviation and mechanical stability.

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