Feasibility of using Earth-bounded NDT techniques for the space environment

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ABSTRACT: In this paper we review non-destructive testing (NDT) techniques with potential use for welding inspection in the space environment. In our comparison of NDT techniques we include fields that have not considered previously: materials to be welded and type of welding to be used.

1 INTRODUCTION

Space structures are very complicated structures that were put in space by man. One of the requirements of these structures is to have a sufficient life to provide economical exposure time in the space environment. Unfortunately space structures are not only complicated but in most cases they cannot be shut down for repair; their maintenance and repair has to be done while working. That is one of the main reasons that preventive maintenance is crucial.

For a weld to have the required reliability throughout its life, it must have a sufficient level of quality or fitness for purpose. On Earth, weld quality is often governed by codes, specifications, or regulations based on rational assessment of both economics and safety. Most of the above is experiential. In the space environment, the quality requirements are especially strict; therefore, welds that might be considered adequate on Earth might not be adequate for space. Previous work done on non-destructive testing (NDT) techniques [1-6] for the space environment involves mostly an evaluation of NDT as a monitoring process of the space structures rather than the welds. The reason is simple: welding has not yet been used as a fabrication process in space. For example, in the International Space Station (ISS), only mechanical joints will be used for the erection. Welding is not considered for the assembly, even though it could save considerable weight.

The advantages of welding as a joining process over mechanical joints are well known. It is only a matter of time before welding will be used for fabrication in space as mankind evolves to its destiny in the habitation of extra-terrestrial places. Russians have already experimented with welding techniques in space, and there is already an on going project in NASA that is dealing with using electron beam welding (EBW) as the technique to bring space fabrication to the next level.

This paper deals with the analysis of Earth-bounded NDT techniques and how they can be applied in the space environment. An analysis of the space environment and its unique characteristics is given, and an original qualitative analysis of the current NDT processes is done in order to examine the possibility of use in space. Later a similar analysis is performed dealing with the possible welding techniques to be used for welded maintenance and repair in space.

2 THE EFFECT OF SPACE ENVIRONMENT ON NDT METHODS

Nondestructive testing as well as any other activity in space faces all the peculiarities of the environment in space. The most important features of the space environment that make it unique are: a) zero gravity, b) vacuum, c) radiation, and d) composition of the residual atmosphere. All the above factors have to be accounted in order to select an Earth-bounded NDT process for use in the space environment.

2.1 *Zero gravity*

Strictly speaking, in space there are never zero gravity conditions (the condition under which the forces acting on an object are zero). It is better to use the term micro-gravity characterizing the condition under which the sum of the forces acting on a body is considerably smaller than on the Earth's surface. This state is usually evaluated by the value of the ratio of acceleration given to the body by the acting force (g) in relation to the force of gravitational attraction on the Earth's surface (g_0). For objects freely flying in space, the value of this ratio is of the order of 10^{-5} to 10^{-7} [7].Under micro-gravity conditions, a lot of the physical processes in liquid and gaseous media related to density, convection, and surface tension change greatly.

2.2 *Space vacuum*

The mean pressure in the height range of 250-500 km is $5x10^{-4}$ Pa (~$5x10^{-9}$ Atm) [7]. The unusual features of space vacuum are the composition of the residual atmosphere and the extremely high pumping rate (diffusion rate) of gases generated in it. The pressure of the residual atmosphere surrounding space structures in low orbits is easily achieved on Earth by the use of vacuum chambers. The thing that significantly differs though is the composition of the two "vacuums". The rarefied atmosphere generated in vacuum chambers on Earth differs from the space atmosphere by the absence of atomic oxygen and the low mobility of molecules. In space, the content of atomic and ionized oxygen is very high and may exert a strong effect on joining of materials both during welding and in further service of joints.

Since space is an open infinite volume, the gas molecules generated at the surface of a space system rapidly move into space. Thus, the thickness of the natural residual atmosphere of space systems is very small. In addition local pressure gradients are almost instantaneously equalized. Therefore substances with high vapor pressure rapidly evaporate in space. That is why it is very difficult to use welding or NDT methods requiring gases or liquids with vapor pressure.

2.3 *Space Radiation*

Space radiation refers to the vacuum ultraviolet radiation (VUV) of the Sun, which greatly intensifies the oxidation processes on the irradiated surfaces, as well as the radiation coming from the radiation belts of the Earth.

The VUV as well as the absence of the atmosphere outside the space system are the reasons of another interesting phenomenon in space: the wide temperature variations of the space structures. The illuminated sections of a space structure, when in the Sun section, maybe heated to a temperature of 420 K (150 ^{0}C). On the other hand when the structure is in the shadow section, it may have a temperature of 160 K (-110 ^{0}C). If any part of the structure is oriented for a long period of time in the same direction and is in the shadow for instance, it may have even lower temperature. Any NDT machine has to account for this temperature.

2.4 *Composition of the space environment*

The space environment in Low Earth Orbit (LEO) (any earth orbit up to approximately 1500 Km) consists of neutral atmosphere, atomic oxygen, atomic hydrogen, meteoroids, and space debris. The content of atomic oxygen in space is responsible for the increased corrosion strength of the space environment. Atomic oxygen results from the interaction of solar radiation with oxygen. In space, the content of atomic and ionized oxygen is very high and may exert a strong effect on the service life of the equipment. Atomic oxygen is considered one of the most damaging aspects of the space environment experienced thus far [2].

3 NDT METHODS

3.1 *Visual*

Visual inspection is the easiest and fastest way to inspect a weld and is the most commonly used method on earth. These techniques apply to welds with discontinuities on their surface. Gross surface effects, such as severe undercut or incompletely filled grooves, can lead to immediate rejection of a weld, before any more detailed testing is undertaken. Considering these limitations as well as the necessity for quality welds in the space environment, visual methods should be used, if at all, only as a preliminary examination before the use of a more elaborate method, especially for critical joints.

3.2 *Radiographic*

In this NDT technique, x-rays, or gamma rays are used to in a manner similar to a medical x-ray to detect sub-surface flaws. The changes in density are indicated on a film, or stored digitally. Even though radiographic methods produce radiation hazards, the radiation protection of the space suits and spacecraft walls might provide sufficient protection. This is true at least for the X-ray inspection of thinner sections. This method is very sensitive and portable, and devices are readily available for earth-bound applications.

3.3 Ultrasonic

The Ultrasonic method refers to techniques that use high frequency sound waves, which are transmitted through or reflected from objects and interfaces such as bond lines or cracks between objects. A variation of the ultrasonic technique is the ultrasonic pulse echo using a pulse sound wave and measuring the reflected pulse from various defects and interfaces.

Another variation of the method is the one in which the transducer is not in contact with the material to be inspected (this is called airborne or non-contact technique). Airborne techniques are not suitable for EVA (Extra Vehicular Activity) space applications because of the lack of atmosphere to transmit the vibrations to the workpiece.

Vacuum and large temperature do not permit the use of common liquid couplants. In a NASA study [1] it was found that some space-graded compounds commonly used as lubricants are suitable for long-term use in the space environment as couplants for the ultrasonic methods. Those kinds of couplants are mainly silicone greases, or fluorinated oils.

3.4 Magnetic

Magnetic methods reveal structural defects through the orientation of magnetic particles on the surface of the work piece. There are two types of Earth-bound magnetic methods: wet and dry. Wet methods are difficult to be implemented in space. Perhaps the use of low vapor pressure oils might enable its use. Because of this difficulty, these methods were ruled out of consideration in a NASA study as a possible NDT technique for the space environment. Dry methods should work in space as well as on Earth.

3.5 Penetrant

There is general agreement in the literature that liquid penetrant methods are unsuitable for NDT applications in space. These kinds of methods can only operate down to 10^{-2} torrs (~10^{-5} Atm) [1], far higher pressure than existing in the residual atmosphere of space.. Thus they will not be further considered in this study.

3.6 Electrical (Eddy current)

Eddy current methods are the electromagnetic method where a magnetic coil is used to induce an electric current in a material. Eddy current methods are useful in surface analysis and shallow crack detection, but not as sensitive as ultrasonic or radiation methods for deep cracks.

3.7 Acoustic Emission

Acoustic emission (AE) is a different concept from the pre-mentioned methods in the sense that it is an entirely passive test (no external signal is put into the material to be tested). AE is elastic radiation generated by the rapid release of energy from sources within a material, which increases as the material approaches fracture. The AE has to be detected in real time. The amount of emission produced maybe affected by the background noise. Another important phenomenon, which must be considered in the AE detection, is the Kaiser effect. According to this effect, no new AE occurs when the specimen is re-stressed until the previous maximum stress has been exceeded. Even though AE was one of the top candidates for in space use in a past study [1], taking the above into consideration, and in particular the fact that AE has to be detected as it occurs, it will not be further considered. This technique may apply in health monitoring of a space structure rather than in weld flaw detection.

4 NDT METHODS EVELUATION

In 1985, the NASA and the TRW space technology group published a final report of a nondestructive equipment study [1]. Part of the report was a table summarizing and comparing various NDT methods, mainly qualitatively. Inspired by this approach a similar comparison table (Table 2.) was constructed in this paper attempting to compare the considered NDT techniques more quantitatively than qualitatively. Furthermore, some different areas of comparison, not mentioned in the previous study are considered (materials, and welding techniques used in space). The visual, penetrant and acoustic emission techniques were ruled out based on the considerations mentioned in the previous section.

In Table 2, various performance factors are considered for the four types of NDT methods selected. These factors deal with the ability that each NDT method has to detect a flaw, the materials welded in space, the geometry of the welds, the ease of operation and the user's safety. A brief analysis of each performance factor gives a more detailed understanding of the ability of each NDT process to perform an inspection in the space environment.

4.1 Flaw detection

The ability of each NDT process is examined by presenting actual values of the minimum size of a flaw that can be detected by each process as well as the maximum depth where the process is effective[8, 9]. The depth for the radiographic method is selected so as to have a reasonable big, portable device, in the size of 500kV. In the ultrasonic method the max depth (150mm), in order to scan for the one side of the weld, was used. The magnetic method is most suitable for cracks open to surface, while some large voids slightly in the sub-surface area might be detected. Finally the values for the eddy current method refer to the standard (37%) depth of penetration[8].

4.2 *Materials*

The materials considered are those used for welding in space or have the potential to be used in the future (Aluminum, Titanium, Metal matrix composites, Austenitic stainless steel, and Martensitic stainless steel). The radiographic method can be used in all metals. Ultrasonic inspection of austenitic welds is difficult because of the microstructure. In the cooling process, after welding, large grains with a high degree of orientation may develop in the form of large elongated columnar crystal with a fibre texture. Thus the ultrasonic velocity is different in different directions and the material exhibits much greater scattering effects. If ultrasonic flaw detection to austenitic steel welds is performed the results will be[9]:

a) much higher attenuation, leading to loss of echo pulses;

b) much greater noise due to scattering;

c) large spurious signals due to either grain boundary reflections or to beam bending;

d) changes in the beam shape and beam path direction;

Only ferromagnetic materials could be inspected using the magnetic method, consequently only two of the materials are not ruled out. As far as the eddy current method the only limitation is that it can only inspect conductive materials.

4.3 *Geometry of welds*

An analysis of the weld geometry of the possible welding techniques for welded repair and maintenance in space is performed. The assumptions made were: a) the weld geometry of electron beam and laser beam welding methods in keyhole mode is similar. The weld geometry of defocused electron beam is similar to that of arc welding processes. b) various arc welding processes (gas tungsten arc welding (GTAW), metal arc welding (GMAW), plasma arc welding (PAW), and gas hollow tungsten welding (GHTAW) have also similar weld geometries and c) the geometry of resistance welding (RW) joints made in space is similar to that on earth. The values of the weld width and depth for each process were found using the minimum and maximum values of several welds performed in simulated space environment and cautiously relaxing the limits[10-13]. The actual geometry values for each welding process are summarized in Table 1.

Table 1. Summary of geometry welds values for the various processes.

	Weld pool diameter or width of weld	Penetration
	mm	mm
B	<100	0.001 - 0.1
EBW	1 - 3	0.5 - 50
LBW	1 - 5	0.5 - 20
AW	5 - 15	0.5 - 10
RW	5 - 10	0.1 - 1

4.4 *Ease of operation*

Currently the NDT technology is advanced enough to make equipment portable, light and fairly easy to get familiar with and use. Possible problems might the process of the data after the NDT process is used. Even in cases like that the new techniques allow to transfer the results of the tests (i.e. digital x-rays or ultrasonic spectrums) to the earth based station for further interpretation.

4.5 *Safety*

Of the NDT processes considered, the only one that raises safety considerations is the radiographic method. The inspection of thick sections, especially of steels and titanium-base alloys, might require doses that exceed the protective capabilities of standard space suits. Since X-rays propagate in “line of sight” trajectories, simple protections, such as lead-lined walls might enable safe operation.

The following abbreviations are used in Table 2:

$Comp_1$ (Metal matrix composites),

SS_1 (Austenitic stainless steel)
SS_2 (Martensitic stainless steel),
B (Brazing),
EBW (Electron beam welding, keyhole mode)
LBW (Laser welding),
AW (Defocused electron beam welding and Arc welding, including gas arc welding, metal arc welding, plasma arc welding),
RW (Resistance welding)
Y (Yes)
N (No).

Table 2. Comparative analysis of the NTD techniques considered for use in space.

Methods		Radiographic	Ultrasonic	Magnetic	Eddy current
Flaw Detection	Size	2% of thickness	> 1 - 5mm depending on frequency	> 0.5 mm	> 0.1 mm
	Depth	25mm SS 80mm Al	<500 mm	Surface or near surface cracks.	<13 mm SS <3.5 mm Al
Materials	Al	Y	Y	N	Y
	Ti	Y	Y	N	Y
	$Comp_1$	Y	Y	N	N
	SS_1	Y	N	N	Y
	SS_2	Y	Y	Y	Y
Geometry of welds	B	Y	N	N	N
	EBW	Y	Y	N	Y
	LBW	Y	Y	N	Y
	AW	Y	Y	N	Y
	RW	N	N	N	Y
Ease of operation		Good	Good	Good	Good
Safety		Radiation	None	None	None

5 SUMMARY

Even though welding in space is in its primary stages there will not be long before the need of repairs arises. Moreover the only way to erect big structures in space that will support habitats for a long period of time is by moving from the mechanical joints, currently used for space structure erection, to welds and together the inevitable need of non destructive inspection as a preventive maintenance.

There are earth-bounded NDT processes that could be used in space. Although there is not a single cure-all technique to be used to non-destructively inspect welds or structures in space. Like on Earth, different techniques are superior in some aspects but inferior in others. This could be also seen from the comparative analysis in Table 2. Furthermore no technique could be actually proven reliable, unless it will actually operate in the environment that it is designed for.

Finally more work should be done as far as the comparative analysis is concerned in the aspect of weld defects. Every welding method generates different defects that may not necessarily be inspected from a NDT method. Thus, another important performance factor that should be taken into account is how the defects associated with the various welding processes preclude the use of different NDT methods.

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