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Analysis of Vibratory Stress Relief (VSR) Parameters on Mechanical and Metallurgical Properties of AISI 1008

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Abstract

Vibrational stress relief (VSR) treatment is a method of stress relief which is currently used for different alloys in different sizes. Since the effect of VSR has not been fully analyzed and compared versus thermal stress relief (TSR) process, its merits require wider investigations. In this paper VSR treatment has been performed with certain parameters to check and assure the advantages of the process in terms of mechanical and metallurgical improvements on AISI 1008 workpiece as a preparatory process. The chosen parameters consist frequency, time, and amplitude of vibration. Factorial design of the experiment using response surface methodology has been performed to obtain an optimal response in numerical and experimental tests. The testing coupons have been evaluated in terms of hardness, tensile strength, elasticity modulus, toughness, elongation before fracture, and micro-structure. Experimental results have been compared with finite element analysis (FEA) results and previous studies. FEA elastic-plastic model was used to extract mechanical properties, while hardening effect has been accounted for in the model. The study has demonstrated the influential performance of VSR on the mechanical properties of the samples i.e., yield strength, toughness, elongation, and elasticity modulus while hardness and microstructure have not been affected significantly.

Keywords

VSR, mechanical properties, microstructure, residual stress

1 Introduction

Alternative stress relief methods such as vibratory methods have been used for long time to reduce residual stresses in manufactured structures. The old sollution utilized for stress relief in large cast or welded parts has been aging (Aging for an extended period of time). Recent studies have demonstrated that vibration methods speed up the process. As claimed by researchers, controlled vibration yields as much stress relief in 1 hour as natural aging process does in months or years [1]. The study results demonstrated by McGoldrick [2] and Sedak [3] in weldedments proved that vibratory treatment in resonant mode can yield to some dimensional accuracy. The weldments were successfully tested under working conditions. Up to 70 percents of stress relief could be reduced by Lokshin [4] in cast aluminum parts using vibratory stress relief (VSR) treatment and it caused redistribution and redcution of residual stress value. A tapered catilever beam was tested under cyclic loading by Moore [5] and stress relief could be achieved to some extent. As proven in the previous studies, it is mentioned that stress relief may be dependent on plastic deformation partially. VSR techniques were indicated to be capable of providing tremendous surface stress relaxation in rolled mild steel, and a certain aluminum alloy in Dawson study [1].

Considerable advantages of VSR over thermal stress relief (TSR) was proven by Yin et al. [6] in steel structures by comparing treated structures in both processes.Vibration parameters such as amplitude and frequency were analysied in finite element models [7, 8] and it has been concluded that vibrations can reduce the magnitude of residual stresses whether in resonant or nonresonant modes.

VSR performance has been tested in different studies on thick sheets of aluminum [9, 10]. In these studies it is believed that VSR has also some effects on stress concentration which influence on hardness and stiffness of the materials. In another study Khan et al. [11] has investigated microhardness in different areas such as heat affected zone (HAZ), base metal, and weld bead as criteria to detect the effect of VSR treatment. Although that is not proven as a guaranteed

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parameter to imply residual stress magnitude, it is a valuable indirect criterion to check the percentage of stress relaxation.

Wang et al. [12] have checked stress releief in Al-Mg-Si-Cu alloy and XRD residual stress measurements are performed. They concluded that microstructure has been affected by cyclic force. Higher levels of vibration can also be effective in changing mechanical properties as referenced by He et al. [13]. It has been concluded clearly that frequency is a key factor in vibratory treatments.

In addition to frequency, amplitude, and time of treatment in VSR, the waveform of load was also checked in an experiment by Wang et al. [14]. Although it is prevalent to use Sinusoidal waves in vibrations, author has believed it could be a different waveform such as "Wavelet"; An innovative waveform, introduced in this study, which has been told to be even more effective in stress reduction.

More recently, VSR process has been evaluted using computational model [15] to include the wider range of influential parameters in the analysis, while peripheral factors such as magnetic vibration [16] and austenitization effect [17] have also been investigated to deepen the sight and knowledge about the merits or limitation of the VSR treatment. The effect of ultrasonic vibration was also considered on mechanical properties and microstructure of hyper-eutectic aluminum alloys by Lin [18]. Results demonstrate that Si average grain size will reduce to about.

In this study, VSR method has been analyzed in terms of mechanical and metallurgical influence on steel alloy 1008 by testing different properties such as hardness, tensile strength, elasticity modulus and microstructure. Since VSR treatment is used here to check the alternations which take place on mechanical and metallurgical properties and the value of such modification, the residual stress is not the focus of this study and thus it is not directly measured. Therefore, the changes in important properties are considered. Experimental results have been compared to a finite element analysis in which mechanical properties of the VSR treated part has been extracted on an elastic-plastic material.

2 Methods and materials

2.1 Materials

Round 15 rod was chosen as the geometry for specimens to be usable for consequent mechanical and metallurgical tests too. The chemical composition of specimens are indicated in Table 1. Specimens had been initially formed by casting and machining processes. Material properties for proposed steel alloy can be seen in Table 2. Material chosen for tools has been AISI 4330 (Table 3).

The diameter of the test specimen was necessarily chosen according to the space and equipment available in the configuration of the test setup. In addition, there has been no reason to choose a large mass of the specimen since the mechanical and metallurgical phenomena occuring during the current study is not necessarily relevant with the workpiece size. Nevertheless, some parameters such as natural frequency would have been affected by the size, but here these parameters haven't been the scope of the study, since most of the vibrations have been mostly set below the resonance frequency.

The major reason to choose a mild carbon steel as the material for the test specimen has been mostly the prevalence and the availability of material due to the formability, high durability, and excellent weldability.

2.2 Design of experiment

Since there are 3 contributing factors in the process, RSM (Response Surface Methodology) CCD (Central Deposite Design) has been utilized to proceed with experiments using the Table 4 to obtain the optimal responses.

Table 1 Chemical composition of workpiece (AISI 1008)

Element	Content (%)
Fe	99.31–99.7
Mn	0.30–0.50
C	0.10
S	0.050
P	0.040

Table 2 Mechanical properties of AISI 1008

Parameter	Value
E (Young modulus) (GPa)	200
S_y (Yield strength) (MPa)	340
S_{ut} (Ultimate tensile strength) (MPa)	350
ρ (Density) (kg/m^3)	7800
v (Poison ratio)	0.3

Table 3 Chemical composition of tool (AISI 4340)

Element	Content (%)
Fe	95.3–98.1
Ni	1.0–1.50
Mn	≤1.0
Si	≤0.80
Cr	0.40–0.60
Mo	0.30–0.50
C	0.20-0.30

RSM has been used as an empirical model that investigates the relationships between explanatory variables and response variables utilizaing statistical techniques to connect input variables (factors) to the response [19]. Other methods, like theoretical models, have mostly been cumbersome, time-consuming, inefficient, error-prone, and unreliable. Additionally, a central composite design is used in RSM here to build a second-order (quadratic) model for the response variable without requiring a complete three-level factorial experiment.

Chosen factor levels can be seen in Table 5 based on CCD. The value of parameters are rounded up or down (with a tolerance about ±0.1) as it cannot have significant effect on results, while setting the levels of amplitudes on eccentric tool is more practical with new values.

The number of designed experiments and factors can be seen in Table 6. Samples are provided separately for mechanical and metallurgical tests before and after VSR. Consequently, 50 parts were prepared (2 samples for mechanical and metallurgical tests before VSR and 2 for mechanical and metallurgical tests after VSR.).

2.3 Method of experiment

2.3.1 VSR

The schematics of VSR setup used here, is indicated in Figs. 1 and 2 demonstrate the beam under VSR treatment. The VSR setup used in the previous study [20] has been chosen here in which a lathe machine is considered to be the source of vibration while tool holder clamps the specimen. Nevertheless there have been modifications such as a more controllable lathe machine and specific crank shaft as tools in the chuck for applying different certain amplitudes (Fig. 3). The frequency is adjusted by setting the spindle speed as each round of spindle resembles one cycle of VSR treatment. The same values as indicated in Table 5 are used to perform the experiments.

Table 4 Maximum and minimum levels considered for DOE

Factor	Minimum value	Maximum value
Time (s)	1	80
Frequency (Hz)	1	5
Amplitude (mm)	0.5	2.5

Table 5 Factors' levels chosen based on CCD

Parameter	Value
Time (s)	1, 20, 42.5, 65, 80
Frequency (Hz)	1, 2, 3, 4, 5
Amplitude (mm)	0.5, 1, 1.5, 2, 2.5

Table 6 Table of experiments for mechanical and metallurgical tests

Run No.*	Amplitude (mm)	Time (s)	Frequency (Hz)
24	1	20	2
17	1	20	4
16	1	65	2
21	1	65	4
2	2	20	2
3	2	20	4
11	2	65	2
1	2	65	4
6	0.5	42.5	3
14	2.5	42.5	3
23	1.5	5	3
5	1.5	80	3
18	1.5	42.5	1
9	1.5	42.5	5
15	1.5	42.5	3
22	1.5	42.5	3
8	1.5	42.5	3
4	1.5	42.5	3
13	1.5	42.5	3
12	1.5	42.5	3
19	1.5	42.5	3
7	1.5	42.5	3
10	1.5	42.5	3
20	1.5	42.5	3
0	0	0	0

* Run No. 0 means before VSR.

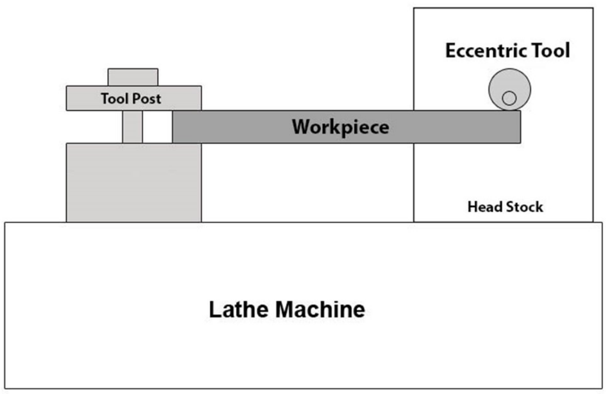


Fig. 1 VSR setup used

2.3.2 Mechanical and metallurgical tests

After VSR treatments, mechanical and metallurgical properties have been evaluated using tensile test machine (Zwick-Roell Z250), hardness test machine (Ernst) (ASTM E10), and optical microscope (Olympus SZX9).

Fig. 2 VSR treatment being performed on parts using eccentric tool clamped in spindle

Fig. 3 Eccentric AISI 4340 tools for applying loads with certain amplitudes

Since the dimensions of parts fitted the tensile strength test machine used here, they did not undergo any further processes for tensile test, but those parts used for hardness test were cut to desired heights. Metallurgical test samples were also initially polished and chemically etched before checking them under the microscope.

2.3.3 Finite Element Analysis (FEA)

For FEA process, a two dimensional diameter wire part has been modelled in Abaqus software for simplicity. This geometrical simplicity has been assumed due to orthogonal nature of the test configuration. Perpendicular thickness of the specimen and tool have also been defined to assure about the validity of the calculations. The tool is considered as a rigid part rotating eccentrically over adjustable pivot to set certain prescribed amplitudes, for cyclic loading on the beam (Fig. 4). The pivot point is set the way it can provide the prescribed eccentricity and required amplitude.

A third step has been defined after VSR treatment, to perform the simulated tensile test and check the mechanical properties such as current strength, toughness, and elongation after hardening effect appeared during VSR. The stress-strain diagram has been extracted using different arithmetic operations on results.

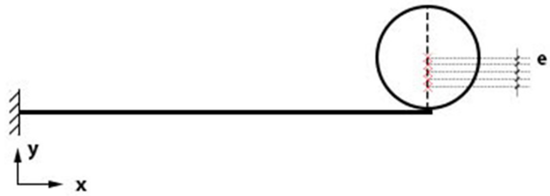


Fig. 4 The geometry of finite element model (FEM) used for numerical solution (e=0.5 mm)

Since the purpose of numerical analysis is investigating the effect of time (cycle numbers), frequency, and amplitude of vibrations on mechanical properties in VSR method, the same values as the values used in experiments were used as input parameters.

Isotropic hardening rule, as well as strain rate dependent data were embedded in the material used in FEM [21, 22]. Therefore the effect of frequency on tool displacement (loading) on workpiece could be accounted for. Yield strength, toughness, elongation (before fracture), elasticity modulus, and hardness were checked in the model after treatment in different positions.

3 Results and discussion

3.1 Results

3.1.1 Experimental results

Mechanical properties

Tensile test was performed to extract required mechanical parameters. The elasticity modulus, tensile strength, toughness, and elongation have been obtained by using the stress-strain diagram for tensile test samples, with and without VSR treatment. Table 7 shows experimental results obtained after VSR treatment.

Metallurgical properties

Microstructure of workpiece before VSR and some of the specimens after VSR, for different experiment runs, are indicated in Fig. 5(a) through Fig. 5(d), with 500x magnification.

Grain size numbers are also indicated in Table 8.

3.1.2 FEA results

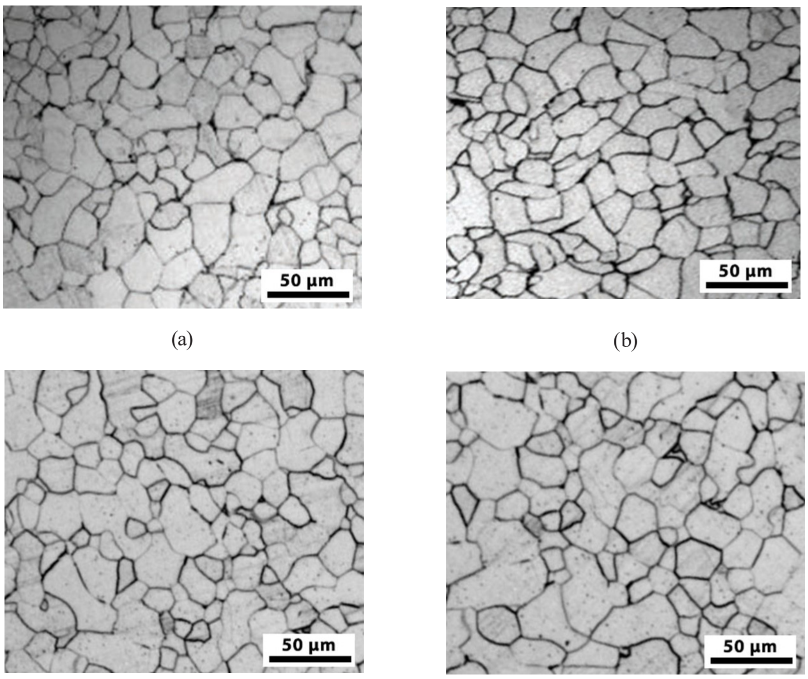
Table 9 demonstrates predicted results obtained by FEA for the same parameters as Table 6.

All of the stress-strain related parameters including tensile strength, elastic modulus, toughness, and elongation

Table 7 Average values of mechanical properties after 2 replicates of experiments

Run No.*	Parameters			Results				
	Amplitude (mm)	Time (s)	Frequency (Hz)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Toughness (MJ/m^3)	Elongation (%)	Hardness (MPa)
0	0	0	0	250.00	200.00	40.25	22.09	106.47
1	2	65	4	272.26	217.16	43.88	24.03	116.07
2	2	20	2	256.75	207.05	41.42	22.69	110.34
3	2	20	4	257.83	206.26	41.34	22.87	110.46
4	1.5	42.5	3	291.24	197.89	32.12	19.73	106.11
5	1.5	80	3	291.82	197.60	32.86	20.02	106.19
6	0.5	42.5	3	281.58	200.48	33.75	20.25	105.63
7	1.5	42.5	3	278.76	190.45	33.41	20.86	105.63
8	1.5	42.5	3	292.70	182.83	34.08	20.23	105.63
9	1.5	42.5	5	294.04	196.28	30.03	19.65	106.22
10	1.5	42.5	3	307.34	191.97	32.38	19.83	109.85
11	2	65	2	273.04	219.74	43.92	24.20	116.98
12	1.5	42.5	3	322.70	201.57	31.08	20.42	104.36
13	1.5	42.5	3	329.16	191.49	32.32	20.83	102.27
14	2.5	42.5	3	291.39	182.96	32.46	20.01	105.61
15	1.5	42.5	3	322.57	189.58	32.65	20.62	100.23
16	1	65	2	271.83	219.21	43.94	24.11	116.58
17	1	20	4	256.39	207.17	41.69	22.86	109.41
18	1.5	42.5	1	291.88	197.67	33.52	20.52	106.19
19	1.5	42.5	3	335.48	193.37	31.34	20.42	95.22
20	1.5	42.5	3	348.90	201.11	30.09	19.81	93.31
21	1	65	4	273.78	216.19	43.86	24.14	116.14
22	1.5	42.5	3	338.43	195.07	30.99	18.82	95.18
23	1.5	5	3	286.30	199.77	28.29	20.19	106.13

* Run No. 0 means before VSR.



(a) (b)

(c) (d)

Fig. 5 Microstructure of the sample obtained (a) as received; (b) with constant amplitude = 2 mm, time = 20 s, and frequency = 2 Hz; (c) with constant time = 65 s amplitude = 1 mm, and frequency = 2 Hz; (d) with constant frequency = 4 Hz, amplitude = 1 mm, and time = 20 s

Table 8 Grain size numbers before and after VSR

Run No.*	Parameters			Result
	Amplitude (mm)	Time (s)	Frequency (Hz)	Average Grain Size (μm)
0	0	0	0	14
1	2	65	4	14
2	2	20	2	14
3	2	20	4	14
4	1.5	42.5	3	14
5	1.5	80	3	14
6	0.5	42.5	3	13
7	1.5	42.5	3	14
8	1.5	42.5	3	13
9	1.5	42.5	5	13
10	1.5	42.5	3	14
11	2	65	2	14
12	1.5	42.5	3	13
13	1.5	42.5	3	15
14	2.5	42.5	3	14
15	1.5	42.5	3	13
16	1	65	2	13
17	1	20	4	15
18	1.5	42.5	1	14
19	1.5	42.5	3	13
20	1.5	42.5	3	15
21	1	65	4	15
22	1.5	42.5	3	15
23	1.5	5	3	13
24	1	20	2	14

* 0: Before VSR.

are obtained by the use of stress-strain extracted diagram for a fixed element at the middle of the model, after performing a tensile test in the final step.

The value of hardness has been calculated by using the following equation [23–25]:

$$H = 0.3\ S_u, \tag{1}$$

where H is the hardness value, and S_u is ultimate strength obtained in FEA.

3.2 Discussion

The results have been compared in terms of mechanical and metallurgical properties including yield strength, elasticity modulus, toughness, elongation, and hardness.

3.2.1 Mechanical properties

Stress-Strain diagram

Fig. 6 indicates the stress-strain obtained in FEA and experiments before (R0) and after VSR run number 9 (R9)

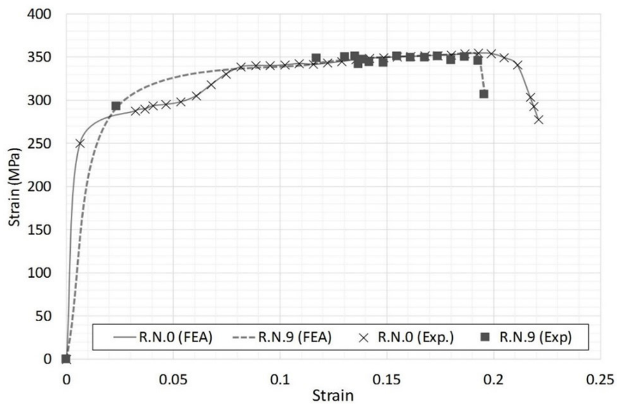


Fig. 6 Stress-Strain output diagram, obtained in FEA and experiment before (R.N.0) and after VSR (R.N.9) according to Table 7 and Table 9

in Table 7 and Table 9. The diagram shows a general decrease in plastic range and toughness, while there is a reduction in elasticity modulus. In addition, yield stress has increased compared to the initial condition. All of these results conform to the claims and results in the previous study on the effect of VSR [20].

Table 9 FEA results

Run No.*	Parameters			Results				
	Amplitude (mm)	Time (s)	Frequency (Hz)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Toughness (MJ/m^3)	Elongation (%)	Hardness (MPa)
0	0	0	0	250.00	200.00	36.51	22.09	106.47
1	2	65	4	273.08	216.94	39.77	23.96	116.65
2	2	20	2	259.85	205.40	37.80	22.73	109.46
3	2	20	4	259.37	207.91	37.88	22.67	109.92
4	1.5	42.5	3	290.32	196.48	25.49	19.70	106.09
5	1.5	80	3	290.39	196.86	32.79	20.00	106.18
6	0.5	42.5	3	280.11	198.14	34.27	20.20	105.60
7	1.5	42.5	3	268.90	196.16	33.24	21.01	109.83
8	1.5	42.5	3	255.46	194.20	33.24	21.22	113.12
9	1.5	42.5	5	290.40	192.58	29.61	19.57	106.18
10	1.5	42.5	3	250.35	196.14	34.90	20.58	118.78
11	2	65	2	273.04	218.43	39.88	24.29	116.98
12	1.5	42.5	3	255.36	205.95	35.95	19.76	123.53
13	1.5	42.5	3	250.25	212.13	37.03	19.76	119.82
14	2.5	42.5	3	290.98	182.33	24.93	20.00	105.60
15	1.5	42.5	3	245.25	203.64	35.55	19.56	124.62
16	1	65	2	270.47	217.03	40.06	23.90	115.65
17	1	20	4	255.87	206.35	37.37	22.86	108.97
18	1.5	42.5	1	290.38	197.02	33.92	20.51	106.18
19	1.5	42.5	3	232.98	197.53	35.19	18.58	124.62
20	1.5	42.5	3	225.99	203.46	35.19	18.77	129.60
21	1	65	4	271.87	216.63	39.99	24.14	115.67
22	1.5	42.5	3	214.69	209.56	34.84	17.83	130.90
23	1.5	5	3	289.61	196.88	28.57	20.13	106.09

* Run No. 0 means before VSR.

Fig. 7 to Fig. 9 indicate the stress-strain obtained in FEA and experiments for different run numbers according to Table 6 to analyze the effect of each factor separately. As inferred out from the diagrams, the general trend shows the reduction of plastic range by increasing each factor. In other words, VSR energy has decreased toughness, and ductility of the material. This result does not necessarily have any relationship to the residual stress relief effect of vibration, as vibratory stress relief takes place when there is residual stress after a mechanical process such as welding, machining, etc., while there has been no initial mechanical process before the treatment. Thus it is not unusual to see such effects as reduction in plastic range, elongation, etc. Furthermore since VSR treatment has been performed here with different amplitudes, most of the amplitudes applied here has made the part exceed the yield stress and this will consequently cause more hardening. This effect can be clearly seen in Fig. 8 in which bigger amplitudes have increased yield strength.

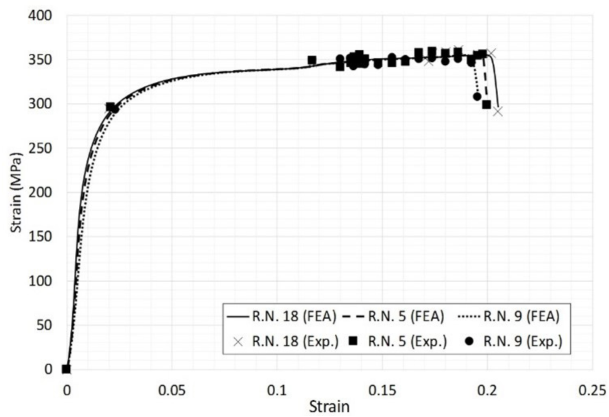


Fig. 7 Stress-strain diagrams obtained in FEA and experiment with amp. = 1.5 mm, time = 42.5 s, and freq. = 1 Hz (R.N. 18), 3 Hz (R.N. 5), 5 Hz (R.N. 9)

Yield strength

The results are demonstrated in Fig. 10. In general, VSR has caused the yield strength to increase however the rate of alternations is different for each parameter. In other

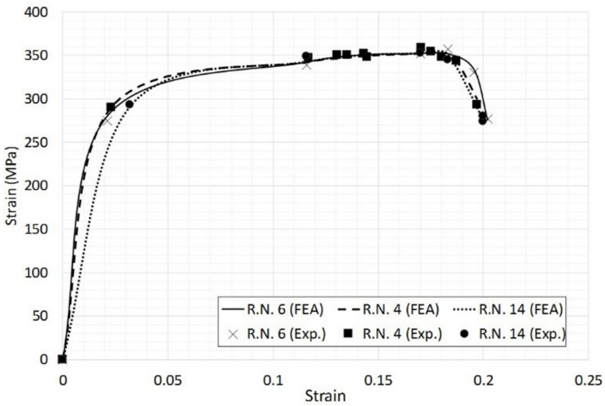


Fig. 8 Stress-strain diagrams obtained in FEA and experiment with freq. = 3 Hz, time = 42.5 s, and amp. = 0.5 mm (R.N. 6), 1.5 mm (R.N. 4), 2.5 mm (R.N. 14)

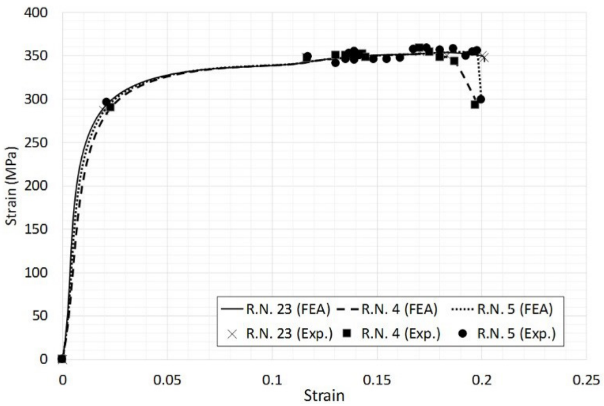


Fig. 9 Stress-strain diagrams obtained in FEA and experiment with freq. = 3 Hz, amp = 1.5 mm, and time. = 5 s (R.N. 23), 42.5 s (R.N. 4), 80 s (R.N. 5)

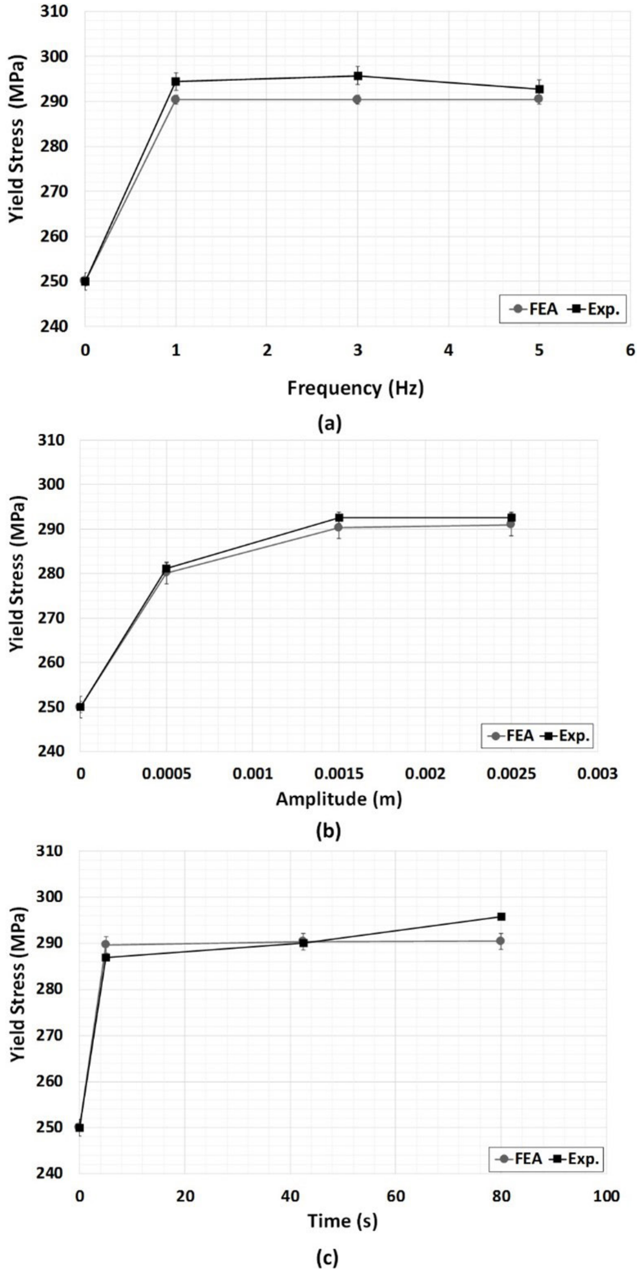


Fig. 10 Yield strength in experimental, and numerical tests for (a) A = 1.5 mm, t = 42.5 s, F = 0, 1, 3, 5 Hz (R0, 18,5,9), (b) t = 42.5 s, F = 3 Hz, A = 0,0.5,1.5,2. 5 mm (R0, 6,4,14), (c) F = 3 Hz, A = 1.5 mm, t = 0, 5, 42.5, 80 s (R0, 23,4,5)

words VSR has improved the strength of the part. Tested parts have not previously undergone any further processes such as welding and machining and VSR treatment has been performed on raw material which has just been shaped to the required initial geometry. A general reason of gain in yield strength can be the hardening effect of VSR process. Such a result is not opposing the stress relieving nature of VSR as it is an optimizing treatment performed after processes to improve the properties, and increase in yield strength could be an advantage if it does not lead to negative effects. In fact VSR is usually used as a tool for residual stress relieving but here it has been just tested to check the changes in mechanical properties.

By looking further at the results of Fig. 10, the effect of each parameter can be analyzed more precisely. As seen in Fig. 10(a) and Fig. 10(c), frequency and time have had similar effect on yield strength since they have made a gain as much as about 40 MPa in yield strength and there has been no more change by increasing the factor to higher levels. For amplitude however it is a bit different as increasing amplitude has changed the gain in yield strength. As indicated in Fig. 10(b), the value of strength has raised to about 290 MPa for 2.5 mm. For time parameter the behaviour is similar to frequency.

These in overall demonstrate the effect of VSR parameters on yield strength. Although the range of changes is about 40 MPa, VSR frequency might become even more influential out of the tested range as each VSR parameter increases the vibrational energy in higher levels which consequently will lead to changes in mechanical properties.

It should be noted that analyzing frequency is a bit more complicated than other parameters as VSR is somehow dependent on natural frequency and the effectiveness of this factor can be considered according to sub-harmonic and super-harmonic vibration which can be considered separately.

Toughness

As we can see in Fig. 11 toughness has generally reduced due hardening effect. This is in agreement with the gains obtained in strength.

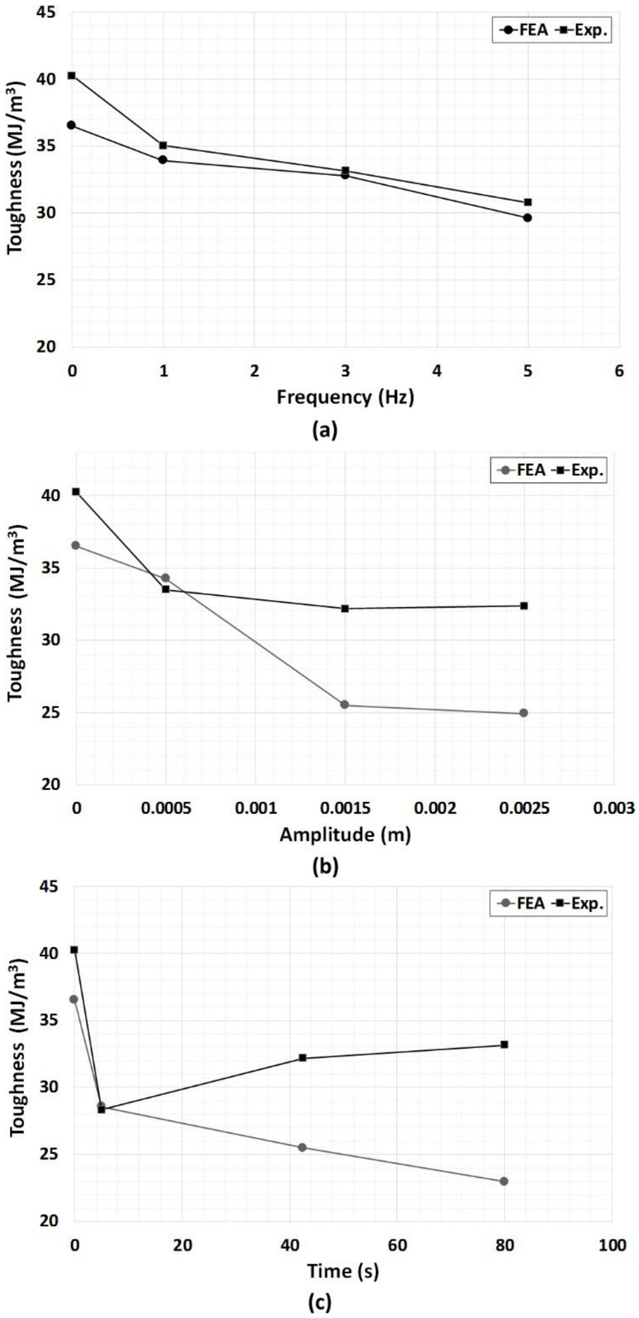


Fig. 11 Toughness in experimental, and numerical tests for different (a) A = 1.5 mm, t = 42.5 s, F = 0,1,3,5 Hz (R0, 18, 5, 9), (b) t = 42.5 s, F = 3 Hz, A = 0, 0.5, 1.5, 2.5 mm (R0, 6, 4, 14), (c) F = 3 Hz, A = 1.5 mm, t = 0, 5, 42.5, 80 s (R0, 23, 4, 5)

For frequency (Fig. 11(a)) the first drop is about $5\frac{MJ}{m^3}$ at 1 Hz from about $40\frac{MJ}{m^3}$. Next fall is very slight for next frequency and it becomes more at 5 Hz as high as $2\frac{MJ}{m^3}$ again. As Fig. 11(b) indicates, toughness has dipped to about $25\frac{MJ}{m^3}$ by increasing amplitude to 1.5 mm but it has plateaued at 2.5 mm. It depicts an almost unstable behavior of toughness versus amplitude, as it has altered toughness only for first amplitudes and has almost no influence in ending amplitude. Although adding more to the amplitude value will definitely change toughness due to considerable crystallographic alternations and increasing boundaries of grain, the current range of tested amplitudes has yielded a stable behavior.

Time (Fig. 11(c)) has shown a nosedive to about $28\frac{MJ}{m^3}$ at 5 s, and a constant fall rate in the next time values which finally reaches to about $23\frac{MJ}{m^3}$ at 80 s. This indicates the modest effect of time on toughness for longer durations of VSR. As mentioned in the previous study [20], the first cycles of VSR have been more effective in alternating mechanical properties, and this is in agreement with the current result.

Elongation

The results for elongation are demonstrated in Fig. 12. The trend is almost the same as toughness as there is direct relationship between toughness and elongation. The biggest drops are still at the first level for each factor in experiments and FEA. The full range of variation in elongation is between about 22% for raw material to less than 20% for the last level of each factor. The reason must be similar to what is explained for toughness as hardening has taken place during VSR and grain boundaries have become more complex not to let larger deformations before fracture.

Elasticity Modulus

The results are demonstrated in Fig. 13. As seen in Fig. 13 elasticity modulus has reduced slightly after performing VSR for almost all factors however some variations can be observed for each factor. There has not been much differences between factors as seen in Fig. 13(a) through Fig. 13(c), as frequency, amplitude, and time have had similar effects on elasticity modulus. In spite of the amplitude in the last level at which the alternation of value is about 15 GPa, for all other situations the value of reduction in each level is less than 10 GPa. In overall the resultant behaviour shows the reduction in elasticity modulus for higher levels. Similar results are obtained by Jafari Vardajnaji et al. [20], in Aluminum alloy performed on a beam having the same boundary and loading conditions. Elastic modulus and hardness have reduced compared to

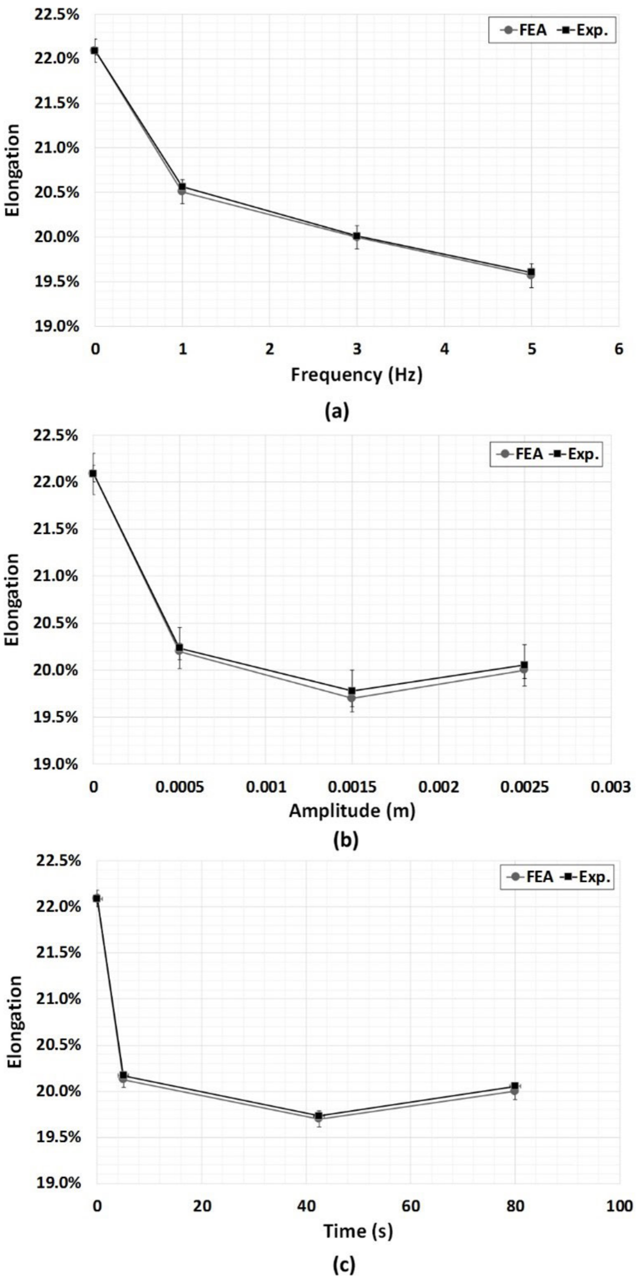


Fig. 12 Elongation in experimental, and numerical tests for different (a) A = 1.5 mm, t = 42.5 s, F = 0, 1, 3, 5 Hz (R0, 18, 5, 9), (b) t = 42.5 s, F = 3 Hz, A = 0, 0.5, 1.5, 2.5 mm (R0, 6, 4, 14), (c) F = 3 Hz, A = 1.5 mm, t = 0, 5, 42.5, 80 s (R0, 23, 4, 5)

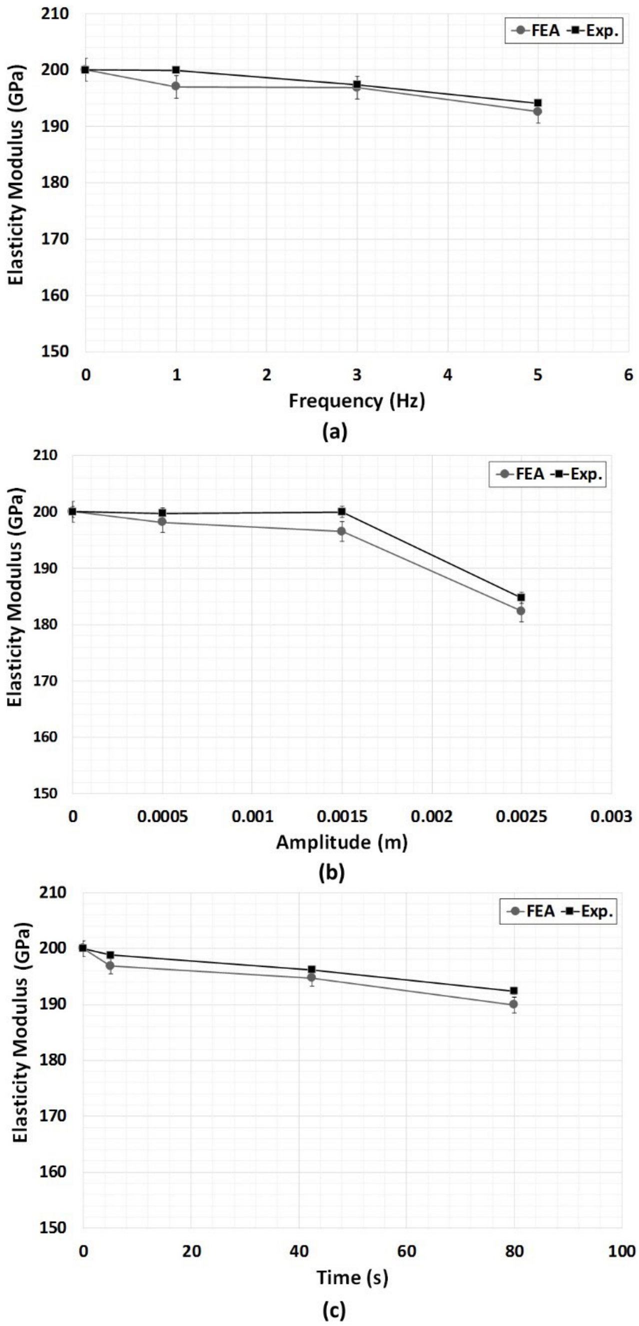


Fig. 13 Elasticity Modulus in experimental, and numerical tests for different (a) A = 1.5 mm, t = 42.5 s, F = 0, 1, 3, 5 Hz (R0, 18, 5, 9), (b) t = 42.5 s, F = 3 Hz, A=0, 0.5, 1.5, 2.5 mm (R0, 6, 4, 14), (c) F = 3 Hz, A = 1.5 mm, t = 0, 5, 42.5, 80 s (R0, 23, 4, 5)

the raw state after VSR treatment. As a brief conclusion, one can tell VSR treatment can alter the elasticity modulus in Aluminum and Steel alloys, however the value of this modification require further researches.

Hardness

The results are demonstrated in Fig. 14. According to Eq. (1) there is direct relationship between hardness and ultimate strength. No considerable effect is observed in Fig. 14(a) through Fig. 14(c). This can be simply predicted by considering stress-strain diagrams as there has been no change observed in ultimate strength after VSR.

In addition, hardness is a parameter measured at surface and near surface thus it can't be influenced much by hardening effect which takes place during VSR.

Most of the results are in agreement with experimental results as they have clearly caused gain and loss in the values while all the factors have had similar effects on output parameters. The results has been compared with previous study [20]. Although the analytical model has been proposed for checking residual stress and amplitude has been substituted with moment, numerical model has yielded

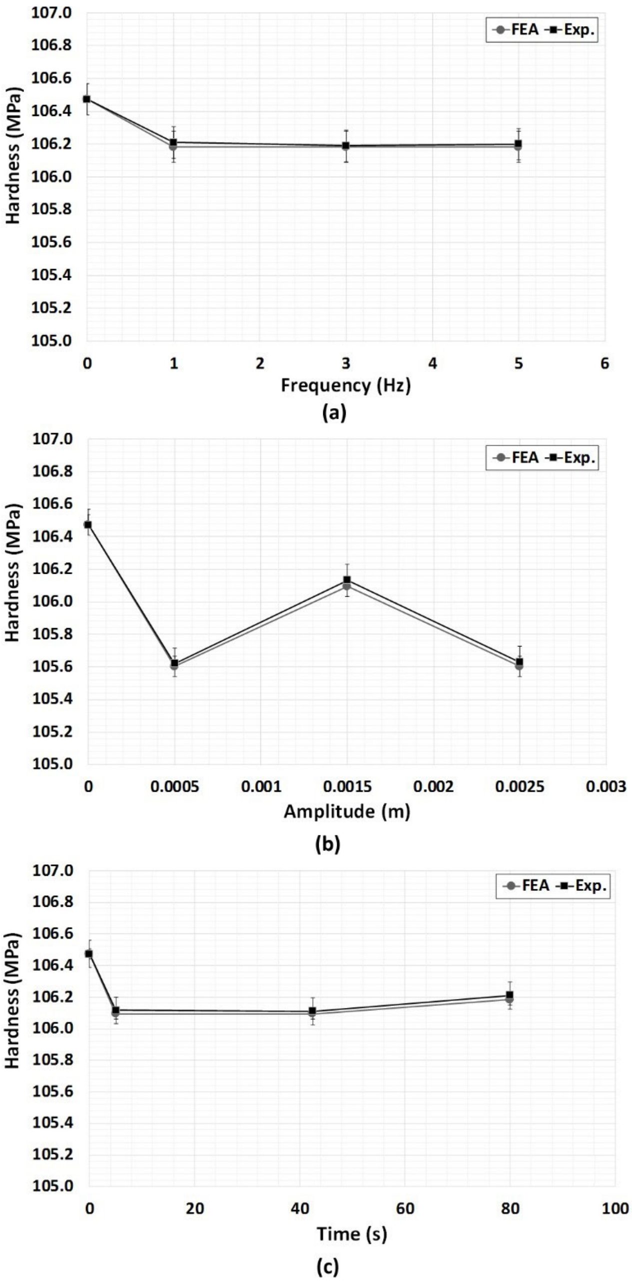


Fig. 14 Hardness in experimental, and numerical tests for different (a) A = 1.5 mm, t = 42.5 s, F = 0, 1, 3, 5 Hz (R0, 18, 5, 9), (b) t = 42.5 s, F=3 Hz, A = 0, 0.5, 1.5, 2.5 mm (R0, 6,4,14), (c) F = 3 Hz, A = 1.5 mm, t = 0, 5, 42.5, 80 s (R0, 23, 4, 5)

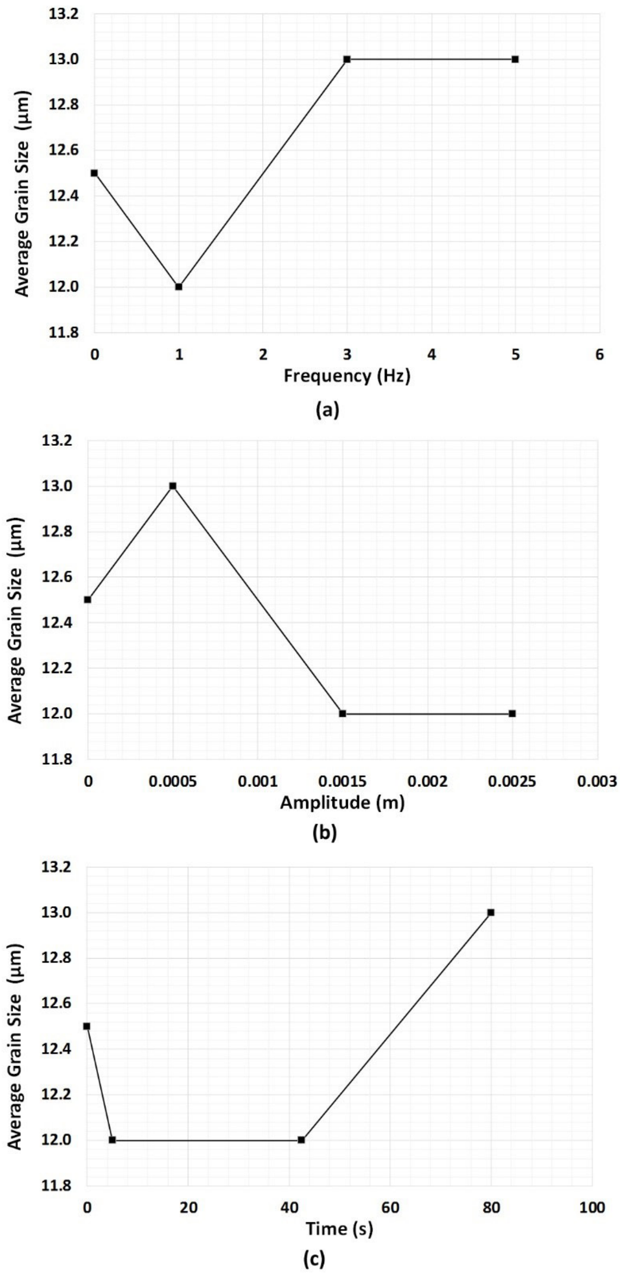


Fig. 15 Average grain size for (a) A = 1.5 mm, t = 42.5 s, F = 0, 1, 3, 5 Hz (R0, 18, 5, 9), (b) t = 42.5 s, F = 3 Hz, A = 0, 0.5, 1.5, 2.5 mm (R0, 6,4,14), (c) F = 3 Hz, A = 1.5 mm, t = 0, 5, 42.5, 80 s (R0, 23, 4, 5)

similar results as residual stress values demonstrate logical relationship with hardness as well as elasticity modulus. As provided in this study, elasticity modulus has reduced after VSR treatment. The same behavior has been observed in experiments and FEA in this paper. This effect is also visible in other mechanical properties as they tend to change after VSR treatment with a similar behavior.

3.2.2 Metallurgical properties

Fig. 15 indicates grain size for different parameters of VSR treatment. As diagram depicts, grain size has reduced by performing VSR however the effect could be negligible for some factor levels. The reduction is almost the same for each parameter as it is fluctuating between 1 and 2 µm. The reason of subtle change in grain size might be related to the short range of testing parameters as higher frequencies and moments will finally cause deeper changes in metallurgical aspects of specimens since it apply larger energies. Similar results have been obtained in the study performed by Hebel et al. [26]. In this study the analysis has been about the alternations in the grain size of the weld. The results show that grain size has been reduced by about 2 and 4 µm by increasing the vibration frequency to about 400 Hz.

Not much effect can be observed in the metallurgical results after VSR treatment, however grains size has reduced a bit and it could be due to plastic deformations which has taken place at the primitive stages of the VSR treatment.

4 Conclusion

In this study, vibratory stress relief has been checked in terms of mechanical and metallurgical aspects of AISI 1008 parts undergone VSR process before welding. Experiments are performed for three important factors including time, amplitude, and frequency of vibration while the same factors are analyzed in finite element model. Previous study is also used to compare the results indirectly in terms of effectiveness of VSR generally.

Following conclusions have been obtained:

1. Mechanical vibration is capable of improving strength, however such an alternation causes reduction in toughness and elongation.
2. Elasticity modulus has had slight reduction by VSR and hardness values are not considerably changed.
3. The changes in mechanical properties demonstrate similar behavior versus VSR parameters although the value of the changes might have been different in size.
4. Yield strength, toughness, and elongation have been easier to change via VSR while the other parameters have had small changes as well as metallurgical aspects.
5. The grain size has not been so much influenced by VSR however they show a trend to decrease in size slightly. It should be noted that larger span of factors might cause even more reduction in size of grains.
6. In overall, according to the results, VSR with effective parameter values can be used to alter the mechanical properties with the purpose of strengthening the metal before welding. It should be noted that the value of factors and alloy type are also effective in the amount of changes.

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