RELIABILITY PAPER

An algorithm to prioritize welding quality deterioration factors

A case study from a piping component fabrication process

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Abstract

Purpose – The purpose of this paper is to present and implement an algorithm to prioritize welding quality deterioration factors for improving welding personnel performance. A case study is carried out in a piping components fabrication process which supplies these components to oil and gas production and processing facilities on the Norwegian continental shelf (NCS).

Design/methodology/approach – The quality deterioration factors’ prioritization is carried out using statistical methods in conjunction with the data recorded in the welding inspection database (WIDB) of the case study company. Data cleaning and rearrangements were performed to reflect final objective. Based on the welding procedure specifications (WPSs) and quality imperfection groups classified in NS-EN ISO 6520-1, the analysis is performed to prioritize the welding quality deterioration factors.

Findings – Based on the WPSs and quality imperfection groups classified in NS-EN ISO 6520-1, it is possible to prioritize the welding quality deterioration factors. These factors are possible to use for improving the performance of welding personnel to assure the quality of welds in steel fabrications.

Practical implications – The factors prioritized are possible to use for improving the performance of welding personnel to assure the quality and reliability of welds in a steel fabrication.

Social implications – Assuring quality as proposed in the manuscript, the catastrophic failures that are potential in production and process plants can be mitigated. This enhances health, safety and environmental performance of welds in steel fabrications.

Originality/value – The value of this paper is to illustrate an innovative approach to a real life quality problem; it demonstrates how the application of qualitative and quantitative quality instruments in accordance with technical specification can help in increasing and maintaining product compliance and in optimizing the management of resources.

Keywords Welding quality deterioration factors, Welding procedure specification, Welder performance, Imperfection groups, Welding, Oil industry, Gas industry

Paper type Case study

1. Introduction

The fabrication process sits squarely at the intersection of manufacturing and construction. Basically, manufacturing provides the elements for the construction of production and process facilities, bridges, highways, buildings, etc. (Ballard and Arbulu, 2004).

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Many of these elements are made-to-stock; however, some key elements are made-to-order, for instance, piping components to offshore production and process facilities, pipe supports, reinforcing steel, heat-ventilation-air-conditioning (HVAC) duct work, etc. These made-to-order products are produced by fabrication shops in project mode. The ability to measure, understand and manage “variability” is critical to manage the projects effectively and efficiently (Hopp and Spearman, 2007). Effective and efficient management of projects in a fabrication shop is mainly focused on the quality of the final product. In this context, it is revealed that “fabricators do not always take full advantage of code-provided latitude for the resolution of many problems,” resulting in a situation where “owners pay too much for structures that have been plagued by delays, unnecessary repairs, and extraneous activities that add little or no value to the project” (Miller, 1996). Hence, it is vital to have a methodology to implement code-provided latitude via measuring, understanding and managing the “variability” in a project.

In the steel fabrication industry, welding dominates. However, experience indicates that there is a great deal of confusion in this area as most of the personnel still regard the quality of welding as a “black art” rather than a science that can be understood and controlled. The welding basically provides a bonding which is connected to the boundary of the material in order to economize the use of material and keep the rigidity of the steel whilst maintaining a good appearance (Sung et al., 2004). Although automatic welding machines are generally used for welding in the fabrication industry, working conditions preclude their use in some areas of manufacturing and construction engineering. For instance, manual metal arc (MMA) welding is widely used in shipyards, but not in automobile manufacturing (Houldcroft, 1986). Hence, man-made welding still dominates in the manufacturing, fabrication and construction industry. However, a good welding skill is essential to reach a specified standard (Hansen, 1995). The specified quality standard can be maintained by detecting and handling weld defects based on the principle of statistics (Sung et al., 2004). However, the first step in the successful production of quality welding is to improve the welders’ performance by providing timely training, as it is important that the welders are well trained in the application of sound welds (Hajikarimi et al., 2009a). For instance, American Welding Society (AWS) D1.1 demands that skilled welders follow the project welding requirements for the execution of critical welds (AWS D1.1, 2006). Also, AWS D1.1 insists that in any quality control (QC) program, significant emphasis should be placed on ensuring that the welding personnel have appropriate qualifications to perform the job (Sacsteel, 1995; AWS D1.1, 2006). If not, welding defects can be induced by improper operations, bad maintenance of welding equipment and the lack of skill of welding operators. Furthermore, due to bad welding techniques, and inappropriate welding procedures and sequences, imperfections occur in the welds, such as: at welding seams, edges of welds under cut, insufficient fusion, inadequate depth of welding, welds containing impurities and air bubbles, insufficient cross-section, unsatisfactory welding shape, welding overlap and distortion. These defects bring stress concentration, lack of strength and residual stress that have a tremendous effect on the quality of the welded fabrication (Schwartz, 1985). Therefore, the welding procedure and welder qualification should be re-evaluated from time to time to achieve a high quality and safe welding fabrication.

Producing quality welds is vital to minimize potential health, safety and environmental (HSE) damage from operating assets (Norrish, 2009). Industrial demand for higher quality welds has influenced welding management to re-evaluate
its production requirements in lieu of the stricter quality requirements imposed by company procedures as well as national and international standards. The re-evaluation reveals that it is vital to “do it right the first time” to realize significant performance and increased profits. For instance, “an acceptable repaired weld may actually be inferior to the weld initially rejected as unacceptable” (Miller, 1997). However, productivity increases through performance improvement has rarely been connected with quality assurance (QA) and QC programs. For instance, QA programs and departments are often looked on as policemen, who hinder production rather than assist in improving productivity. Hence, it is vital to achieve a more disciplined approach to all the quality-related activities of a welded fabrication from “cradle to grave” (Burgess, 1989).

A weld is considered to be “in quality” if it can meet, and continue to meet, the intended requirements. For instance, “A good weld is any weld which does what it is intended for during the service of the structure” (Miller, 1997). If the quality of a weld is better than aforementioned, it may increase the cost without any added benefit (Schwartz, 1985). The Lincoln Electric Company suggests the five “Ps” of weld quality as:

1. **Process selection.** The process must be right for the job.
2. **Preparation.** The joint configuration must be correct and compatible with the welding process.
3. **Procedures.** To assure uniform results, the procedures must be spelled out and they must be followed.
4. **Pretesting.** By full scale mockups on simulated specimens, the process and procedures are proven to give the desired standard quality.
5. **Personnel.** Qualified people must be assigned to the job.

“The five P’s are important in that their requirements must be met long before any inspection will take place” (Schwartz, 1985). However, there is no single factor in the avoidance of failures in welded construction; many different factors may be involved, not only within a particular company, but also externally, with suppliers, sub-contractors, customers, inspection authorities, etc. Obviously, properly qualified and experienced employees are an essential ingredient in the successful accomplishment of any mission. Hence, in order to achieve continuous improvement it is vital to have an approach to assess the main factors that are prone to quality deterioration.

This manuscript discusses how welding processes have evolved over time towards an improvement in quality and performance the role of personnel performance in welding, as well as QC and drawbacks in QC in welding processes, respectively. Finally, it proposes an algorithm to analyze welding imperfections as specified in NS-EN ISO 6520-1 (1998) and the causes for such imperfections. This is done based on the data recorded in the welding inspection database (WIDB) of a leading welding fabricator who supplies welded piping components to the North Sea offshore oil and gas industry. The suggested analysis enables errors to be kept to their random levels by mitigating assignable causes. The results and interpretation of the analysis are useful to improve welder and related personnel performance in the welding trade.

### 2. Evolution of welding processes towards quality and performance

For several thousand years, the blacksmith had a monopoly on welding. However, by the mid-nineteenth century the new discoveries of science provided an opportunity
for competition among different welding methods. During the period from 1880 to
1914, the invention of the following equipment and methods took place: “autogenous
soldering” and “welding iron” by use of air or oxy-hydrogen flames (1865); carbon-arc
welding (1881 and 1885) (Kornienko, 1982); metal-arc welding (Nunes, 1976); resistance
butt welding (1886); torches suitable for burning acetylene (1903); the coated electrode
to obtain better arcing and metallurgical properties (1907); better coatings for coated
electrodes (1909) (Houldcroft, 1973); flash welding, resistance spot welding, and thermit
welding. By 1914, the major welding processes had all been invented and the processes
known at that time were: gas; carbon-arc; bare wire metal-arc; covered electrode
metal-arc; resistance butt, spot and seam; and thermit, both with and without forge
(Heaton, 1914).

The period from 1935 to 1945 is described as “developing for production and proving
in service”. Until the early 1930s, welding had been confined to being a manual process.
However, after that, various mechanized forms appeared such as various resistance and
submerge-arc welding processes. This was mainly due to the fact that the period covered
Second World War and the rearmament programme which preceded it (ESAB, 2004).

During the period from the end of Second World War until 1970, many new welding
processes were developed. These were based on all known methods of generating heat
locally, as every welding process requires heat energy in some form (with the exception
of cold pressure welding). By 1970, each feasible heat source had been pressed into
service, and no fundamentally new processes have appeared since then. When the new
welding methods come into existence they were keenly investigated and the impact of
the new processes on the bulk of steel fabrication was found to be limited. Hence, later
steelmakers changed their attitude to developing steels for welding rather than
expecting to develop welding methods for steel (Houldcroft, 1986). There was no
change in the steel makers’ attitude when the requirements of the oil and gas industries
were for notch tough weldable steels (Cotton, 1979).

Since the early 1970s, Japanese shipyards have played an important role in the
application of mechanized welding methods. However, they were relatively high order,
lacking automation with adaptive control. Apart from that, initially monitoring as a
basis for QC was much investigated in the context of resistance welding. Later, the
measurement of welding parameters was studied to assist the application of automatic
welding in different welding processes such as arc welding, having the objective of
aiding set-up, improving reliability and providing records for QA (Needham, 1983).
Furthermore, plant for arc welding developed with special electronically controlled
power sources allowing the welding current to be pulsed to give improved control of
the welding pool and greater consistency in operation (Weman, 2001). Within the
automobile industry from the mid-1970s, welding robots began to function as carriers
of spot welding heads.

Since 1985, a sub-division of the “quality and performance” period has started. This
period includes machine and automated welding where the traditional skill of
manipulation has increasingly been displaced by intelligent machines. On these
grounds, the welder becomes more and more a technician, a skilled machine setter and
minder. The future intelligence of a welding machine can be an in-built ability to select
the appropriate welding procedure and also to carry out a number of QA checks
(Houldcroft, 1986). However, the selection of the welding process or method is dependent
upon what is needed and where the welding fabrication is made. The ultimate decision
began to rest not just on technical considerations, but also on relative costs. For instance, MMA welding is widely used in shipbuilding and the offshore industry, but not in automobile manufacture. Hence, in order to achieve low cost and high quality in welding, the present focus is to reduce waste via performance-improvement strategies like Six Sigma (Antony et al., 2005). Six Sigma is a process performance improvement strategy that aims to reduce the number of mistakes/defects to as low as 3.4 occasions per million opportunities (Desai and Shrivastava, 2008). It has a major impact on the quality management approach, while still being based on the fundamental methods and tools of traditional quality management (Goh and Xie, 2004). The Six Sigma implementation enhances process survival in the twenty-first century via statistical measurement, management strategy and quality culture (Park et al., 2001). Furthermore, the Six Sigma approach provides support to: improve profitability, drive out waste, reduce quality costs and improve the effectiveness and efficiency of operational processes that meet or exceed customers’ needs and expectations (Antony and Banuelas, 2001).

3. Role of personnel performance in the welding fabrication industry

The fabrication and construction industry is facing numerous challenges: increasing competition, globalization of the construction market, increased demands from clients and society, the impact of new technology, and the requirement to maintain a highly skilled workforce at all levels (Egbu and Robinson, 2005). Largely project based, the construction sector is a complex, dynamic and changing environment (Raiden and Dainty, 2006). The uniqueness of projects, fragmentation within the construction process, mobile staff and changing teams, the increasing need to become more customer-oriented and the high level of external knowledge required by construction companies all make the case for performance improvement more compelling (Graham and Thomas, 2006). In today’s business environment, knowledge is considered to be the most important driver behind sustained competitive advantage (Grant, 1996). However, beyond this simple truth, there’s a plethora of research that underscores the quantifiable connection between personnel performance (i.e. skill or talent) and business performance. Apart from that, personnel performance is a rapidly increasing source of value creation. For instance, in 1982, a study found that 62 percent of an average organization’s value could be attributed to its physical assets (i.e. equipment, facilities, etc.), while only 38 percent was attributed to intangible assets (i.e. patents, intellectual property, brand, and in particular, personnel). Moreover, just one generation later in 2002, these percentages more than reversed themselves, with 85 percent of value attributable to intangible assets and just 15 percent related to tangible assets (Kaplan and Norton, 2000; Weatherly, 2003). Figure 1 shows this global shift in the percentages of an organization’s value in relation to intangible and tangible assets from 1982 to 2002.

Due to the nature of the fabrication industry, the project cost, safety, and time is extremely dependent on personnel performance. In this context, knowledge, personal attributes, competencies (or skills) and the experience of the personnel have a direct effect on personnel performance (Figure 2) and alternatively, sustainable performance of the fabrication industry. In particular, welding personnel and their performance are the last and the most important factor in fabricating high quality weld connections in a steel structure (Hajikarimi et al., 2009b).

Safety and security in the welding process as well as quality of welds come from suitable instruments and the proficiency of welders. Attracting, developing and
retaining professional welders are not only a cost, but also an investment in human capital resources. For instance, “in terms of cost and productivity it is evident that in most of the common welding operations labor accounts for 70% to 80% of welding cost” (Norrish, 2009). Furthermore:

 [...] welding is one of the few professions that require personnel to demonstrate their skills even if they are already certified. They are often required to demonstrate their knowledge and skills before being hired as welding requires a high degree of eye-hand coordination. The method commonly used to test welders’ ability is the qualification or certification test. Welders who have passed such tests are referred to as “qualified welders” whilst if proper written records are kept of the test results, they are referred to as certified welders. Welder certification is divided into two major areas: 1) Traditional welder certification; and 2) Welding certification developed by the AWS. The first method was used to demonstrate welding skills for a specific process on a specific weld, to qualify for welding a welding assignment. The second method has three levels: 1). Entry-level welder skills; 2). Advanced welders; and 3). Expert welders. AWS QC10 and AWS D9.1 sheet metal welding code, both provide provisions for written and oral examinations incorporated into them (Cengagesites, 2011).

Steel structures play a significant role in a construction and most of their problems relate to different kinds of faults and weaknesses in connections (Hajikarimi et al., 2009b). The welder has an enormous effect on welding quality, and most of the faults in welding
depend on the welder’s performance. On the other hand, repair, QC processes and testing could be destructive and costly for a construction firm (Hajikarimi et al., 2009a). Hence, the welder’s performance improvement makes him more effective for the firm whilst improving the quality level of welding and the safety of the structure. Thus, it is vital to recognize that the most important quality improvement factors are attributed to welder performance.

4. Weld imperfection groups, testing and repair

NS-EN ISO 6520-1 defines a welding imperfection as “any deviation from the ideal weld”. It also classifies imperfections into six groups:

(1) cracks;
(2) cavities;
(3) solid inclusions;
(4) lack of fusion and penetration;
(5) imperfect shape and dimension; and
(6) miscellaneous imperfections (NS-EN ISO 6520-1, 1998).

Moreover, it provides a detailed numbering system for further illustrating imperfection (Table I).

For example, Figure 3 shows the imperfection variety 2011, which represents “gas cavity of essentially spherical form”.

When the level of imperfection is higher than an acceptable level as specified in standards (e.g. NORSOK M-601 (2004): welding and inspection of piping), then it is considered to be a “defective weld”. Once it is identified as a defective weld, then, based on the size, different remedial actions are indicated in the company or welding

<table>
<thead>
<tr>
<th>Imperfection group</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Cracks</td>
</tr>
<tr>
<td>200</td>
<td>Cavities</td>
</tr>
<tr>
<td>300</td>
<td>Solid inclusions</td>
</tr>
<tr>
<td>400</td>
<td>Lack of fusion and penetration</td>
</tr>
<tr>
<td>500</td>
<td>Imperfect shape and dimension</td>
</tr>
<tr>
<td>600</td>
<td>Miscellaneous imperfections</td>
</tr>
</tbody>
</table>

Table 1. Types of imperfections as categorized in NS-EN ISO 6520-1:1998

Figure 3. Examples of welding imperfection sub-groups
fabrication yard procedure. For instance, the fabrication yard in the case study uses a welding repair procedure which states that if the pipe diameter is:

- less than 2 inches, then it shall be cut and re-welded; and
- 3 inches, if the first time straightening fails then the pipe shall be cut and rewelded, and greater than 4 inches, then the minimum repair length shall be 100 mm.

In practice, both destructive testing (DT) (e.g. macro etch, fillet weld break, transverse tension, and guided bend) and nondestructive testing (NDT) (e.g. X-ray, ultrasounds, liquid penetrant, magnetic particles, etc.) trials (Halmshaw, 1997) are used to validate that the performed seams satisfy the established quality standards. Basically, DT is used for welding procedure qualification and welder performance qualification testing. Apart from that, DT is also used for sampling inspection of production welds, research inspection, failure analysis work, etc. The testing process as to whether it is DT or NDT, consumes a significant cost in terms of productivity. Also, a significant time is spent on a welding process itself and the related reworking (or repair). For instance, based on test results, some of the weld seams have to be reworked and evaluated for the second time.

5. Welding QA and QC process
The generally accepted definitions of QA, QC and related terms based on ISO 8402 are:

- **Quality.** The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs.

- **Quality assurance.** All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality.

- **Quality control.** The operational techniques and activities that are used to fulfill requirements for quality.

- **Inspection.** Activities such as measuring, examining, testing and gauging one or more characteristics of a product or service and comparing these with specified requirements to determine conformity.

- **Quality surveillance.** The continuing monitoring and verification of the status of procedures, methods, conditions, processes, products and services, and analysis of records in relation to stated references to ensure that specified requirements for quality are being met.

The major participants in a field of welding QA and QC in a welding pre-fabrication trade are shown in Figure 4 (Cook, 1985).

The solid lines indicate reporting and supervision, while the large arrows indicate specific activities. The QA activities are performed by the QA group (see, on the left of Figure 5), and they report directly to top management through a chain of command different from that of the fabrication execution process to assure that it is unbiased and independent. Furthermore, the QA group is also primarily serving as an auditor of fabrication QC activities.

QC is performed by the fabrication organization and the personnel responsible for execution who are supposed to comply with the welding specifications and approved welding procedures to assure all are designed to the intended quality level. The project sponsor’s first level of QC is performed by the welding inspector(s) and the nondestructive
evaluation (NDE) inspector(s) on each spread. The NDE inspectors are assisted by NDE personnel and they oversee the NDE inspectors. The focus of the inspectors, their supervisors, and the spread chief is welding quality, as it relates to spread. However, the director of fabrication is concerned about welding quality on a project-wide basis. Figure 5 shows a QC system that indicates a flow of the key welding activities performed by the welding and NDE inspectors, NDE contractor, and execution personnel (Cook, 1985).
The execution personnel’s welding process is shown on the left of Figure 6. This is the fabrication process on which quality is being controlled. All welding comes under the review of the welding inspector, who visually inspects the welds and accepts or rejects them. Accepted welds are first radio-graphed by NDE personnel, and then the radiographs are interpreted by a qualified radiographic interpreter. Multiple interpretations may be required, as shown in Figure 6 by the dotted box. The interpretations are usually signed by the NDE inspector, which constitutes the final acceptance or rejection of the weld.

The NDE statistics are carefully analyzed by the NDE inspector to determine whether trends or patterns are developing that show that the welding quality is deteriorating or is below the specified standards. In addition, a careful analysis of the NDE records and other data provides the inspector with information on how well the NDE personnel are doing their job. Their analysis may result in corrective action by the NDE inspector, shown in Figure 6 as the feedback paths entitled “reduce NDE errors” and “reduce welding flaws”. The welding and NDE inspectors report to the spread chief, who must assure that the spread is meeting the quality standards established by the director of fabrication.

**Figure 6.** An algorithm for optimized welder training actions to improve welding quality.
6. Possible errors in a welding QC system
Almost all activities in a fabrication process, including its QC system, are susceptible to error. Hence, welding operations, whether they are manual or automated, produce some welds that are unacceptable in relation to a specified standard (API 1104, 1999). This is further exacerbated by the susceptible error and variations in NDE activities. These types of errors are quite obvious, since even a fully automated fabrication process which is designed to function optimally can always produce a certain number of random errors or variations. The random variations take place from many unrelated causes. There is no possibility to prevent, when the random variations occur by chance (Maul et al., 1996).

6.1 Assignable variations and role of control charts
On the other hand, a fabrication process can also produce non-random or assignable variations. The non-random or assignable variations are comparatively larger or more numerous, whilst they are attributable to non-random and identifiable causes (Maul et al., 1996). For instance, wrong welding parameter settings leading to lack of welder competence or partial machine failure are some of the possible events that can produce assignable variations. Hence, it is vital to design a QC system that can identify and eliminate the assignable variations which are produced by the fabrication process. This enables only chance variations to be left, which is not possible to eliminate completely at the source (i.e. prevented from occurring again) without excessive expense by identifying and correcting the specific problem that is causing them.

In general, almost all the welding and NDE processes or activities are imperfect by their very nature. As a result of that, they always produce a certain number of chance variations or errors (Wessel et al., 1996). Apart from that, the welding and NDE processes also produce some assignable errors when they are not working properly. For instance, some of the assignable errors in welding include: a large number of arc burns, frequently caused by welder carelessness in handling the electrodes; high frequency of gas pockets (porosity), which can be minimized by using the correct amperage and arc length; high incidence of slag inclusion, which may be prevented with better inter-pass grinding; and high frequency of incomplete fusion, which generally stems from excessive welding speed or insufficient attention to proper welding techniques (Kim et al., 2006). Almost all the aforementioned are attributed to lack of welding personnel performance. Hence, it is vital to have a proper welding QC system that can quickly discover and eliminate such assignable errors resulting from lack of welding personnel performance.

The product “perfection” is rarely necessary in the fabrication industry, as it is either impossible or too costly to achieve in most of the cases. Hence, a certain number of imperfect products are tolerated. However, increasingly industries are utilizing techniques of statistical QC to assure that the quality of the output remains above a certain level. In this context, product sampling systems are employed to statistically estimate what the number of imperfect products is likely to be in a particular production run (Woodall and Montgomery, 1999). For instance, control charts or fraction-defective charts are often used to keep a running record of the number of defective items (Wang et al., 2009). These charts will exhibit a central defect level, around which will cluster the values for percentage of defectives in each sample. This level represents the random variations (Maul et al., 1996). A significant divergence from it, in either quantity or kind, probably represents the presence of assignable variations which need to be investigated and corrected. Once these assignable variations are corrected, the process
should yield samples with percentage-defective values that cluster around the central level again (Nelson, 1988). Processes like welding have many different kinds of defects or variations. Consequently, a number of different factors must be inspected to determine whether the product is acceptable. Hence, it may be necessary to maintain separate control charts on each of the different types of factors or defects (Maul et al., 1996). Finally, the random level for total repairs and cutouts are analyzed based on: all control charts for spreads, any historical records on similar projects that may be available, the results of any corrective feedback given to the welders, and the specific types of defects.

In piping component fabrication, it is common to have different kinds of unacceptable imperfections. Thus, maintaining control charts for each major type of defect and for certain welders is often recommended. If the frequency of a particular defect increases, it may often be reduced by a slight adjustment to the welding procedures (Welding Technology Machines, 2011). This is mainly because certain types of unacceptable imperfections are often associated with specific welding tasks or procedures. Therefore, it is essential to have a methodology to gather timely and continuous feedback about welding procedure specifications (WPS) that are prone to significant quality deterioration.

6.2 Random (chance) variations
When the defective level is tolerable, the control charts and statistical samples are sufficient to control a fabrication process. However, it is not possible to employ a statistical sampling technique if the fabrication organization plans to reduce the amount of defects to a level substantially below the random defect rate, unless the process being controlled has no random variations. This is particularly not the case for most of the fabrication processes, including manual piping components welding. For a process that has random errors, quality sampling and probability theory will only allow one to estimate, within certain confidence limits, the number of chance or random defects in a population. Therefore, if the goal is to reduce the defects substantially below the random defect rate or to eliminate almost all defects, it is essential to inspect virtually every item produced by the process (i.e. 100 percent inspection). For instance, 100 percent inspection is carried out in pipeline or piping components welding by means of the radio-graphing (or any other appropriate NDE method) of all welds and the interpretation of all radiographs.

However, an additional complexity arises, when the inspection process itself is prone to errors or variations. Many inspection processes, such as radiography and the interpretation of radiographs, are susceptible to errors of their own. As a result, the inspection processes will not identify all the unacceptable welding imperfections (i.e. defects or unacceptable welds) produced by the welding fabrication process, even when 100 percent inspections are carried out. Thus, the inspection process (e.g. radiography and interpretation) should be controlled just like the welding process to reduce errors to their random levels. In order to properly control the inspection process, it is vital to follow steps such as: maintaining control charts on radiograph quality and interpretation errors, comparison with data from other spreads and other projects, and timely and continuous feedback to the NDE personnel on the results.

The effect of all of these errors or variations (which exist to some extent even when the QC process is working optimally) is that a certain number of welds containing flaws that are unacceptable under a specified standard will be placed in service. Hence, it is vital to
reduce the welding errors by providing proper training to welding personnel via recognizing the factors that lead to significant welding quality deterioration.

7. An algorithm for welder performance improvement

It is not worthwhile to mitigate all the quality deterioration factors at once to improve the welding quality. Instead, it is important to select an optimum number of quality deterioration factors that can lead to significant quality improvements. The case study company records welding fabrication data in the WIDB. For instance, data such as the batch number of a metal delivered from a foundry to final assembly are recorded in WIDB. Hence, using these data, it is possible to identify the WPSs that are prone to significant quality deterioration and corresponding imperfection groups as specified in NS-EN ISO 6520-1 (1998). After that the factors pertaining to imperfections are identified.

The level of quality in welding is assessed in terms of: number of welds performed using a certain \( W_{WPS} \), number of defective welds produced as result of a certain WPS \( d_{WPS} \), number of imperfection groups \( I_{G} \) (as specified in NS-EN ISO 6520-1 (1998)) resulting from a WPS, total defective welds produced by all WPSs \( N \), factors pertaining to defective welds \( FPDW \), etc.:

\[
\text{Level of quality in welding} = f(W_{WPS}, d_{WPS}, I_{G}, N, FPDW, \text{ etc.})
\]

Hence, the algorithm shown in Figure 6 is used to determine the most important quality deterioration factors which would enable optimized welder training actions to be provided to assure the welding quality.

7.1 Mathematical formulations to implement the algorithm

The most vulnerable WPSs that result in a higher percentage of welding quality deterioration are calculated and prioritized using formulas (1) and (2):

1. The percentage of defective welds (PDW) produced by \( i \)th WPS is calculated using the following equation:

\[
PDW_{WPS_i} = \sum_{j=1}^{k} \left( \frac{d_{WPS_j}}{N} \right) \times 100
\]

where:

\( PDW_{WPS_i} \) = percentage of defective welds attributed to \( i \)th WPS w.r.t. total number of welds produced in a year.

\( d_{WPS_j} \) = number of defective welds produced by a WPS during \( j \)th welding project.

\( N \) = total number of welds produced in a year.

\( j = 1, 2, 3, \ldots k \).

2. Arrange the calculated percentages of defective welds corresponding to each WPS in descending order. Then calculate the cumulative percentage of defective welds at \( i \)th WPS:
\[ CPD_{WPS_n} = \sum_{i=1}^{n} PDW_{WPS_i} \]  

where:

\[ CPD_{WPS_n} = \text{cumulative percentage of defective welds at } n\text{th WPS.} \]

\[ PDW_{WPS_i} = \text{percentage of defective welds attributed to } i\text{th WPS w.r.t. total number of welds produced in a year.} \]

(3) Plot both calculated values in Steps (1) and (2) vs the WPS number in a single diagram. With the help of the cumulative percentage of defective distribution, the WPSs that are mostly affect overall quality deterioration are determined. These WPSs are designated as significant welding procedure specifications (SWPSs).

Depending on the target quality level, the cutoff point for the number of the most vulnerable WPSs can be found. Once the most vulnerable WPSs are found, equations (3) and (4) are used to calculate and prioritize the imperfection group (i.e. as specified in the quality standard NS-EN ISO 6520-1 (1998)) that attributes significant quality deterioration in relation to each SWPS:

(1) The percentage of defective welds in an SWPS due to \( i \)th IG is calculated using the following equation:

\[ PDW_{IG}^{SWPS} = \frac{\sum_{j=1}^{n} (d_{IG})_j}{N_{SWPS}} \times 100 \]

where:

\[ PDW_{IG}^{SWPS} = \text{percentage of defective welds produced by an IG in the selected SWPS.} \]

\[ (d_{IG})_j = \text{number of defective welds produced by } i\text{th IG during } j\text{th welding project carried out by using the selected SWPS.} \]

\[ N_{SWPS} = \text{total number of welds carried out using the selected SWPS.} \]

(2) Arrange the calculated percentages of defective welds relative to each SWPS in descending order. Then calculate the cumulative percentage of defective welds at \( k \)th imperfection group:

\[ CPIG_{SWPS}^{IG_k} = \sum_{i=1}^{k} \left( PDW_{IG}^{SWPS} \right)_i \]

where:

\[ IG_k = k\text{th imperfection group (as specified in the NS-EN ISO 6520-1) in the selected SWPS.} \]

\[ CPIG_{SWPS}^{IG_k} = \text{cumulative percentage of } PDW_{IG}^{SWPS} \text{ at } IG_k. \]

(3) Plot the calculated values in Step (1), Step (2) and the imperfection group in a single diagram. With the help of the cumulative percentage distribution, each individual imperfection that is mostly contributable to quality deterioration can
be determined. The percentages of imperfections are calculated with respect to total number of welds produced by using $i$th most vulnerable WPS. Hence, the final result helps to determine the most critical imperfection groups that are highly attributable to the quality deterioration link to selected SWPS.

When the IGs that are attributed to higher quality deterioration (in the selected SWPS) are found, formulas (5) and (6) are used to calculate and prioritize the factors that are attributed to significant quality deterioration of the selected SWPS:

1. The percentage of defective welds due to $i$th factor ($F_i$) in a selected SWPS is calculated using the following equation:

   \[
   PDW_{SWPS}^{F_i} = \frac{\sum_{j=1}^{k} (d_{F_i})_j}{N_{SWPS}} \times 100
   \]

   where:
   - $PDW_{SWPS}^{F_i}$ = percentage of defective welds that are attributed to a particular factor in a selected SWPS.
   - $(d_{F_i})_j$ = number of defective welds produced by $i$th factor during $j$th welding project carried out by using the selected SWPS.
   - $N_{SWPS}$ = total number of welds carried out using a selected SWPS.

2. Arrange the calculated percentages of defective welds relative to each WPS in descending order. Then calculate the cumulative percentage of defective welds at $n$th imperfection group:

   \[
   CPDW_{SWPS}^{F_n} = \sum_{i=1}^{n} \left( PDW_{SWPS}^{F_i} \right)_i
   \]

   where:
   - $F_n$ = $n$th factor that are attributed to quality deterioration in the selected SWPS.
   - $CPDW_{SWPS}^{F_n}$ = cumulative $PDW_{SWPS}^{F_i}$ at $F_n$ that attributes to quality deterioration.

3. Plot the calculated values in Step (1), Step (2) and factors (that are attributed to quality deterioration) in a single diagram. With the help of the cumulative percentage distribution, each individual factor that is mostly contributable to quality deterioration can be determined. The percentages of defects are calculated with respect to total number of welds carried out using the selected SWPS. Hence, the final result helps to determine the most critical factors that are highly attributable to the quality deterioration link to selected SWPS.

7.2 Holistic approach for welding QC

Figure 7 shows a holistic approach to welding QC. The approach consists of four steps:

1. identification of WPSs prone to quality deterioration;
2. identification of quality deterioration factors;
(3) welding performance improvement (internal); and
(4) welding performance improvement (external).

The first component, identification of WPSs that are prone to quality deterioration
(Step 1: Figure 7) is carried out by analyzing data available in the welding fabrication
databases of a particular construction firm. This is carried out by using formulas (1) and
(2). Similar analysis can be performed to identify the corresponding quality deterioration
factors (Step 2: Figure 7) pertaining to each of the WPSs that are significantly prone to
annual quality deterioration. After that, welder performance improvement trainings can
be organized according to the factors discovered in Step 2: Figure 7. Basically, the internal
welding performance improvement is carried out by providing training, performance
management, coaching, special projects, job design, career development, etc. External
performance improvement (Step 4: Figure 7) is essentially recruitment and selection,
where the organization goes out into the labor market to identify, attract, select and
motivate the required skilled welders to join the organization. However, by performing
Steps 2 and 3, the welding fabrication organization can improve the engagement,
motivation and retention of potential skilled welders by providing appropriate training.

8. Implementation of the algorithm via a case study
Using the WIDB, the analysis has been carried out (for all projects) for the period from
2008 to 2010 based on the registered defective welds. The analysis of the weld data
exported from the WIDB has been performed individually for different projects.
However, the WIDB has data for several years and the exported data comprised of
welds performed other than during the periods of interest. Also, depending on the type
of information registered for each of the projects, the exported data have different
columns of information. Therefore, data cleaning has been preformed as follows:

- reorganizing the exported data from each project to enable one single table of
data;
- verification of date for all records;
removing records with dates other than during the period of interest; and
- removing possible duplicates.

Furthermore, cleaning has been performed by means of various filtration criteria on the different columns of information. This is mainly due to the fact that the data in different columns did not represent the same date. However, based on the NDT record date in the different columns of the exported data from WIDB, the test date of each weld is determined.

Moreover, during the cleaning process, some records with no testing date were identified. It is calculated that they contribute only 0.36 percent of the whole dataset. Hence, records with no testing date were disregarded. With the help of a pivot table, all the WPSs were counted with the status “not ok” based on the NDT records and then summed up into a single table. Imperfection group and identified factors were connected to each test record alongside WPS number.

Step 1: determine “N” number of SWPSs that cause a higher percentage of welding quality deterioration (cutoff point is determined according to the company QC philosophy).

The WPSs are analyzed over three years: 2008-2010. The results of the analysis (using equations (1) and (2)) are shown in Figures 8, 9 and 10, respectively (Ratnayake and Vik, 2012).

Figure 8. WPS vs percentage and cumulative percentage welding defects in 2008

Figure 9. WPS vs percentage and cumulative percentage defects in 2009
The general observation about 2008 data is that only eight WPSs out of 22 are attributed to 80 percent of defects.

The general observation about 2009 data is that only five WPSs out of 22 are attributed to 80 percent defects. The percentage of defects in 2009 and 2010 indicate quite similar behavior.

The general observation is that only six WPSs out of 22 are attributed to 80 percent of defects. For instance, the WPSs P150-05, P250-05, P410-05, etc. are SWPSs during all three years.

Step 2: select a WPS from “Step 1” and determine “n” imperfection groups (i.e. the NS-EN ISO 6520-1 (1998) classifies imperfections into six main groups) that cause higher percentages of welding quality deterioration.

Among the SWPSs, P150-05 has been selected in order to illustrate the implementation of the algorithm Step 2. Figure 11(a)-(c) shows the percentage of defects attributed to P150-05 during 2008-2010. Figure 11(d) shows the average of these over the three years (Ratnayake and Vik, 2012).

The results of the analysis (using the equations (3) and (4)) are shown in Figure 12 (Ratnayake and Vik, 2012).

The analysis indicates that (Figure 12) imperfect shape and dimension (500), cavities (200), and lack of fusion and penetration (400) are the most common types of imperfections. These are all workmanship defects (Burgess, 1989), revealing that welders have to be re-trained and re-qualified. The general observation is that only three IGs out of six are attributed to 99 percent of defects linked to WPS P150-05. Similar analysis should be performed for other identified SWPSs.

Step 3: select an imperfection group from “Step 2” and determine the factors that are prone to highest imperfection varieties.

Among the significant imperfection groups in P150-05, the imperfection group 500 (i.e. imperfect shape and dimension) has been selected in order to illustrate the implementation of algorithm Step 3. The results of the analysis (using equations (5) and (6)) are shown in Figure 13.

The general observation is that only about seven factors out of 22 are attributed to significant quality deterioration. These factors provide feedback to the management of the fabrication organization to re-evaluate and improve welder performance.
Similar analysis can be performed for all the IGs that are attributed to significant quality deterioration. Carrying out such analysis, it is possible to recognize the factors that are most frequently present and generate different kinds of imperfection groups. For instance, “many fabricators retest welders unnecessarily. Also, it can be very
difficult to identify the welders whose qualifications are close to expiring” (Brightmore and Bernasek, 2000). Hence, the analysis proposed in the manuscript provides an overview about the factors that are attributed to significant quality deterioration. Alternatively, it provides feedback about the right time and areas in which the welding personnel need to be re-qualified or trained.

9. Conclusion

A welding fabrication process can produce non-random or assignable variations. Generally, the non-random or assignable variations are comparatively larger or more numerous, whilst they are attributable to non-random and identifiable factors. This study illustrates a methodology to recognize the non-random and identifiable factors that are attributed to significant quality deterioration. Moreover, it is not possible to prevent a certain number of welds containing unacceptable imperfections in relation to a particular standard being placed in service as a result of errors and variations present in QC systems and inspection methods. This challenge can be mitigated by providing appropriate training to welders by identifying the main quality deterioration factors attributed to welder performance. The algorithm suggested in the manuscript supports to the identification of the aforementioned. Alternatively, this viewpoint enables “to build quality into the fabrication process not for inspection”.

Also, the methodology assists in recognizing WPSs that are attributed to significant quality deterioration. Once they are identified, the frequency of quality deterioration can be reduced by making slight adjustments to the corresponding welding procedures or requalification of WPSs. This is very useful as certain types of unacceptable imperfections are often associated with specific welding tasks or procedures.

Apart from that, although computers have always been good at storing, sorting and searching through large amounts of data, and making them suitable for pure database applications, it is a challenge to build all the welding expertise into a single
piece of software. This is due to the fact that it is necessary to have a deep understanding of both software development and computerized technology. In the steel fabrication industry, the required expertise includes: metallurgy, engineering, production, QC, and procedures and standards fabrication organization specific to a fabrication organization. Hence, the algorithm presented in this study shall be utilized when the efforts have been made to develop such software.

In addition, further research should be carried out to perform analysis over a number of WPS together with analysis at corresponding imperfection subgroups level. This would enable the development of a comprehensive database to recognize the factors that can be taken into consideration to improve the performance of welding personnel and WPSs.

References


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