ASSESSING STUDENT CAPABILITY TO VISUALLY INSPECT WELDED JOINTS USING ATTRIBUTIVE MSA TECHNIQUE

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ABSTRACT: Measurement system analysis (MSA) is a critical component for any quality improvement process. Most problematic measurement system issues come from measuring attribute (discrete) data, which are usually the result of human judgment. The purpose of an attributive MSA technique is to determine if inspector personnel have sufficient training and experience before performing visual inspection and to discover areas where inspection process must be improved. In manufacturing of engineering structures, the welding processes are of great importance. Typically, 70 – 80% of weld common problems are found through visual inspection. It is the aim of this paper to address an attributive MSA in an educational environment, in order to evaluate how capable or effective are the students to visually inspect welded joints. The results were analyzed using MINITAB software with its module called Attribute Agreement Analysis.
KEY WORDS: welded joints, visual inspection, attributive MSA technique.

1 BASICS OF WELDING

1.1 The welding process

Welding is a process, defined as "a joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure, or by application of pressure alone, and with or without the application of filler metal" (American Welding Society, 2000). The welding process can be classified in different ways (ISO 4063, 1998): arc welding, oxyfuel gas welding, resistance welding, solid state welding and others. Welding techniques are one of the most important and most often used methods for joining pieces in industry, particularly in the manufacture of automobile bodies, aircraft frames, railway wagons, machine frames, structural works, tanks, boilers, pipeline construction and shipbuilding. The result of the welding process is a permanent union (joint) between materials, named weld.

1.2 Welding inspection

Inspecting welds for quality is important because many welded structures can be dangerous if they fail. Welding inspection is a critical part of an overall weld quality assurance program and inspections must be made during and after the manufacturing cycle to ensure that parts meet the requirements of the specifications.

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Depending on the final use of the weldment, several types of inspection may be required, ranging from simple visual inspection to rigorous testing. Inspection includes non-destructive examination (NDE), in which no portion of the completed weld is destroyed and destructive examination (DE) in which the weld is destroyed. Typically, the commonly used NDE methods are visual (VI), magnetic particle (MI), liquid penetrant (PI), leak (LI), eddy current (EI), radiographic (RI) and ultrasonic (UI) methods. This important and growing welding industry is involved in applying these proven techniques and procedures to the full range of engineering structures. Table 1 (Adil, 2015) lists various weld joint types and common NDE methods available for inspection.

Table 1. Capability of the applicable NDE methods for weld type joints

Weld Joints	Inspection methods						
	RI	UI	PI	MI	VI	EI	LI
Butt	A	A	A	A	A	A	A
Corner	O	A	A	A	A	O	A
Tee	O	A	A	A	A	O	A
Lap	O	O	A	A	A	O	A
Edge	O	O	A	A	A	O	A

Legend: A – applicable method; O – marginal applicability.

Destructive tests include bend tests, tensile tests, notch-toughness tests, cross section tests and nick-break tests. To verify the weld quality, weld integrity inspection may also be required in addition and it includes pressure tests, hardness tests, corrosion tests and ferrite tests.

In the field of welding, visual inspection is one of the most extensively used tool to examine certain ne-conformities of welds, before other more expensive or time-consuming forms of inspection are performed. If a weld cannot pass VI, no further NDE methods should be applied until the welds imperfections are corrected.

Advantages of weld VI are: easy to apply, relatively inexpensive, low cost equipment, no power requirement and fastest. Like all other NDE methods, VI has specific disadvantages: inspector training is crucial, good eyesight required, opened to human error, can miss internal defects and report must be recorded by inspector.

Because neconformities are inherent in every manufacturing process and in the field of welding every discontinuity can influence performance of the engineering structures, there is a stringent VI required of welded joints.

In order to be effective, there are three important times: prior to welding, visual inspection of the joint configuration and its compliance with the weld procedure specification (WPS) should be verified; during the welding process when proper weld pass cleaning, interpass temperature and maximum width can be confirmed visually; after welding, VI can identify any discontinuity on the weld surface that is not permissible under the part tolerances and specifications. At this point, the inspector must observe, identify, record (measure) the features of the weld and decide whether the weld is acceptable, must be removed and corrected or rejected. Visual inspection includes either the direct or indirect observation of the exposed surfaces of the weld and base metal.

To ensure the quality of welded structures, VI should be carried out by appropriately qualified, capable and experienced personnel that must be familiar with relevant standards, rules and specifications, be informed about the welding process and able to detect even small any welding imperfections. In addition, a basic set of optical aids and measuring tools, specifically designed for weld inspection can assist the inspector.

1.3 Welding imperfections

All welds have imperfections. Discontinuity is any imperfection of the typical structure or configuration of the weld or the base material, such as a lack of homogeneity in its mechanical, metallurgical or physical characteristics. A weld imperfection may be allowed by one acceptance standard but be classed as a defect by another standard and require removal.

An imperfection or unintentional discontinuity which is detectable by the non-destructive inspection is a flaw. Discontinuities (flaws) are classed as defects when they are of such a size, shape, orientation, location or property that make the weld unacceptable (American Welding Society, 2000), (Grant, 1996).

Welding imperfections are classified into 6 groups (American Welding Society, 2000), (ISO 6520-1, 2007), (ISO 6520-2, 2013), namelly:

- Cracks: microcracks; longitudinal, transverse and radiating cracks; crater cracks;
- Cavities: wormholes; scatter, cluster, piping, porosities; crater pipes; surface pores;
- Solid inclusions: linear and isolated inclusions;
- Lack of fusion (cold lap) and penetration: lack of side fusion, inter-run fusion and root fusion;
- Imperfect shape and dimensions: undercut, underfill, overlap, excessive convexity, melt through, linear misalignment, burn through, root concavity;
- Miscellaneous imperfections: stray arc, spatter, copper pickup, surface pocking.

Visual inspection reveals surface flaws and is a valuable indication of weld quality. Visual inspection only identifies surface discontinuities. Typically, 70 – 80% of weld common problems are found through visual inspection. Some of the more common surface discontinuities of welds that can be detected by visual inspection are: cracks, cavities, solid inclusions, lack of fusion and penetration, undercut and overlap. Table 2 (Adil, 2015) lists the detection capabilities of the most common NDE methods.

Table 2. Capability of the applicable NDE methods vs. some typical surface discontinuities

Typical discontinuities	Inspection methods						
	RI	UI	PI	MI	VI	EI	LI
Cracks	O	A	A	A	A	A	A
Cavities (Porosities)	A	O	A	O	A	O	A
Solid inclusions	A	O	A	O	A	O	O
Lack of fusion	O	A	U	O	O	O	U
Lack of penetration	A	A	U	O	O	O	U
Undercut	A	O	A	O	A	O	U
Overlap	U	O	A	A	O	O	U

Legend: A – applicable method; O – marginal applicability method; U – unapplicable method.

Following welding, some typical action items requiring attention by the visual inspector should include the following: examine weld surface quality, verify weld dimensions, verify dimensional accuracy and review subsequent requirements (American Welding Society, 2000).

2 ATTRIBUTIVE MEASUREMENT SYSTEM ANALYSIS

2.1 Generalities

Quality management of materials and welded joints needs good measurement systems and measurement system analysis (MSA) is a critical component for any quality improvement process. A measurement system is the collection of operations, procedures, gages and other equipment, software and personnel used to assign a number or grade (qualificative, classification) to the characteristic being measured or categorized. MSA is an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variability and it falls into two categories: attribute and variable. MSA is applicable in 98% of quality improvement projects within an organization.

Most problematic measurement system issues come from measuring attribute (discrete) data, which are usually the result of human judgment. Because most processes require at least some form of visual inspection, the assessment of human capability is crucial to obtain the confidence in the inspection process and to see where are the problems in order to eliminate them.

The purpose of an attribute MSA is to determine if inspector personnel have sufficient training and experience before performing visual inspection and to discover areas where inspection process must be improved.

The objectives of an attribute MSA are (Open Source Six Sigma, 2007): to determine if all inspectors use the same criteria to determine “good” from “bad”; to assess organization inspection standards against customer’s requirements; to determine how well inspectors are conforming to themselves; to identify how inspectors are conforming to a “known master”: how often they ship defective product and how often they dispose of acceptable product; to discover areas where training is required, procedures must be developed and standards/visual aids are not available.

Attributive MSA study looks at how effective or capable an inspector is in accepting good products and sorting out bad products repeatedly and also looks at the probability of a bad product being missed and a good product being rejected.

2.2 Methodology

The methodology for conducting an attributive MSA study is (Chew, 2010):

Step 1: select at least 20 products (more is preferable, ussually between 20 and 30) from the process, that should represent the full spectrum of process variation; for maximum confidence, a 50-50 mix of conforming/non conforming products is recommended but a 30:70 ratio is acceptable.

Step 2: have an expert which rates each test products into its true attribute category (true status), classifying it as “OK/C/Y/G” for conforming products and “NOK/NC/N/NG” for non conforming.

Step 3: select the number of inspectors/appraisers (two or more) and number of trials (two or more checks per product per inspector) to be conducted.

Step 4: inspectors rate (categorize) each part, independently and in a random order, without knowing the master results and record the classification result in data sheet.

Step 5: calculate some measures (scores, statistics), defined as follow:

- Inspector score / Individual Repeatability / Within Appraiser (in Minitab) analyzes how consistent operators are by measuring various products more than once;
- Agreement sau Concordance (with standard) / Individual Effectiveness / Each Appraiser vs. Standard (in Minitab) analyzes the ability of the operators to not only be consistent but also correct in their judgments;
- Disagreement OK/NOK (Wrong Classification, False positive or Miss) is the chance of not rejecting a non confoming products; this is a serious type of error since a non conforming product is accepted;
- Disagreement NOK/OK (False Alarm or False negative) is the chance of rejecting a conforming products; this type of error is not as serious as a miss, since a conforming product is rejected;
- Disagreement mixed (Mixed);
- Between inspectors / Reproducibility of Measurement System / Between Appraisers (in Minitab) analyzes the differences between inspectors when rate the same parts and represents the agreement percentage between different inspectors;
- All inspectors vs standard / Overall Effectiveness of Measurement System / All Appraisers vs Standard (in Minitab) represents the overall agreement percentage of both within and between inspectors; it reflects how precise the measurement system performs.

The key in all measurement systems is having a clear test method and clear criteria for what to accept and what to reject. The attribute MSA consists mainly of qualificative/classification counting and division, and the results are evaluated using criteria from table 3 (Automotive Industry Action Group AIAG, 2010), (Koostan, 2012). For any marginally acceptable or unacceptable measurement system, corrective action is required and when corrective action is completed, the attribute MSA must be redone.

Table 3. Decision criteria for attributive MSA study

Measures	Accept.	Marg. accept.	Unaccept.
Within Appraiser	> 90%	80% - 90%	< 80%
Each Appraiser vs. Standard	> 90%	80% - 90%	< 80%
Disagreement OK/NOK	< 2%	2% - 5%	> 5%
Disagreement NOK/OK	< 5%	5% - 10%	> 10%
Between Appraisers	> 90%	80% - 90%	< 80%
All Appraisers vs Standard	> 90%	80% - 90%	< 80%

3 RESEARCH

3.1 Introduction

Throughout a variety of professions, there appears to be recognition of a need to develop and use practical means to evaluate and improve skills. A technical curriculum often focuses on various theories in order to enhance understanding, but there is often also a need to provide the students with specific technical skills. Regarding the welding discipline, course and laboratory activity, it is not only important for students to gain mechanical skill but also to gain a perception of the quality of welds. Visual inspection of weld joints, based on a defined set of standards, is a common and accepted practice for welding professionals. While there are widely accepted standards and nomenclature to guide welding visual inspection, there is still concern about the capability of individuals to accurately evaluate welding quality (Smith, Drake & Bridwell, 2008).

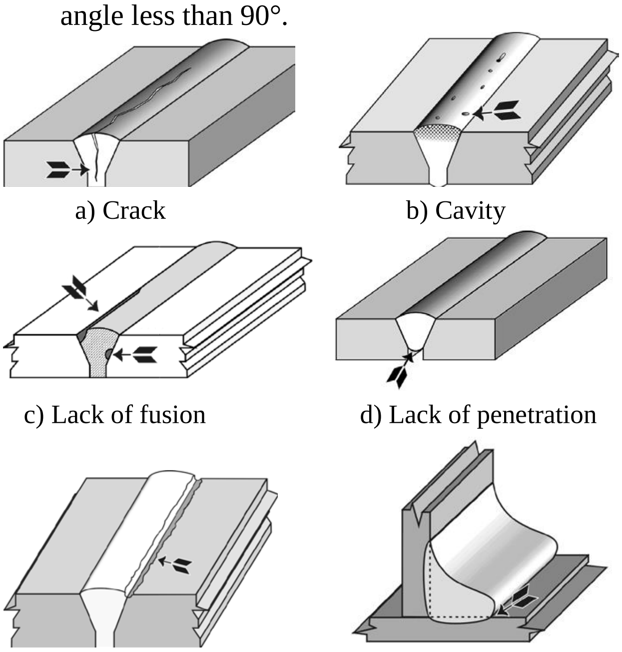
The literature mentions the importance of using attributive measurement system analysis (MSA) in the industry to evaluate and improve the accuracy of visual inspections in different fields, but in actual practice of welding inspection, MSA technique is a poorly used component.

It was the aim of this paper to present a study that demonstrates the application of the attributive MSA technique to evaluate the capability of students, enrolled in a welding course and laboratory, to visually inspect the more common surface discontinuities of welds.

3.2 Methodology

First step was to remind the students which are the more common surface discontinuities of welds that can be detected by visual inspection (American Welding Society, 2013) (Fig. 1):

- Crack (the most serious defect): a tear, fracture or fissure in the weld or base metal appearing as a broken, jagged or straight line;
- Cavity: an open hole in the weld formed by gas escaping from the molten weld during solidification. It can occur at the surface of the weld or inside the weld (difficult to detect);
- Solid inclusions: refers to the nonmetallic layer that forms on top of the molten metal;
- Lack of fusion (cold lap): the weld metal does not fuse or completely bond with the base metal or previously deposited weld metal.
- Lack of penetration: the weld metal does not penetrate as deeply as required.
- Undercut: an imperfection that appears as a groove melted into the base (parent) metal and left unfilled by weld metal, directly along the edges of the weld.
- Overlap: the weld metal rolls over forming an angle less than 90°.



a) Crack b) Cavity

c) Lack of fusion d) Lack of penetration

e) Undercut f) Overlap

Figure 1. Some more common surface discontinuities of welds

The second step was to present the methodology for conducting the MSA study.

The third step in the project was handled as follows: thirty weld joined samples were selected for use in the study. Some of these present one or more of the common surface discontinuity types presented at the beginning of laboratory class and students have to make a personal judgment (two trials) regarding the sample having or not having discontinuities. Because there was insufficient time during the laboratory class to allow all students to inspect visually individually the quality of weld joined samples, the student class population (twelve students in total) was devided in three teams.

The fourth and fifth steps were critical for the attribute MSA. Basically, students were asked to do a first visual inspection (trial 1) of each sample, identify if there are common surface discontinuities of welds and rate (categorize) each weld joints as conforming (OK) or nonconforming (NOK) and then record their inspection results on a worksheet. Then, after some time passed to allow participants to forget their first evaluation results, a second visual inspection (trial 2) was performed (Figure 2).

Worksheet 1 ***

↓	C1-T	C2-T	C3-T	C4-T	C5-T	C6-T	C7-T
	True status	Team 1-1	Team 1-2	Team 2-1	Team 2-2	Team 3-1	Team 3-2
1	OK	OK	OK	OK	OK	OK	OK
2	OK	OK	OK	OK	OK	NOK	OK
3	NOK	OK	NOK	NOK	NOK	NOK	NOK
4	NOK	NOK	NOK	NOK	NOK	NOK	NOK
5	OK	OK	NOK	OK	OK	OK	OK
6	OK	OK	OK	OK	OK	OK	OK
7	NOK	NOK	NOK	NOK	NOK	NOK	NOK
8	OK	OK	OK	OK	OK	OK	OK
9	NOK	OK	OK	NOK	OK	OK	OK
10	OK	OK	OK	OK	OK	OK	OK
11	OK	OK	OK	OK	OK	OK	NOK
12	NOK	OK	NOK	OK	OK	OK	OK
13	OK	OK	OK	OK	NOK	OK	OK
14	OK	OK	OK	OK	OK	OK	OK
15	OK	OK	OK	OK	OK	OK	OK

Figure 2. Worksheet of first visual inspection

To further minimize the memory effect, samples were assigned random numbers and were mixed up between trials. The study coordinator maintained the sample's true identity for data analysis purposes.

The six step in the project was data analysis, using MINITAB software (Minitab 16, 2010) with its module called Attribute Agreement Analysis. The results of the weld initial inspection are presented in figure 3 and tables 4 to 8.

The seven step was to discuss results with students. In addition, the trial samples were provided to students for further review relative to the existence or nonexistence of discontinuity.

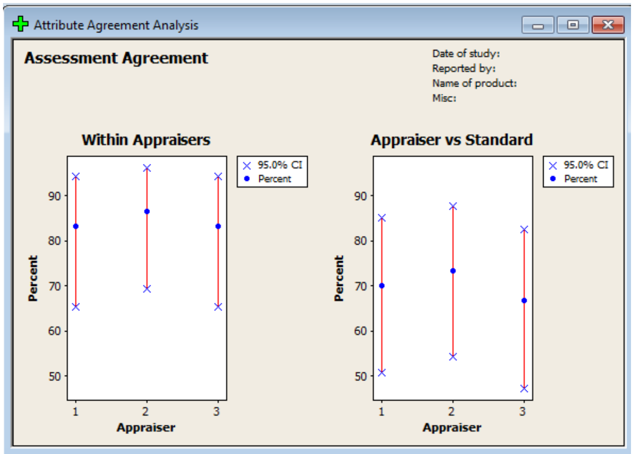


Figure 3. Graphs of first visual inspection

Table 4. Within Appraisers

Assessment Agreement			
Appraiser	# Inspected	# Matched	Percent
1	30	25	83.33
2	30	26	86.67
3	30	25	83.33

Matched: Appraiser agrees with him/herself across trials

Table 5. Each Appraiser vs. Standard

Assessment Agreement			
Appraiser	# Inspected	# Matched	Percent
1	30	21	70.00
2	30	22	73.33
3	30	20	66.67

Matched: Appraiser's assessment across trials agrees with the known standard

Table 6. Each Appraiser vs. Standard

Assessment Disagreement				
Appraiser	# OK /NOK	Percent	# NOK /OK	Percent
1	4	33.33	0	0.00
2	4	33.33	0	0.00
3	5	41.67	0	0.00

OK/NOK: Assessments across trials = OK/standard = NOK

NOK/OK: Assessments across trials = NOK/standard = OK

Table 7. Between Appraisers

Assessment Agreement		
# Inspected	# Matched	Percent
30	18	60.00

Matched: All appraisers' assessments agree with each other

Table 8. All Appraisers vs. Standard

Assessment Agreement		
# Inspected	# Matched	Percent
30	15	50.00

Matched: All appraisers' assessments agree with the known standard

The eight step was to establish an improvement plan, resulted from each student being able to identify specific discontinuity types that were consistently inaccurate or inconsistent.

The last step in the project was to repeat the inspection and data analysis again.

3.3 Analysis of the initial inspection results

The initial results show a visual inspection system not capable to inspect weld joints the same way. The students evaluated differently, not only between the students, but also within by assessing the same weld several times contrarily.

The conclusion is as follows:

- Individual Repeatability of all teams is between 80% and 90%, so marginally acceptable; this means that students are not consistently with themselves;
- Individual Effectiveness of all teams is under 80%, so unacceptable; this means that students are not in agreement with the standard;
- Assessment Disagreement adds some useful information: all teams accepted non conforming welds (a serious type or error).

Team 1 and 2, on 4 occasions classified a non conforming weld as a conforming (33.33%). Team 3 classified a non conforming weld as a conforming one on 5 occasion (41.67%).

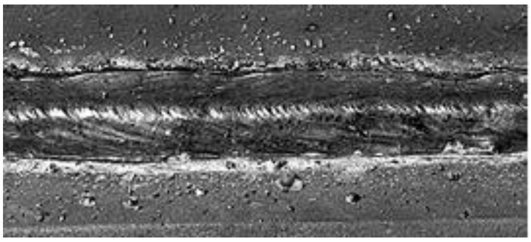
- Reproducibility of Measurement System, shows that all three teams agreed with each other on both assessments only 60%, so on only 18 out of 30 weld inspected (unacceptable). They may not be all using exactly the same operational definition for conforming/non conforming all the time or may have a very slight difference in interpretation of what constitutes a conform and a non conform weld;
- The last metric, overall Effectiveness of the Measurement System tells that for only 15 out of 30 weld inspected all three teams agreed with the standard, so on only 50% (unacceptable).

The results show that there is a great problem with the ability of students to assess carefully the weld joints so, ways of improving this situation had to be considered.

The conclusion was that the inspection process of welded joints had to be improved by student retraining and developing visual aid samples for all common surface discontinuities of welds (Fig. 4) (American Welding Society, 2013), (Gulham, 2015).

a) Crack

b) Cavity



c) Solid inclusions

d) Lack of fusion

e) Lack of penetration

f) Undercut

g) Overlap

Figure 4. Visual aid samples

3.4 Analysis of the second inspection results

The conclusion was as follows:

- Individual Repeatability of all teams is above 90% (96.67% for all teams), so acceptable; this means that students are consistently with themselves;
- Individual Effectiveness of all teams is also above 90% (96.67% for team 1 and 3 and 93.33% for team 2), so acceptable; this means that students are in agreement with the true status of weld;
- Assessment Disagreement results show that only team 2 classified a conforming weld as a non conforming on 1 occasion and all teams were inconsistent in their judgment on 1 occasion;
- Reproducibility of Measurement System, shows that all three teams agreed with each other on both assessments to 86.67%, so on 26 out of 30 weld inspected, so marginally acceptable;
- The last metric, overall Effectiveness of the Measurement System tells that for 26 out of 30 weld inspected all three teams agreed with the true status of weld, which represents 86.67%, so marginally acceptable.

4 CONCLUDING REMARKS

Human measurement systems are often used in a lot of processes to perform visual inspection, so their assessment is important to see where are the problems, in order to eliminate them and to guide the process improvement.

The paper demonstrated an effective mean by which to evaluate student capability to assess welding quality through visual inspections, using attributive MSA technique. Periodic inspector training along with developing visual aid samples are critical to ensure any visual inspection method be consistent.

An attributive measurement system analysis can normally be performed at very low cost but with great impact on any quality improvement process. By analysing existing measurement systems, one can better understand the data provided by those systems and make better decisions.

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