Assessment of Advanced Joining Technologies for Metal Pipe in the Construction Industry

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Abstract

Pipe joining is one of the most critical aspects of most industrial projects, but it is regarded as one of the most inefficient processes in the construction industry. The primary objective of this paper is to explore the applicability of advanced joining technology to the use of metal pipe in the construction industry. This paper begins with a review of current practices with respect to metal joining in the construction industry. The current status of pipe joining is examined. Needs for, and benefits of, advanced joining technology are identified, and a tool for evaluating the applicability of various methods to construction is presented. Joining technologies, including mechanical joining, adhesive bonding, welding, and welding automation, are then introduced, and their applicability to the construction industry is assessed by means of this evaluation tool. It is concluded that there is significant benefits for improvement of piping process in the construction industry through the use of advanced joining technologies.

Keywords : Automation, Advanced Technology, Pipe-Joining, Analytical Hierarchy Process

1. Introduction

Virtually every manufactured product contains joints, which are used to assemble similar materials into a more complex shape or product. In the U.S., joining technology as a whole is a $50 billion per year business, and is high tech in general(Kluger, 2000); therefore, research efforts in this industry are intense. In contrast to other industries, however, joining technology in the construction industry has not seen much advancement. In particular, metal-pipe joining is an extremely labor-intensive and costly process. In 1982, the Business Roundtable released its Construction Industry Cost Effectiveness Report, which states that pipe joining is one of the highest-cost and most inefficient elements of major industrial construction projects, and that the task with the greatest potential for technological advancement is pipe welding(Rickard and Tucker, 1982). Despite the fact that this report was issued twenty years ago, the inefficiency of processes used in metal-pipe joining persists. In fact, according to the benchmarking and metrics(BM&M) data published by the Construction Industry Institute(CII) in 2002, the percentage of work that has to be redone in piping processes is much higher than in other types of construction tasks. Besides the need for improved processes, the shortage of skilled labor has also become an issue of deep concern in the construction industry. Because welders are offered lower compensation in construction than in other industries, many competent welders do not even consider going into construction work.

Successful adoption of advanced joining technology for metal pipe could yield notable results, such as (1) significant reductions in both processing time and the need for skilled labor, (2) a decrease in costs associated with the joining process, and (3) improvements in the strengths of joints. In other words, advanced joining technology may have an impact not only on costs and scheduling but also on productivity and maintenance. Although considerable research has been conducted outside of the construction industry in the area of welding, not all of the available technology is being used to its potential(Tucker, 1982). Successful application of advanced joining technology requires a deep understanding of both current joining practice and advanced joining technologies(Eager, 1990).

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The primary objective of this paper is to explore the applicability of advanced joining technology to the use of metal pipe in the construction industry. In support of this objective, this paper investigates current practice in metal-pipe joining in construction as well as utilization of advanced joining technologies in other industries. It is expected that an enhanced understanding of both of these areas would result in a better determination of the potential for application of alternative joining technologies in the construction industry and a more effective implementation of those technologies. Needs for, and benefits of, advanced joining technology are identified, and a tool for evaluating the applicability of various methods to construction is presented. Joining technologies, including mechanical joining, adhesive bonding, welding, and welding automation, are then introduced, and their applicability to the construction industry is assessed by means of this evaluation tool. In addition, recommendations are made in regard to the adoption of advanced joining technology that could serve as a replacement for current practice.

2. Current Joining Processes in the Construction Industry

2.1 Status of Pipe Joining

Piping comprises a large portion of the work done in the construction industry, in terms of both the amount of labor required and the cost of construction(table 1). This is especially true of construction in heavy industry and in the power sector, where piping is the largest single contributing factor of all the different categories of work involved in the construction enterprise(Tucker, 1982).

In spite of its importance, piping is the most inefficient of all major construction areas(Tucker, 1982). According to the BM&M data published by the CII in 2002, the amount of piping work that has to be redone is about 13.3% of the total(table 2), compared to only 6% of the total, on average, for all areas of construction combined(CII, 2002).

Table 1. Profile of Piping Surveyed (Tucker, 1982)

	Building	Light Industry	Heavy Industry	Power
Average Project Cost ($ millions)	25	120	190	470
Average Peak Work Force (person)	300	600	900	1600
Labor Percentage by Craft (%)	9	14	22	18
Avg. Construction Cost Distribution (%)	3.4	11.6	23.9	16.1

Table 2 Percentage of Rework in Piping (CII, 2002)

	Total
Rework (hours/year)	288,480
Total work (hours/year)	2,170,244
Percentage	13.29%

Given its low productivity, piping is the area with the greatest need for technological advancements that would yield improved processes. According to the technology needs assessment by Tucker, piping ranked ahead of all other categories of construction in terms of the need for technology improvements(Tucker, 1982).

Generally, the piping encompasses six different tasks: lifting, joining, aligning, inspecting, transporting of materials, and procurement. Among these tasks, joining is the most important in the overall process of piping. It not only consumes 25% of the cycle time but also requires a greater degree of skill than any of the other five tasks. But most of the problems associated with piping are related to the field of joining(Tucker, 1982).

2.2 Current Method of Metal-Pipe Joining

Stick welding(shielded-metal arc welding) is the most popular method in use in the construction industry. Even though MIG and TIG welding offer better performance than stick welding, it is still dominant because there has been considerable reluctance on the part of welders in the various construction trades to use other methods.

Two of the major reasons for the stick welding process being so inconvenient and costly are the need to utilize heavy equipment and the high degree of skill required. It is not uncommon for welders to have to take an hour or more of their time to break down the heavy equipment before moving it to the place where the next set of welds is to be made. Some of the factors that contribute significantly to the high cost of stick welding stem from the complexity of the welding process itself. There tends to be an unacceptably high degree of variability in the welds that are produced, which results in a frequent need for rework(Tucker, 1982).

3. Estimation of the Cost of Pipe Joining

This research performed the analysis to estimated direct cost of pipe joining in the industrial construction to understand the relative importance of pipe joining. One factor that figures heavily in the analysis is the ratio of pipe-welding costs to the total cost of a construction project. An estimate of this ratio has been made on the basis of the scope of the CII Model Plant project and data, which is a hypothetical installation valued at about $85 million that is to be constructed over a period of 78 weeks and R.S. Means. The data on labor and equipment costs that were incorporated into the analysis were taken from R.S. Means.

The results of the analysis show that the total direct cost of pipe joining for the CII Model Plant project is about $3.47 million. Since the total construction cost of the project is $80 million, the cost of pipe joining makes up more than 4% of the total. Therefore, we conclude that about 4% of the total cost of a typical industrial construction project is associated with pipe joining. Even though the cost of estimation is derived from R.S. Means, cost data for U.S., it would not be irrational to approximate that the proportion of the cost of pipe joining to the total cost of industrial construction project in Korea remained the same.

4. Need for Advanced Pipe-Joining Technology

4.1 Motivation for Advanced Pipe-Joining Technology

There are three major factors that are forcing the construction industry to find alternatives for pipe joining: (1) the shortage of skilled labor, (2) the low productivity of existing joining methods, and (3) the reluctance of skilled laborers to adapt to new joining methods.

4.1.1 Shortage of Skilled Labor

The shortage of skilled welders has become an issue of deep concern in the construction industry. Welders are offered lower compensation in construction than in other industries, so many competent welders do not even consider going into construction work.

4.1.2 Low Productivity of Existing Methods

Because of the low productivity of traditional joining methods in the construction industry, piping is one of the most inefficient aspects of construction work. As mentioned previously, some of the main causes of this low productivity are the variability of the joints produced and the high incidence of a need for rework.

4.1.3 Reluctance of Skilled Laborers to Adapt to New Methods

The reluctance of skilled laborers to adapt to new joining methods is one of the major factors that militate against the willingness of the construction industry to switch to improved joining processes, even when such are available. For instance, the reason why stick welding has remained the dominant welding process is the considerable degree of reluctance on the part of welders in the various construction trades to give other methods a try.

4.2 Benefits/Requirements of Advanced Joining Technology

Successful adoption of advanced joining technology for metal pipe could yield notable results, such as (1) significant reductions in both processing time and the need for skilled labor, (2) a decrease in costs associated with the joining process, and (3) improvements in the strengths of joints(Eager, 1990).

To reap the benefits of new technology, however, certain requirements must be satisfied. The basic characteristics that any viable joining technique with a wide range of applicability must offer include the following: (1) production of strong and reliable joints, (2) suitability for small- and large-area bonding, (3) minimal need for surface preparation, and (4) suitability for use in a production environment(Silverman, 1989). The study by Thompson suggests six factors that are critical to the success of a pipe-joining operation: (1) pressure-temperature ratings, (2) material compatibility, (3) external loading, (4) operability, maintainability, and reliability, (5) long-term effects, and (6) cost(Thompson, 1998).

The following discussion of the impact of using advanced joining technology is broken down into four main categories: (1) structural integrity, (2) management concerns, (3) productivity factors, and (4) maintenance issues.

4.2.1 Structural Integrity

The structural integrity of a joint is determined by its ability to function properly within the overall system(s) of which it is a part. Structural integrity comprises three elements: (1) joint strength, (2) material compatibility, and (3) durability.

Joint strength is a measure of the ability of a joint to sustain internal forces(such as internal pressure) and external forces (including shear forces, torsion, and bending) that are due to factors such as variations in temperature. Material compatibility is the degree to which the individual elements of a joint are able to function as a unit and resist the tendency to corrode one another; this is important, since corrosion can reduce the strength of a pipe joint(Thompson, 1998). Durability is the ability of a joint to retain its strength and serve its intended purpose over an extended period of time.

4.2.2 Management Concerns

Management concerns encompass all the factors that have an impact in terms of cost. Any given type of joining technology that is adopted has the potential to affect not only the direct costs of production, such as labor and equipment, but also indirect costs such as training of the welders. The costs that must be considered by management in choosing a joining technique can be classified as follows: (1) training, (2) materials, (3) equipment, and (4) labor.

4.2.3 Productivity Factors

Productivity factors consist of everything that affects the efficiency of the joining process. Productivity of any joining technique is dependent on the following six properties: (1) processing time, (2) degree of rework, (3) ease of installation, (4) field usability, and (5) extent of surface preparation.

4.2.4 Maintenance Issues

Maintenance issues have to do with the long-term effects of joining technology. The initial cost of producing a pipe joint is only part of its total cost. What needs to be considered are all the costs that accrue over the expected life of the plant, as well as the performance of the joints that are produced. Long-term effects due to erosion, fatigue, and creep, all of which can affect the performance of a pipe joint, may be significant. Maintenance issues can be grouped into two categories: (1) long-term performance reliability and (2) life-cycle cost.

5. Investigation of Joining Technologies

The three predominant reasons for joining materials or parts into assemblies or structures are to achieve function, to achieve structural efficiency, and to minimize costs(Messler, 1993). A number of different joining technologies exist, each with its own set of advantages and disadvantages.

Joining processes are usually divided into four categories: mechanical joining, adhesive bonding, welding and welding automation. A brief discussion and assessment of the applicability of each of the various joining technologies to the joining of pipe are follows.

5.1 Mechanical Joining

In mechanical joining, materials are joined by the use of fasteners (mechanical fasteners) or through an integral design feature (mechanical interlocking; Messler, 1993). The mechanical joining process relies on residual stresses, which ensure the integrity of the joints(Brandon and Kaplan, 1997). These stresses may occur either in the fastening(mechanical fastener) or in the components themselves(mechanical interlocking; Brandon and Kaplan, 1997).

Mechanical joining has several advantages, such as ease of installation and stability of the chemical composition of the materials. Because of significantly concentrated stresses resulting from this approach, however, mechanical joining has limited applicability (Messler, 1993). In general, mechanical joining is uncomplicated and effective, requiring little mechanical skill to install, so it has been effectively applied to pipe joining. Because of the requirement of using thick pipe in this process and the high cost of the materials involved, however, its applicability to pipe joining is limited. In addition, many situations do not readily lend themselves to mechanical joining.

5.2 Adhesive Bonding

In adhesive bonding, the materials are joined with adhesives that hold the materials together by means of surface-attachment attraction forces(Messler 1993). The adhesives are applied at room temperature to the surfaces to be bonded; they harden after curing and treatment such as heating or irradiation(Brandon and Kaplan, 1997). Adhesive bonding is divided into two categories: structural adhesives and non-structural adhesives. In structural adhesive bonding, the adhesives have the capacity to endure strengths very close to the point at which the member collapses. Currently, structural adhesive bonding extends the limits of applicability of metal-to-metal bonding all the way up to those of structural bonding. Non-structural adhesive bonding is widely used in modern automobiles(Messler 1993).

Currently, adhesive bonding is used for many applications, on account of its low cost and convenience of use. In addition, it is of sufficiently high strength that it can be used in the assembly of airplane parts. The low resistance of adhesive-bonding techniques as a function of bending load, however, had been regarded as the most significant obstacle to the use of adhesive bonding(Lea et al., 1998). This limitation has been lessened with technology advances in adhesive bonding. In fact, 3M has developed a high-strength adhesive bonding technique that offers a normal tensile strength of 160 psi and dynamic shear strength of 100 psi.

Adhesive bonding has great potential, and it may become one of the best alternatives to current pipe-joining methods in the near future.

5.3 Welding

According to Messler, welding is defined as a process in which materials of the same type or class are joined together through the formation of primary bonds under the action of heat, pressure, or the combined action of heat and pressure(Messler, 1993). The primary reason why welding has been used so extensively as a joining process is that it offers high integrity of joints, a wide variety of processes and approaches, and considerable opportunities for automation. In spite of its many benefits, however, welding has serious disadvantages, such as high operating costs, a shortage of skilled labor, and lack of controllability of the process itself(Messler, 1993).

Even though there are several classification systems for welding processes, welding is typically classified as either fusion welding or non-fusion welding, depending on whether or not significant melting is involved(Messler, 1993).

5.3.1 Fusion Welding

In fusion welding, the materials to be joined are heated to a temperature that lies above the melting points of both of them. Fusion welding processes include all those in which the melting or fusion of portions of substrates play a significant role in the formation of joining(Messler 1993). Fusion welding includes gas, arc, resistance, and high-energy beam welding; it requires significant melting, and usually produces a joint via the application of heat rather than pressure(Ageorges, et al., 2001).

5.3.1.1 Arc Welding

In general, arc welding techniques have been widely used for pipe joining for decades, and still dominate this area because of their good track record for durability and performance. However, various industries are reluctant to use these methods, because of the requirements for highly skilled labor and the inconsistent quality of the welds, so they are forced to find alternative technologies. Among arc welding methods, stick welding is the most popular joining method in the construction industry, even though it offers low productivity compared to gas-tungsten arc welding(TIG) and gas-metal arc welding(MIG). In spite of the advantage that they have to offer in terms of performance, however, MIG and TIG welding suffer from some of the same problems as stick welding, such as a shortage of highly skilled labor. Another factor that contributes to the relatively low degree of adoption of MIG and TIG welding in the construction industry is the reluctance of welders to switch to new techniques.

5.3.1.2 Gas Welding

The oxyacetylene-gas welding process is simple and highly portable, and the equipment needed for its use is inexpensive. The main drawbacks to its use in pipe joining in the construction industry may be its low productivity and the need for highly skilled labor.

5.3.1.3 High-Energy Beam Welding

High-energy beam welding offers excellent performance, so it is extensively used in joint-fabrication applications that require high accuracy in terms of placement of the weld. Advances made in electron-beam welding, one of the high-energy beam welding techniques, have eliminated the need to work in vacuum, so this method can now be used in the atmosphere. Research on high-energy beam welding is ongoing.

5.3.1.4 Resistance Welding

Resistance welding is a very useful joining technology because of benefits such as short processing time, mechanizability of the process, and high performance. It is widely used in the manufacturing industry for the joining of overlapping sheets or plates.

Flash butt welding, one form of resistance welding, is recognized as a very satisfactory method for fabrication of pipe(Thompson, 1998). It offers good quality and productivity because of its automated, remote-control system. However, it requires large equipment, so its applicability is limited to shop fabrication.

5.3.2 Non-Fusion Welding

Non-fusion welding is defined as a welding process that occurs through plastic deformation by the application of pressure, or a combination of heat and pressure, at a temperature that lies below the melting point of the base material and without the addition of a filler that melts(Messler, 1993). In non-fusion welding, the base metals are heated but not significantly melted, and melting is not directly responsible for the joining process(Messler, 1993). In this regard, non-fusion welding has an advantage over fusion welding, in that the heat-affected zone is kept to a minimum, resulting in negligible alterations in the characteristics of the materials involved. Non-fusion welding is divided into four categories with respect to the source of energy: cold pressure, hot pressure, friction, and diffusion welding (Messler, 1993).

5.3.2.1 Explosion Welding

Explosion welding, one of the hot pressure welding techniques, has been successfully applied to the welding of tubes, either for joining one tube to another or for joining a tube to a tube plate. It has also been used for welding plugs into leaking tubes in order to seal the leaks (Davies, 1993).

5.3.2.2 Friction welding

Friction welding has several advantages, such as ease of use, low cost, and speed of processing. In addition, it can be operated in the field, on account of the simplicity of the process. TWI developed radial friction welding for the specific purpose of welding pipe; this technique overcomes some of the handling problems associated with other types of friction welding. In view of its high cost and the need to use very heavy machinery that has large hydraulic and power requirements, however, radial friction welding has seen relatively little use, as it is best suited to the shop environment.

5.3.2.3 Diffusion welding

Diffusion welding is a very precise joining process, with no fusion zone and no heat zone, so it is an ideal joining technology. However, the high cost of the materials used with this method militates against its applicability(Messler, 1993).

5.3.3 Brazing and Soldering

Brazing and soldering are widely used in the manufacturing industry because of their utility in joining large structures under relatively low-stress conditions and their high potential for automation(Messler, 1993). Because of the low melting point of the filler metal used in these processes and the weakness of the joints produced, brazing and soldering are generally used in low-pressure pipe work.

5.4 Welding Automation

Welding automation is an emerging technology that has already been successfully employed in the manufacturing industry. Benefits such as improvements in productivity and reliability, reductions in labor costs, and elimination of variability in weld quality have been realized through welding automation. In addition, the shortage of skilled welders in the construction industry may force companies to use welding automation in the near future. Despite its high initial cost and its lack of availability under certain circumstances and in certain environments, the advantages of using welding automation in pipe joining will eventually become evident to those in the construction industry.

Orbital arc welding is one of best alternatives to current practice in the construction industry, because it offers highly productivity and the process is simple and portable. Mechanized MIG welding is most suitable for the shop environment than the field environment, because of the heavy equipment that is required for its use.

6. Evaluation of Joining Technologies

This section provides a discussion of an evaluation process that can be used to determine the applicability of each of the various joining technologies and results of evaluations of advanced joining technologies. In earlier sections, factors that have a significant impact on the applicability of those techniques to the joining of pipe were pointed out. The Analytic Hierarchy Process(AHP) is used in order to weight the various factors according to their degree of impact.

6.1 Factor-Weighting Methodology

In section 4, various factors which should be considered in selecting joining technology for piping in the construction industry were identified. Not all of these factors are equally important, however, in terms of their potential impact on the joining of pipe. Certain factors are higher in the hierarchical order than others with respect to their relative importance. Therefore, it is necessary to weight all of the factors relative to one other.

6.1.1 AHP (Analytic Hierarchy Process)

The Analytic Hierarchy Process(AHP) is a powerful and flexible decision-making process for establishing priorities among quantitative and qualitative sets of criteria by using data and the user's knowledge or experience as input(Saaty, 1990). The process has been formalized by Saaty and used in a wide variety of problem areas. The AHP process involves the structuring of a problem according to a primary objective and then proceeding to secondary levels of objectives. Once the hierarchies have been established, comparison matrices are constructed(Saaty et al., 1983).

6.1.2 Factor-Weighting Process

By the use of AHP, a weighting of the major factors that contribute to decisions regarding the use of various advanced joining technologies is derived. Experts of joining technology in the construction industry from Breakthrough Strategy Committee (BTSC) of the Construction Industry Institute(CII) had participated in factor-weighting process. Those participated factor weighting process consisted of 12 persons who have over 20 years industrial experience in the construction industry, 2 persons from academia and 2 persons from NIST(National Institute of Standards and Technology). The detail description of the AHP weighting process is given in the CII publication entitled "New Joining Technology for Metal Pipe in the Construction Industry."(Kim and Haas, 2003)

6.2 Finalizing the Weighting Process

Once the factor-weighting process is completed, the weight for each factor is finalized by multiplying its weight by the weight for its category. For instance, if the weight for the structure category is 0.18 and the initial weight for joint strength is 0.61, then the final weight for joint strength is (0.18)(0.61) = 0.110. The completed score sheet for pipe joining overall is given in Table 3. The factors with the highest weights may be regarded as the most important factors in making decisions about the use of advanced joining technology. The table shows that the most important factors turn out to be labor cost, joint strength, equipment cost, field usability and rework reduction.

Table 3. Pipe Joining Score Sheet

Category	Weight	Subcategory	Weight	Final Weight
Structure Integrity	0.18	Joint Strength	0.61	0.110
		Material Compatibility	0.27	0.049
		Durability	0.12	0.022
Management Concern	0.4	Training Cost	0.07	0.028
		Labor Cost	0.52	0.208
		Equipment Cost	0.27	0.108
		Material Cost	0.14	0.056
Productivity Factor	0.32	Processing Time	0.14	0.072
		Rework Reduction	0.24	0.102
		Field Usability	0.40	0.102
		Ease of Installation	0.13	0.022
		Surface Preparation	0.08	0.035
Maintenance Issue	0.1	Performance Reliability	0.67	0.067
		Life-Cycle Cost	0.33	0.033

6.3 Evaluation Model

An evaluation model is established, on the basis of the weights of the various factors in the table just constructed (Table 4). First, each factor is divided into three categories-high, medium, and low-and then the various joining technologies are classified on the basis of their impacts on that factor. Once the different joining technologies are assessed relative to each factor, a weighted score is computed for each, and the joining technology with the highest total score is the one of greatest applicability.

6.4 Evaluation of Advanced Joining Technologies

The applicability of each of the various joining technologies to the joining of pipe has been determined by BTSC members of CII. According to the results of this evaluation, the processes that are of greatest applicability to pipe joining are orbital arc welding and adhesive bonding while traditional process, stick welding, is of the lowest applicability to pipe joining(Table 5).

7. Conclusion

Pipe joining is one of the most critical aspects of most industrial projects, but it is regarded as one of the most inefficient processes in the construction industry. This report identified several of the underlying causes of inefficiency in pipe-joining processes currently in use in the construction industry: (1) the shortage of skilled labor, (2) the low productivity of joining processes currently in use, and (3) the reluctance on the part of welders to switch to newer technology. Also discussed in this report is the general agreement within the construction industry of the need for identifying breakthrough methods that would improve the pipe-joining process.

This paper covered several advanced joining technologies including (1) mechanical joining, (2) adhesive bonding, (3) welding, and (4) welding automation that, to varying degrees, have the potential to supplant conventional methods. As a result of evaluation, advanced technologies which hold the most promise are adhesive-bonding technology to improve metal pipe joining practice and exploiting the benefits of orbital welding technology.

It is concluded that advanced joining technologies exist and that their eventual impact on pipe joining in the construction industry is evident.

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Table 4. Evaluation Model for Pipe Joining

Category	Weight	Subcategory	Weight	Final Weight	Level of Impact	Weight	Weighted Score
Structure Integrity	0.18	Joint Strength	0.61	0.110	High	1	0.110
					Medium	0.7	0.077
					Low	0.3	0.033
		Material Compatibility	0.27	0.049	High	1	0.049
					Medium	0.7	0.034
					Low	0.3	0.015
		Durability	0.12	0.022	High	1	0.022
					Medium	0.7	0.015
					Low	0.3	0.006
Manage -ment Concern	0.4	Training Cost	0.07	0.028	High	1	0.028
					Medium	0.7	0.020
					Low	0.3	0.008
		Labor Cost	0.52	0.208	High	1	0.208
					Medium	0.7	0.146
					Low	0.3	0.062
		Equipment Cost	0.27	0.108	High	1	0.108
					Medium	0.7	0.076
					Low	0.3	0.032
		Material Cost	0.14	0.056	High	1	0.056
					Medium	0.7	0.039
					Low	0.3	0.017
Product - ivity Factor	0.32	Processing Time	0.14	0.056	High	1	0.056
					Medium	0.7	0.039
					Low	0.3	0.017
		Rework Reduction	0.24	0.077	High	1	0.077
					Medium	0.7	0.054
					Low	0.3	0.023
		Field Usability	0.4	0.128	High	1	0.128
					Medium	0.7	0.090
					Low	0.3	0.038
		Ease of Installation	0.13	0.042	High	1	0.042
					Medium	0.7	0.029
					Low	0.3	0.012
		Surface Preparation	0.08	0.026	High	1	0.026
					Medium	0.7	0.018
					Low	0.3	0.008
Mainten -ance Issue	0.1	Performance Reliability	0.67	0.067	High	1	0.067
					Medium	0.7	0.047
					Low	0.3	0.020
		Life-Cycle Cost	0.33	0.033	High	1	0.033
					Medium	0.7	0.023
					Low	0.3	0.010

Table 5. Assessment of Advanced Joining Technologies

Major Category	Sub-category	Mechanical Joining		Adhesive Bonding	Fusion Welding						Non-fusion Welding			Brazing and Soldering	Welding Automation	
		Mechanical Joining	Mechanical Interlocking		TIG	Stick	MIG	Oxy Gas	Electron Beam	Flash Butt	Explosion	Friction	Diffusion		Orbital Arc	Mechanized MIG
Structure Integrity	Joint Strength	0.077 (Med)	0.077 (Med)	0.077 (Med)	0.11 (High)	0.11 (High)	0.11 (High)	0.11 (High)	0.11 (High)	0.11 (High)	0.11 (High)	0.11 (High)	0.11 (High)	0.033 (Low)	0.11 (High)	0.11 (High)
	Material Compatibility	0.034 (Med)	0.034 (Med)	0.049 (High)	0.049 (High)	0.049 (High)	0.049 (High)	0.049 (High)	0.049 (High)	0.049 (High)	0.049 (High)	0.049 (High)	0.049 (High)	0.034 (Med)	0.049 (High)	0.049 (High)
	Durability	0.015 (Med)	0.015 (Med)	0.015 (Med)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)	0.022 (High)
Management Concern	Training Cost	0.028 (High)	0.028 (High)	0.028 (High)	0.008 (Low)	0.008 (Low)	0.008 (Low)	0.008 (Low)	0.028 (High)	0.028 (High)	0.02 (Med)	0.02 (Med)	0.02 (Med)	0.02 (Med)	0.02 (Med)	0.02 (Med)
	Labor Cost	0.208 (High)	0.208 (High)	0.208 (High)	0.062 (Low)	0.062 (Low)	0.062 (Low)	0.062 (Low)	0.208 (High)	0.208 (High)	0.146 (Med)	0.146 (Med)	0.146 (Med)	0.146 (Med)	0.208 (High)	0.208 (High)
	Equipment Cost	0.108 (High)	0.108 (High)	0.108 (High)	0.032 (Low)	0.032 (Low)	0.032 (Low)	0.032 (Low)	0.032 (Low)	0.032 (Low)	0.032 (Low)	0.032 (Low)	0.032 (Low)	0.076 (Med)	0.032 (Low)	0.032 (Low)
	Material Cost	0.017 (Low)	0.017 (Low)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)	0.039 (Med)
Productivity Factor	Processing Time	0.056 (High)	0.056 (High)	0.056 (High)	0.039 (Med)	0.017 (Low)	0.039 (Med)	0.017 (Low)	0.056 (High)	0.056 (High)	0.056 (High)	0.056 (High)	0.056 (High)	0.039 (Med)	0.056 (High)	0.056 (High)
	Rework	0.054 (Med)	0.054 (Med)	0.077 (High)	0.054 (Med)	0.023 (Low)	0.054 (Med)	0.031 (Low)	0.077 (High)	0.077 (High)	0.077 (High)	0.077 (High)	0.077 (High)	0.054 (Med)	0.077 (High)	0.077 (High)
	Field Usability	0.128 (High)	0.128 (High)	0.128 (High)	0.128 (High)	0.128 (High)	0.128 (High)	0.128 (High)	0.038 (Low)	0.038 (Low)	0.038 (Low)	0.090 (Med)	0.038 (Low)	0.09 (Med)	0.09 (Med)	0.038 (Med)
	Ease of Installation	0.029 (Med)	0.029 (Med)	0.042 (High)	0.012 (Low)	0.012 (Low)	0.012 (Low)	0.012 (Low)	0.029 (Med)	0.029 (Med)	0.012 (Low)	0.029 (Med)	0.012 (Low)	0.029 (Med)	0.042 (High)	0.042 (High)
	Surface Preparation	0.026 (High)	0.026 (High)	0.008 (Low)	0.026 (High)	0.026 (High)	0.026 (High)	0.026 (High)	0.026 (High)	0.026 (High)	0.008 (Low)	0.018 (Med)	0.008 (Low)	0.026 (High)	0.026 (High)	0.026 (High)
Maintenance Issue	Performance Reliability	0.047 (Med)	0.047 (Med)	0.047 (Med)	0.047 (Med)	0.047 (Med)	0.047 (Med)	0.047 (Med)	0.067 (High)	0.067 (High)	0.067 (High)	0.067 (High)	0.067 (High)	0.067 (High)	0.067 (High)	0.067 (High)
	Life-Cycle Cost	0.023 (Med)	0.023 (Med)	0.033 (High)	0.01 (Low)	0.01 (Low)	0.01 (Low)	0.01 (Low)	0.023 (Med)	0.023 (Med)	0.023 (Med)	0.023 (Med)	0.023 (Med)	0.023 (Med)	0.033 (High)	0.033 (High)
Total Score		0.85	0.85	0.915	0.638	0.593	0.638	0.593	0.804	0.804	0.679	0.805	0.679	0.698	0.915	0.819