

A Gage Study Applied in Shear Test to Identify Variation Causes from a Resistance Spot Welding Measurement System

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Resistance welding processes, especially spot welding, have wide applicability in the industry, especially in the automotive sector, due to its fast execution and the non-use of consumables. In addition, the search for quality improvement of the final product is incessant and, in a capable process, there should be no error related to the measurements. In this study, the NGR&R was used by the ANOVA method to identify the variation components of the measurement system in the shear test for two quality characteristics: tensile-shear strength and ultimate strain. The experiments were conducted on a hot dip galvanized steel by using design of experiments to select the parts in order to represent the real amplitude of the process. From the results it was possible to verify that one of the destructive test machines used in this study has a strong variability, evidencing that some adjustments and improvements are necessary in the coupling of the specimens for steels with coating layers (such as galvanized steel, which has a layer of zinc).

Keywords: spot welding, measurement system analysis, shear test, NGR&R, ANOVA

Highlights

- A nested GR&R study applied in shear test for a resistance spot welding process.
- Design of experiments to select the parts in order to represent the real amplitude of the process.
- The analysis of variance method to identify variation causes for two tensile machines and two quality characteristics: tensile-shear strength and ultimate strain.
- The results showed that Machine 1 presents greater contribution on the system variability, with measurement results outside the control, as well as a lower degree of repetitiveness than Machine 2.

0 INTRODUCTION

Resistance spot welding (RSW) is a structural joint technique widely used in the automotive sector [1]. RSW is highlighted among welding processes due to its features that favor the industry such as agile operation, which is easily suitable for automatic processes, simple handling, diverse applications and low cost [2] to [4]. Because of its wide applicability and importance, new methodologies for parameter adjustment have been applied to RSW improvement, contributing to the process control and capability.

Among the available methods for verification of the weld point, there is the shear test, which is characterized by the application of opposing forces causing stress in a sliding movement for a given sample. Since this type of test allows to evaluate the quality of welded point, it is being increasingly used, as described by Feng et al. [5], Zhang et al. [6], Martín et al. [7], Shan et al. [8], Chen et al. [9], Manladan et al. [10].

The search for quality improvements has been leading industries to improve their efficiency.

However, devoting improvements only to the process may not contribute to make it better, as the variability can also be caused by the measurement system. Therefore, it is necessary to verify the measurement system variability in industrial processes, such as RSW.

There are several methods for controlling and monitoring quality in the RSW process, such as: expulsion detection in materials [1] and [11]; strength estimation based on sonic emission [12]; welding current analysis on weld strength [13]; temperature measurement [14]; electrode displacement [15] and [16]; and other types of control (i.e. electrical variables, ultrasound transmission and acoustic emission) [17]. However, the control approaches must be verified through specific tests, which illustrate the mechanical characteristics necessary for their capability evaluation, such as the shear test.

The shear test is characterized as a destructive test that evaluates the mechanical strength of the weld point in relation to shear stresses. Destructive tests are performed from time to time, by sampling, being widely employed in the automotive sector.

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Thereunto, quantitative methods are used to verify the process quality, in which the measuring device must be validated before data collection [18].

The variability in destructive test results may arise from the measurement system itself as well as from the manufacturing process [19] to [21]. In this case, the measurement error must be avoided in experimental procedures.

On the other hand, in quality methodologies such as Six Sigma, before analyzing the process, it is necessary to verify the capability of the measurement system (MS). One of the techniques used to evaluate the variation components of MS, according to Peruchi et al. [22], is gage repeatability and reproducibility (GR&R), in which the MS variability is quantified and analyzed through an analysis of variance (ANOVA). The repeatability (Fig. 1a) is characterized by the variation within the system under fixed and already defined conditions of measurements (part, environment, operator, instrument among others), i.e., the variation acquired in a measuring equipment used several times by an operator, which is based on a single part [23] to [27].

In this way, the reproducibility (Fig. 1b) is characterized by the average variation between evaluated systems, being the variation found in the mean of different operators using the same equipment to perform the measurement of a single part [23] and [28] to [31].

ANOVA is a statistical method applied together with GR&R, as described by: Shi et al. [32]; Deshpande et al. [33]; Zhua et al. [34]; García & del Río [35]; Woodall & Borror [20]; Johnson et al. [36]. However, there are few applications focused on the RSW process, reinforcing the potential contribution of this work.

There are several studies in scientific literature related to the measurement system analysis on RSW processes, such as: Wan et al. [37]; Degidi et al. [38]; Wang et al. [39]; Xia et al. [40]; Simončič, & Podržaj [15]; Al-Jader et al. [41]; Lei et al. [42]; Lai et al. [43]; Podržaj et al. [11].

Conduct the measurement system analysis by comparing tensile machines for destructive tests (such as the shear test) on RSW process is original, since published studies that have performed this type of analysis in this process do not present a similar evaluation. In addition, considering the accessed references in this current work, it is possible to confirm the relevance of applying the galvanized steel in this process. Given the importance that a measurement system presents in industrial processes (especially in RSW), this paper aims to perform a gage repeatability

and reproducibility for nested design (NGR&R) applied to the shear test to verify variation causes in a RSW process measurement system, using univariate method ANOVA, comparing two tensile testing machines. The limits of the process parameters were defined from preliminary tests, in order to guarantee desired failure modes. Design of experiments (DOE) methodology was used, being a statistical strategy to model experiments [44], thus that the characteristics of the parts represented a real amplitude of the RSW process.

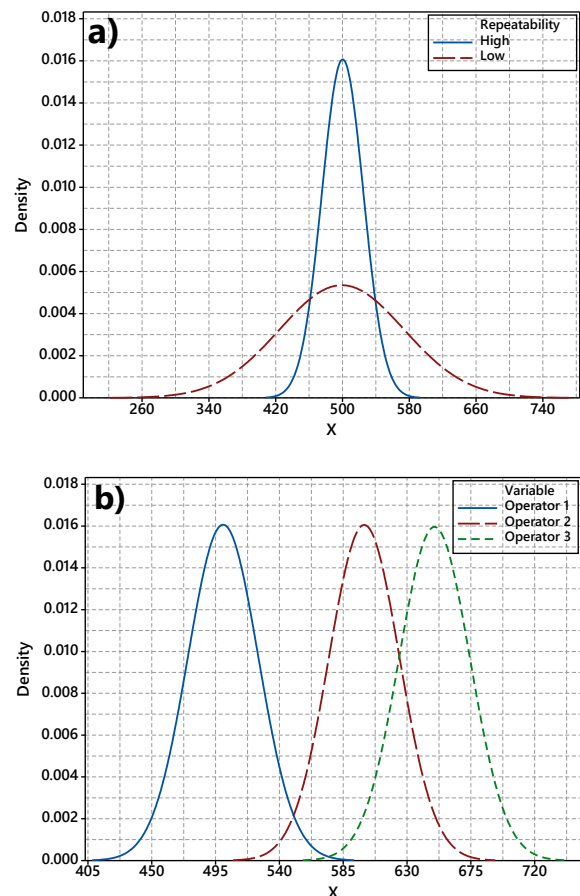


Fig. 1. a) Repeatability and b) reproducibility on a measurement system

This article is organized as follows: a bibliographic review on the RSW process and GR&R study. Subsequently, section 3 describes the materials and methods used in the development of this work. Experimental and statistical results are presented in section 4. Finally, section 5 presents pertinent and relevant conclusions about the subject.

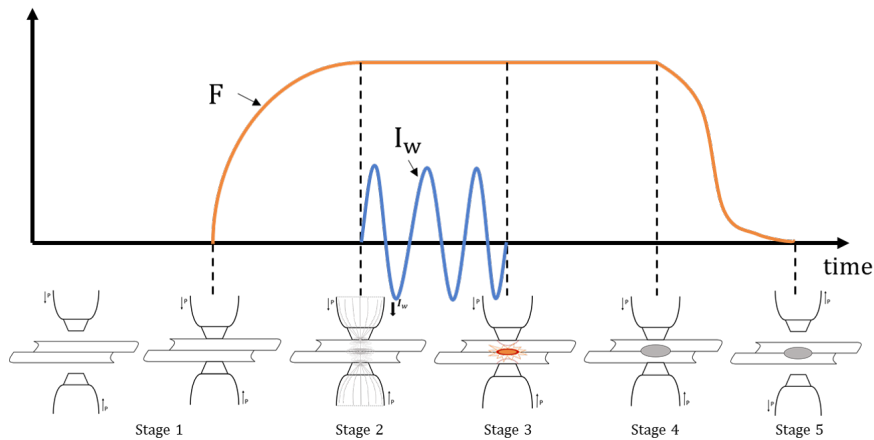


Fig. 2. The spot welding cycle showing the five main phases of the process

1 THEORETICAL BACKGROUND

1.1 The Process of RSW

Commonly used in large-scale manufacture, the RSW process consists in joining two metal parts through the fusion of the metal, overlaid by two electrodes that generate sufficient force and heat at the weld point, during the passage of an electric current [45].

The welding cycle for RSW presents a series of stages, which are described below:

- Stage 1: the electrodes intercept the parts to be welded, providing a certain force (F) on them and ensuring a good settlement;
- Stage 2: still under pressure, the electric current (I_w) passes through the system initiating the weld point formation;
- Stage 3: after the point being established, the electric current is interrupted, but the mechanical pressure generated by the electrodes is maintained on the pieces until the point solidification;
- Stage 4: the exerted force (F) ceases;
- Stage 5: the electrodes stop intercepting the parts.

The sequence of the welding process is presented in Fig. 2.

RSW is controlled by three parameters: welding current, welding time and electrode pressure. These control parameters are presented in several scientific researches which use RSW, such as: Wan et al. [46], Zhang et al. [47], Pouranvari [48], Ighodaro et al. [49], Fan et al. [50], Moos & Vezzetti [51], Amaral et al. [52], Florea et al. [53], Podrżaj & Simončič [54], Podrżaj et al. [55]. Knowing controllable and uncontrollable process factors, as well as adequately configuring these parameters, helps to ensure a good

welded product, since these factors impact on its geometry and final quality [56].

There are several types of tests to evaluate the quality and performance of RSW [57], such as destructive tests, which are usually performed by sampling. Such methods are described by the American Welding Society (AWS) [58], in order to guarantee and monitor the quality of welding nugget, as shown in Fig. 3.

It should be noted that in the shear test, the specimens are fixed in specific equipment for tensile tests, in which opposing forces are applied until their rupture, according to the scheme shown in Fig. 3. In this test it is possible to collect the responses of tensile-shear strength (SS) and ultimate strain (US), which may indicate the energy absorbed (toughness) by the specimen.

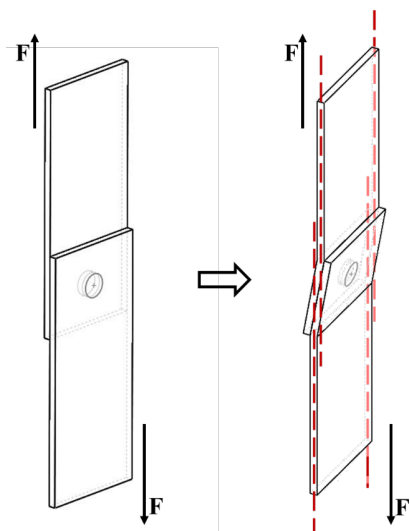


Fig. 3. Shear test on standard specimens after welding

1.2 GR&R Study

The total process variation comprises the sum of variations derived from measurement system and part-to-part. The GR&R seeks to estimate how much of the total process variation is caused by the measurement system, and determining how significant it is, compared to the part-to-part variation [59].

Two cases of control can be considered for MS, product and process:

- Product: associated with binary decisions, for approved and unapproved products, under 100 % sample inspections or inspections, in which GR&R aims to estimate the tolerance of the product, without verifying the process;
- Process: associated to decisions directed to the adequacy of the measurement system to the process control. Searching to stabilize (and understand) the natural process variability in order to make this appropriate.

The process can be divided into a certain number of categories and may be represented from a variability statistics of the MS named number of distinct categories (*ndc*) [60] and [61]. This paper presents a literature review about this subject. The number of distinct categories must be greater or equal to 5. Table 1 presents the guidelines for the MS acceptance [23].

When a single characteristic is evaluated in GR&R studies, a single response variable is analyzed in order to verify the measurement system capability. Besides the traditional univariate approaches, Wang & Chien [31] say that ANOVA, among the known statistical methods, is the best one. ANOVA method stands out in relation to the mean and amplitude (M&A), because it estimates the variance more accurately. In addition, the ANOVA method presents more information about the data than the M&A approach.

Table 1. Classification criteria for the measurement system

Measurement System	GR&R [%]
Acceptable	< 10
Marginal	10 to 30
Unacceptable	> 30

1.2.1 Analysis of Variance (ANOVA)

The variability in measurements of univariate cases can be originated from operator mistakes, measuring instrument variation or even from the product itself. Thus, for a complete GR&R study, it is mandatory to follow the model described in Eq. (1) [24] and [26].

$$Y = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \quad \begin{cases} i = 1, 2, \dots, p \\ j = 1, 2, \dots, o \\ k = 1, 2, \dots, r \end{cases} \quad (1)$$

In the Eq. (1), Y refers to the response variable, μ to the values mean, $\alpha_i \sim N(0, \sigma_\alpha)$ is the random variable for each part, $\beta_j \sim N(0, \sigma_\beta)$ is the random variable for operator, $\alpha\beta_{ij} \sim N(0, \sigma_{\alpha\beta})$ refers to the interaction and $\varepsilon_{ijk} \sim N(0, \sigma_\varepsilon)$ is the estimated error term.

When operators cannot measure all parts, which is a common feature in destructive tests, a NGR&R must be used [62]. This type of design does not present an interaction term between the factors. The variance components for the model are described in Eq. (2).

$$Y = \mu_N + \beta_j + \alpha(\beta)_{i(j)} + \varepsilon_{ijk} \quad \begin{cases} i = 1, 2, \dots, p \\ j = 1, 2, \dots, o \\ k = 1, 2, \dots, r \end{cases} \quad (2)$$

where μ_N is the average values from the nested design, $\beta_j \sim N(0, \sigma_\beta)$ and $\alpha(\beta)_{i(j)} \sim N(0, \sigma_{\alpha(\beta)})$ are the random and independent variables for operator and for parts nested within operators, respectively. The $\varepsilon_{ijk} \sim N(0, \sigma_\varepsilon)$ is the estimated error term. Still in the Eq. (2), p is the number of parts, o the number of operators and r the number of replicas.

The variation components of a NGR&R study with no significant interaction are estimated as in Table 2.

Table 2. Variance components for nested design

$\sigma_{process}^2$	$\sigma_{\alpha(\beta)}^2$	$\sigma_{\alpha(\beta)}^2 = \frac{MS_{\alpha(\beta)} - MS_\varepsilon}{r}$
$\sigma_{repeatability}^2$	σ_ε^2	$\sigma_\varepsilon^2 = MS_\varepsilon$
$\sigma_{reproducibility}^2$	σ_β^2	$\sigma_\beta^2 = \frac{MS_\beta - MS_{\alpha(\beta)}}{pr}$
$\sigma_{NGR\&R}^2 = \sigma_{repeatability}^2 + \sigma_{reproducibility}^2$		
$\sigma_{total}^2 = \sigma_{process}^2 + \sigma_{NGR\&R}^2$		

Table 2 describes the mean squares for operators, parts within operators and the error term.

In a nested design, the %R&R and *ndc* are the two main indicators commonly used to measure and evaluate the MS [60]:

- %R&R is the percentage statistics of repeatability & reproducibility (R&R), which measures the MS standard deviation against the total standard deviation, represented by Eq. (3).

- ndc , also known as the signal-noise index (SNR), measures the variability of the MS. Eq. (4).

$$\%NGR \& R = \left(\frac{\sigma_{NGR\&R}}{\sigma_{total}} \right) \cdot 100 \quad [\%], \quad (3)$$

$$N - ndc = \left(\frac{2\sigma_{process}^2}{\sigma_{NGR\&R}^2} \right) = 1.41 \frac{\sigma_{process}}{\sigma_{NGR\&R}}. \quad (4)$$

2 EXPERIMENTAL PROCEDURE AND PARAMETERS DEFINITION

All test specimens used in this study were performed on a stationary classification machine (Presol Transweld® brand, model TWPRV50) with rated power of 50 kVA, AC and maximum current of 6 kA, as shown in Fig. 4. In addition, a chromium-zirconium electrode (Group A, class 2) was used for welding the specimens (0.10 % to 0.15 % C, 0.3 % to 0.6 % Mn, 0.005 % Al, ≤ 0.03 % P, ≤ 0.05 % S, 40 g/m² to 50 g/m² Zn) with 0.8 mm thickness. The dimensional specifications of Specimens were made according to the AWS [58] standard, as shown in Fig. 5.



Fig. 4. TWPRV50 Presol Transweld® machine

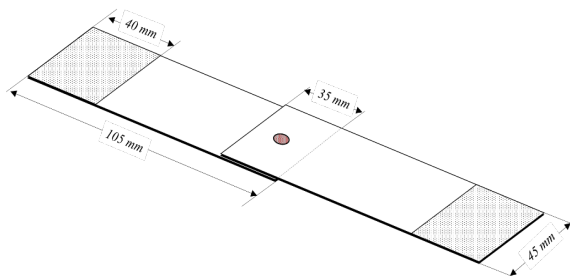


Fig. 5. Dimensions of the specimen for the shear test

The main welding parameters were established based on preliminary tests, thus the minimum parameter limits ensure that the “interfacial” type of

failure mode does not occur at the weld point. Table 3 shows the defined values (maximum and minimum). The electrode pressure was set at 2 bar.

Table 3. Control factors and respective levels

Setup	Unit	Levels	
		-1	+1
$T_{preheating}$	Cycles	5	11
$I_{preheating}$	% kA	66	74
$T_{welding}$	Cycles	7	17
$I_{welding}$	% kA	75	83

From the limits specified in Table 3, the DOE statistical technique was used to generate the fractional factorial design (FFD) as shown in Table 4, in order to have parts with different characteristics as well as representing the process amplitude.

Table 4. Experimental matrix

Run	Setup			
	$T_{preheating}$ [cycles]	$I_{preheating}$ [% kA]	$T_{welding}$ [cycles]	$I_{welding}$ [% kA]
1	11	74	7	83
2	11	66	17	83
3	5	74	7	83
4	11	74	7	75
5	5	66	17	83
6	11	66	17	75
7	5	74	17	83
8	11	74	17	83



Fig. 6. Equipment used in the shear test: a) EMIC® (Machine 1) and b) Instron® (Machine 2)

Forty-eight welds were performed for shear test. Two operators (or simply the tensile machines) were considered in the NGR&R study: An EMIC® DL2000 (Fig. 6a) with an axial force of 30 kN and an Instron® hydraulic servomotor model 8801 (Fig.

6b) with an axial force of 100 kN. Table 5 shows the 48 measurements with two critical-to-quality characteristics (CTQ).

3 RESULTS AND DISCUSSION

From the data collected in the shear test, two quality characteristics will be analyzed separately, which are tensile-shear strength (TSS) and ultimate strain (US).

Table 5. Measurement of quality responses (CTQ)

<i>i</i>	<i>k</i>	Machine 1		Machine 2	
		TSS [N]	US [mm]	TSS [N]	US [mm]
1	1	3217.58	1.47	3737.14	0.3
1	2	2783.24	0.28	3139.77	0.22
1	3	3247.12	0.35	3105.44	0.2
2	1	4779.46	1.45	5030.16	1.14
2	2	5498.73	2.67	5458.82	1.21
2	3	5326.73	1.29	5450.11	1.31
3	1	2096.99	0.17	2100.57	0.09
3	2	1747.78	0.14	2098.47	0.09
3	3	1848.55	0.15	2720.33	0.14
4	1	1228.31	0.09	2539.37	0.11
4	2	2199.49	0.22	2379.70	0.11
4	3	1388.15	0.15	2864.78	0.14
5	1	4484.11	1.16	5580.03	1.35
5	2	4395.51	1.60	4275.08	0.81
5	3	4482.38	1.15	4364.20	0.91
6	1	2413.19	0.22	4329.65	0.9
6	2	2593.87	0.27	3067.30	0.15
6	3	2011.86	0.14	2813.81	0.13
7	1	5385.80	1.97	4983.90	1.16
7	2	5378.85	6.63	4931.34	1.13
7	3	4935.82	1.31	5145.93	1.15
8	1	4656.11	1.20	5838.03	1.37
8	2	4607.46	1.22	4692.68	0.95
8	3	4711.71	1.20	4453.84	0.82

3.1 Results for Tensile-shear Strength

In destructive tests, the TSS vector, which holds the set of original responses of the shear test, does not present an interaction term, so it can be represented by Eq. (2). The analysis of variance for the TSS characteristic is found in Table 6. From the ANOVA, the hypothesis of parts being equal must be rejected, but it is not possible to reject the null hypothesis of different operators replicate the same measurement to a specific part, since *p*-values are equal to 0.561 and 0.000, respectively.

From Eqs. (3) and (4), it is possible to measure the square roots of variances, the %R&R and *ndc*

indicators for the TSS response. Considering the results from Table 7, %R&R presented a value of 29.91 %, being considered marginal, given the conditions established in Table 1. The number of distinct categories (*ndc*) identified by the system was classified as unacceptable, according to the AIAG [23] recommendations.

Table 6. ANOVA for TSS results

Source	DF	SS	MS	F	P
Operators	1	1952795	1952795	0.354	0.561
Part (Operators)	14	77233406	5516672	31.5346	0.000
Repeatability	32	5598088	174940	-	-
Total	47	84784289	-	-	-

Table 7. Variance components contribution of TSS

Source	σ	% Contribution
$\sigma_{GR\&R}$	418.26	29.91
$\sigma_{repeatability}$	418.26	29.91
$\sigma_{reproducibility}$	0.00	0.00
$\sigma_{part-to-part}$	1334.38	95.42
σ_T	1398.40	100
<i>ndc</i>	4	

In addition, Fig. 7 shows the result of measurements for the TSS characteristic. It is possible to verify the dispersion between the measured values and the average of these values. For this characteristic, it is possible to verify that the two machines (operators) present different values of average for each part, properly representing the process amplitude.

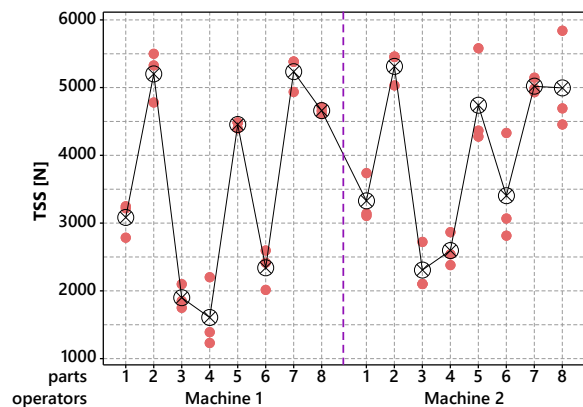


Fig. 7. Measurement results for the TSS characteristic

3.2 Result for Ultimate Strain

The same procedure performed for the TSS characteristic was repeated to verify the study for

the US quality characteristic. From the analysis of variance for the US characteristic (Table 8) it is possible to verify that it does not reject the null hypothesis of operators replicating an equal measurement for the same part (p -value equal to 0.309). However, the null hypothesis of parts being equal must be rejected, confirming that the choice of parts represents the process amplitude.

Table 8. ANOVA for US results

Source	DF	SS	MS	F	P
Operators	1	2.3464	2.34638	1.11418	0.309
Part (Operators)	14	29.4829	2.10592	3.41443	0.002
Repeatability	32	19.7367	0.61677	-	-
Total	47	51.566	-	-	-

Table 9 presents the results concerning the variation components for the US characteristic calculated from Eqs. (3) and (4). Based on the outcomes, it is possible to verify that the %R&R indicator presented a value of 74.4 %, being deemed as unacceptable under the established conditions from Table 1. In addition, the number of distinct categories (ndc) identified by the system presented a value equal to 1, which is considerably unacceptable according to the AIAG [23] recommendations.

Table 9. Variance components contribution of US

Source	σ	% Contribution
$\sigma_{GR\&R}$	0.7917	74.70
$\sigma_{repeatability}$	0.7854	74.1
$\sigma_{reproducibility}$	0.1001	9.44
$\sigma_{part-to-part}$	0.7046	66.48
σ_T	1.0598	00
ndc	1	

After the results were obtained, the control R chart (Fig. 8a) and boxplot (Fig. 8b) were plotted in order to represent the performance of the two operators to measure the US characteristic. The control R chart highlights the out-of-control point on the Machine 1 for the part 7, which indicates that there was not a considerable measurement repetitiveness of this part in the Machine 1. In addition to that, the boxplot reinforces that there is a measurement problem on the Machine 1, where it is possible to identify the presence of the outlier.

In order to identify an outlier in part 7 for the Machine 1, a new analysis was performed for the US characteristic. Given the parameter configuration $x^*_{uncoded} = [7; 74; 17; 83]$, a new experiment was carried out under the same conditions, aiming to

replace the outlier and perform a new diagnosis ($TSS = 5219.7$ N; $US = 1.72$ mm). The results of the new NGR&R study, for US characteristics, showed that the %R&R was 48.31 %, after outlier removal, reducing the variability of the measurement system. However, it is still classified as unacceptable according to AIAG recommended criteria [23]. It is important to highlight that for the TSS there was no statistically significant difference.

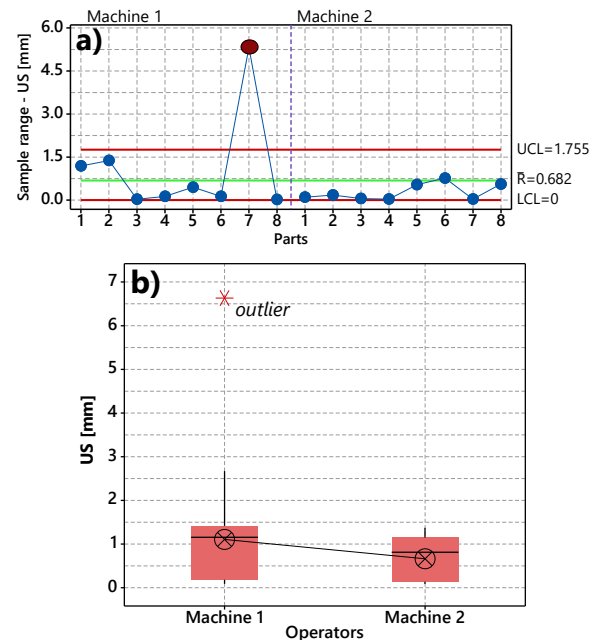


Fig. 8. a) Control R Chart for US characteristic, and b) boxplot for US characteristic

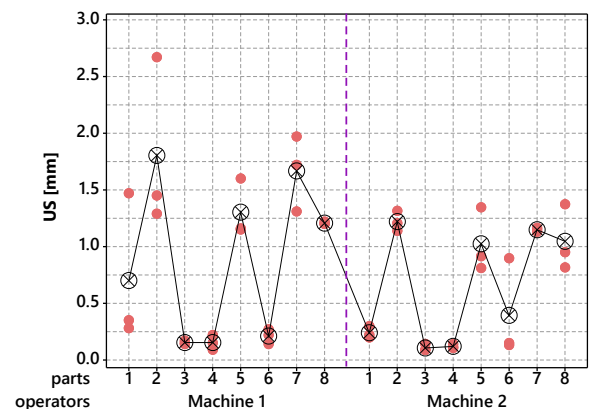


Fig. 9. Measurement dispersions to the US after outlier removal

Fig. 9 highlights the metric dispersions for the US characteristic after the removal of an outlier in part 7, evidencing the metrics behavior of each part.

Because of outlier removal, the upper limit control (UCL) presented a new range, going from

a value $UCL = 1.755$ to $UCL = 1.005$. Lower limit control (LCL) remains the same. Thus, the control R chart now has two out of control points in part 1 and 2 for Machine 1, as seen in Fig. 10.

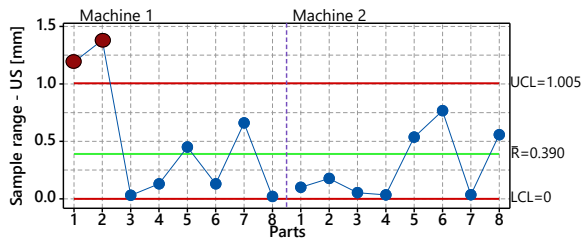


Fig. 10. Control R Chart for US characteristic without outlier

3.3 Analysis of the Results

After verifying the results from the gage study by using the ANOVA method, it was found that, although one of the characteristics presents a result of variation classified as acceptable, there is a great variability attributed to the Machine 1 (EMIC® machine), presenting less repeatability for the measurements, as well as an out-of-control point for part 7. After detecting this variation cause, the new study showed that the $\%R\&R$ decreased, but still remained unacceptable for MS. This result can be explained since the Machine 1 did not exhibit an adequate behavior during the tests, as it led to specimens slips, implying in a non-faithful reading of the CTQ even with the proper preparation usually performed for this procedure.

It can be inferred, from this analysis, that Machine 1 needs adjustments and improvements, especially with respect to the parts fitting in the machine, since its coupling presented slips during the test due to the metal part composition, which presents a layer of zinc (galvanized steel). Such an improvement could hold the coupling of the part during the shear test in order to not compromise future diagnostics in tests performed by it. Fig. 11 shows the boxplot, which illustrates the form, central tendency and variability of the sample analyzed for the TSS characteristic (Fig. 11a) and US (Fig. 11b). Fig. 12, in turn, presents the result from the gage run chart for the two characteristics analyzed, in which is possible to verify that the test outcomes from Machine 2 present greater homogeneity than the results obtained by the Machine 1.

4 CONCLUSION

In order to verify the assigned variability of the measuring instrument for the resistance spot welding

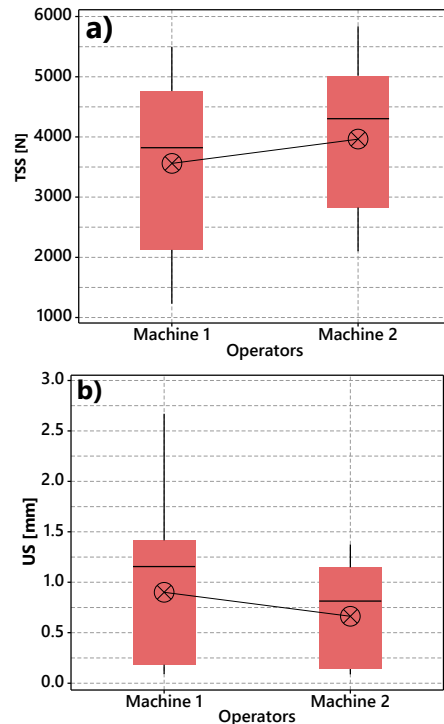


Fig. 11. Boxplot for a) TSS and b) US

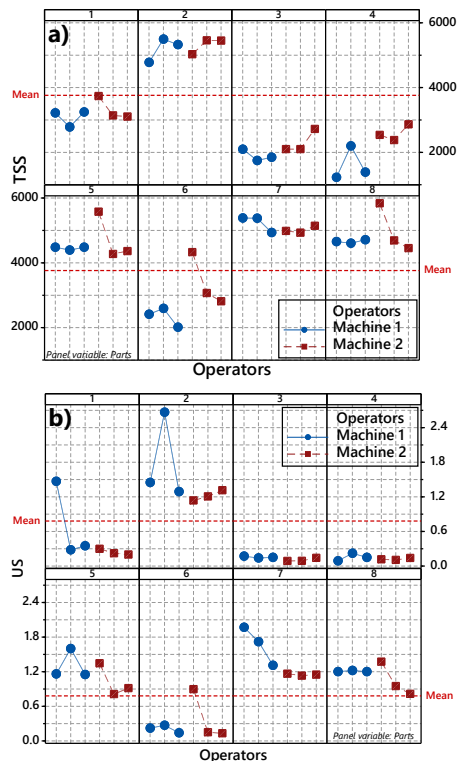


Fig. 12. Gage Run Chart for a) TSS and b) US

process. A MSA for the shear test, by using different tensile machines, was performed in this paper, in

order to verify the reliability of the outcomes obtained in the RSW process.

From the shear test analysis, it was possible to verify that the Machine 1 was responsible for the greater contribution on the system variability, presenting measurement results outside the control, as well as a lower degree of repetitiveness than Machine 2. In addition to that, Machine 1 was not well adjusted, since some specimens have slipped during the tests. This result evidences that some improvements in the parts coupling, which have a coating (such as galvanized steel) are necessary in order to avoid future slips and, therefore, to favor more reliable results, without compromising future diagnoses in tests performed by this type of equipment. Regarding the specimens, it was verified that part 7 presented greater variability in measurements, especially for Machine 1, which may indicate a generalized measurement error for this part. In addition, after identifying this outlier, the new study showed a decrease in the variability of the measurement system to the US characteristic, being able to identify new out of control points in parts 1 and 2.

5 ACKNOWLEDGMENTS

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