AN INTELLIGENT PROCESS PLANNING GENERATOR FOR ROTATING-TUBES TIG WELDING

M.G. Abou-Ali and A.B. Khairy
Production Engineering Department, Faculty of Engineering,
Alexandria University, Alexandria, Egypt.

ABSTRACT

This paper investigates the development of an expert system for automated Tungsten Inert Gas (TIG)welding as applied to rotating tubes configuration. The system was developed using an Object-Oriented expert system shell and designed to work either as a stand-alone or to be interfaced with a Computer Aided Design (CAD) setup, before conducting the actual welding task. The system so developed is fast responding and capable of producing comprehensive TIG welding procedures. The procedures developed through the system are found to be very comparable to those produced by the traditional "from the book" approach. The system was shown to provide optimum choices for the welding parameters that were consistently and precautionary cited through the consultation session with its knowledge base and inference engine structure.

Keywords: Expert systems, Process planning, TIG welding.

1. INTRODUCTION

Mechanized arc welding processes such as TIG (tungsten inert gas) and MIG (metal inert gas) are being increasingly used in fabrication. Joining of tubes by the TIG welding process is a particularly preferred process in situations where high quality welds are required such as in the root runs of tube welds for high pressure steam lines and chemical plants. This has stemmed from a requirement to obtain a more consistent weld quality in terms of both joint integrity and uniformity of weld surface and profile. The TIG welding process allows precise control over the weld penetration to produce a smooth internal bead profile, with no cleanup or weld spatter. It is almost applicable for all materials and welding positions.

The rotating tube TIG welding process operates by means of the welding equipment being fixed at the 12 o'clock position while the tube-to-tube joint preparation is rotated underneath. Figure (1) demonstrates the process setup. These tubes are normally used in the fabrication of boilers and superheaters for fossil fuel-fired power stations.

In the context of tubes welding many conflicting choices have to be made for the welding variables to suit a certain tube material. Steel alloys, for instance, as the most commonly utilized materials in welded structures, are varying significantly in chemical composition and mechanical properties. Hence, many precautions should be considered when a welding procedure is prepared for such a material or any other material that is candidate for TIG welding.

The use of conventional and intelligent computer software in welding technology has increased over the last decade. Indeed, the conventional computer systems which have been developed to support the welding engineers in their decision making cover many domains of welding practice such as costing and selling [1], preheat calculation [2], storage of welding procedures [3] and data storage and data retrieval [4]. These programs were built using either conventional computer programming such as Basic and Fortran or general purpose packages such as database and spread sheet. On the other hand, expert systems which represent the horizon of intelligent computer implication to industry have been developed in the past few years to include many welding applications. These applications may be categorized as follows: procedure generators, process selection, consumables and equipment selectors, risk evaluation, equipment/process diagnostics and defect assessment [5-13]. Examples of the expert systems presently available for various welding techniques can be found elsewhere [5]. Further, several systems are currently being developed in the European Eureka Project [6], for in-house use or as commercial products.

In welding, the process plan of generating a welding procedure is lengthy and may include the selection of, among other variables, welding process, filler material and consumables, the preheat and interpass temperatures, post weld heat treatment and the number of weld runs. A qualified welding procedure contains all the process information necessary to produce a sound weld compatible with design and/or client requirements. Basically, it consists of two elements: a written explanation of the welding process conditions with a sketch of the joint design showing the details of individual passes (welding procedure specification report) and a record of test results certified by an appropriate agency. When a qualified welding procedure is generated by the traditional manual approach two types of situations may arise: the welding procedure to be generated is similar to one produced before (variant process planning), or the welding procedure is required for a completely new design or material (generative process planning). The generative approach to welding procedures draws heavily upon the experience of welding specialists to develop new process plans.

The formulation of an optimum welding procedure requires inputs of several different types of experts' knowledge and it may differ from one job to another. Moreover, the initial values of the welding conditions listed in the welding procedure are determined by welding specialists from their past experience. To some extent these values are approximate, and only by producing a number of welded samples, by trial and error, these values can be re-adjusted and eventually the optimum values determined. The development of an expert system that can integrate and contain such diversified welding knowledge and make it easily and fast accessible through computers seems to be very attractive particularly in TIG welding applications.

The process of generating welding procedures in which both heuristic and numerical algorithms are involved is found to draw heavily upon the experience of the welding specialists. The development of an expert system for optimum TIG welding necessitates the incorporation of human expertise together with relevant data and information available from Standard Codes. This involves investigating the domain of TIG welding applications and building a knowledge base system to generate welding procedures. Because of the diversity of welding tasks and the amount of knowledge and information required in the generation of welding procedures it was necessary to limit the knowledge base to cover the welding of rotating tubes with special reference to the material types and sizes as contained in the B.S. 3059: Part 2: 1990 [14].

The aim of this investigation is twofold. Firstly is to create a system that is capable of automating the process of generating welding procedures and hence contribute to the automated process planning. Secondly is to create a system that compensates for the lack of knowledge and assists welding specialists at the manufacturing stage to obtain the optimum welding conditions and in turn, lead to higher quality weldments.

Since the goal of this work is to create a knowledge based system capable of generating a report for the welding procedure specification for rotating tubes TIG welding it was necessary to comprehend all the technical aspects of the process. This however, could be a lengthy and tedious task. Therefore, this work focuses on the welding procedure globally rather than looking at every single element of that procedure.

2. DOMAIN OF KNOWLEDGE

2.1 *Welding Procedure (WP) Specification:*

The B.S. 4870: Part 1: 1981 [15], has been adopted for stating the welding requirements i.e.

specifications. These requirements are often those of a general specification or standard, which the fabricator may follow as a quality standard.

2.2 The Knowledge Structure:

The aim of creating a knowledge structure for the TIG welding is to identify all variables which affect the decision making process of a welding specialist, i.e. inputs and outputs. The main process input variables are

- Parent metal composition,
- Parent metal dimensions,
- Joint type,
- Quality specification.

2.3 Input and output information:

The expert system receives a specified amount of information (input) to produce a certain amount of valuable information (output). A WP output is mainly dependent on the initial specification of the two mating tube parts (the first and second tube). Inputs can be classified into primary and secondary inputs while outputs can be classified into intermediate and outcome. Figure (2) shows the relationship between the different input and output levels and the inter-relationships between these levels.

a) Primary inputs:

Primary inputs are more critical and essential to be known at the early stages of generating a WP for TIG welding. They include

- parent metals,
- wall thickness,
- welding position and tube diameter (s),
- joint type,
- quality standard,
- welding site, and
- contractor's specific requirements.

b) Secondary inputs:

Secondary inputs are variables dependant on the primary inputs. They can be determined from Standard Codes, previous experience and/or process variables. These variables include, but may not be limited to, the following

- chemical composition and mechanical properties of parent metals,
- chemical composition and mechanical properties of deposited weld metal,
- dilution of parent to weld metal,
- initial parent metal temperature.

c) Intermediate outputs:

Intermediate outputs are produced during the decision making process and do not necessarily appear in the final report. They may include

- welding process,
- hydrogen content,
- heat input,
- methods of heat treatment,
- shielding gas flow rate,
- carbon equivalent,
- filler-wire size, and
- welding torch specification.

d) Outcome outputs:

Outcome outputs are the final welding variables which appear in the welding procedure specification report. They include

- preheat and interpass temperature,
- post weld heat treatment,
- welding conditions, e.g. welding current, arc voltage and polarity of process,
- filler-wire feed rate,
- speed of tube rotation (travel speed)
- number of weld runs.
- Heat input (arc energy),
- Temperature distribution,
- Filler metal type, and
- chemical composition of filler-wire material,

In fact it is difficult to distinguish between the secondary inputs and intermediate outputs. Intermediate outputs are formed from primary and secondary inputs, and once they are formed they will act as a secondary input for another intermediate or outcome output.

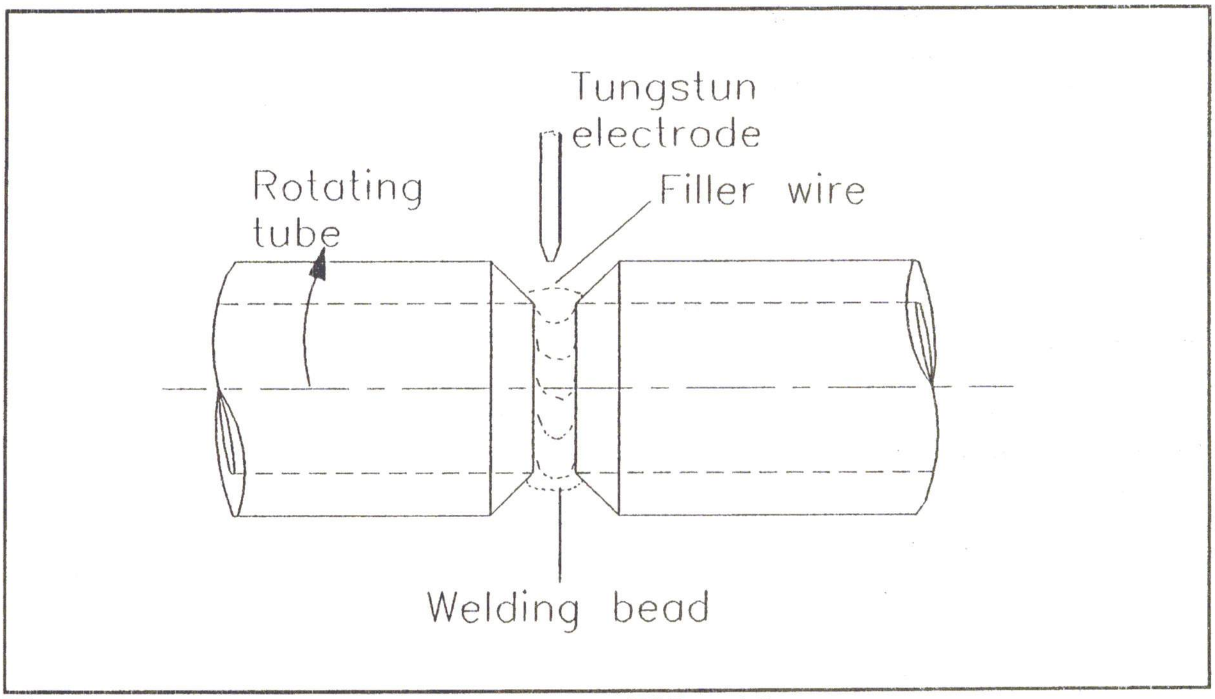


Figure 1 Configuration of rotating tube TIG welding

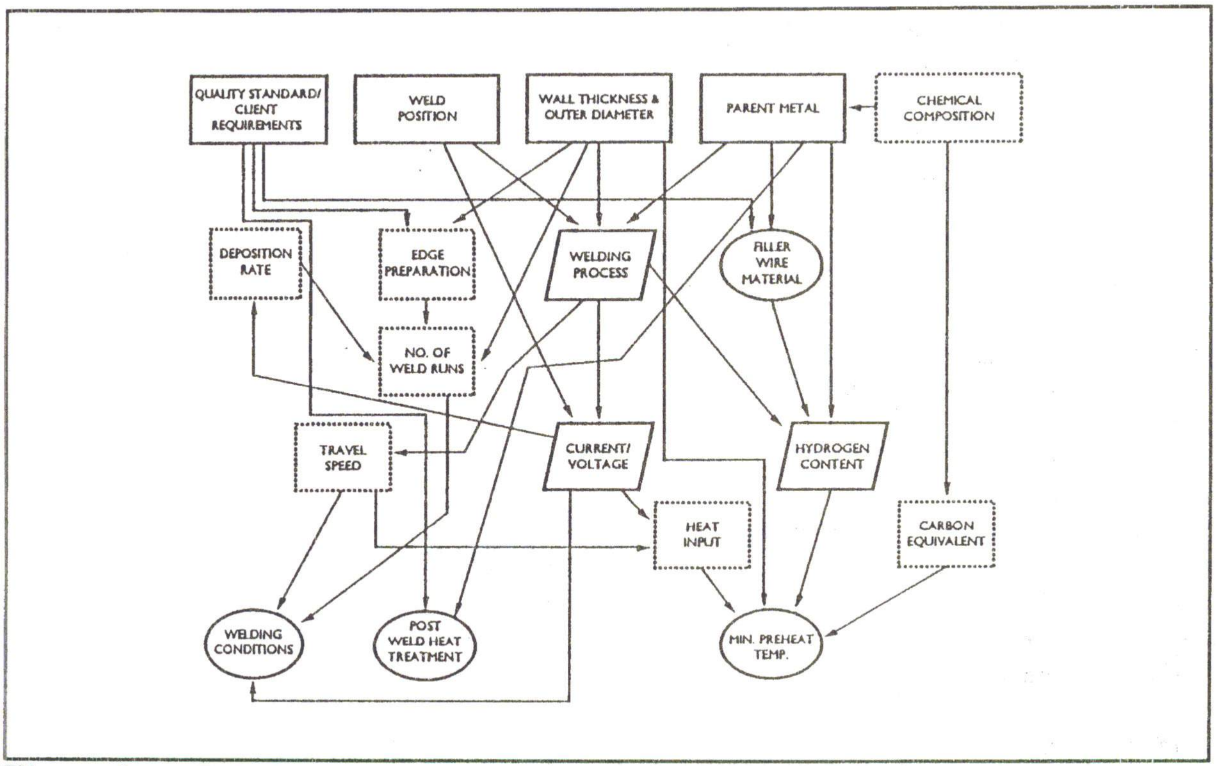


Figure 2 Relationship between Input specification and Output selections by the system

3. BASIC ASSUMPTIONS

Prior to building the knowledge base for the system some assumptions or constraints, as given below, have to be made upon which the system was built

Manufacturing specification	B.S. 1113: 1989 [16]
Application	Boiler and superheater tubes
Welding process	Tungsten Inert Gas (TIG)
Material range	B.S. 3059: Part 2: 1990
Geometrical configuration	Tubes
Wall thickness range	2.8 mm to 10.44 mm
Outer diameter range	38 mm to 76 mm
Welding technique	Automatic Rotating Tube (fixed head)
Weld preparation	V-bevel

It is usual practice that many of the outcome outputs, e.g. welding variables, are to be determined when the welding technique is selected. In connection with the previously mentioned constraints the following set of conditions have been identified;

Preparation method	Machined ends
Electrode type	Tungsten (2% Thoriated), diameter 2.4mm
Electrode point angle	30 degree
Electrode position	12 o'clock 3 mm rear TDC
Torch type	400 Ampere DC water cooled Torch
water cooling	650 cc/minute
Shielding gas type	Argon, high purity
Rate of shielding gas	7 liters/minute
Pre-purge time	30 seconds
Post-purge time	50 seconds
Slope up	zero
Wire angle to electrode	75 degree
Wire start position	feeding 2 mm below electrode, starting 5 mm from electrode

The variables of welding task as mentioned above should appear in all welding procedure specification reports generated under certain constraints.

4. BUILDING THE EXPERT SYSTEM

The following three main steps were followed to build the system knowledge base for rotating tubes TIG welding.

1. Acquiring and formalizing the related knowledge. This involved interviewing the functional experts in the domain of TIG welding and creating flow diagrams and decision trees.
2. Designing and developing the knowledge base using the techniques provided by the development tool, i.e. the expert system shell. This involved representing the knowledge in the form of rules and objects.
3. Testing and refining the knowledge base to validate knowledge until performance criteria were met. This was done through the knowledge process mode by executing the program a number of times and observing the inferencing mechanism.

These steps will now be discussed with more details.

4.1 *Acquiring and Formalizing the Related Knowledge*

Welding, in general, is such a complex operation with numerous possible interactions of process variables, procedures and materials that accurate data is not always available so that personal experience and judgement play a fundamental role in preparing it. The main source of expertise in building the knowledge based system should, therefore, be through a professional body working in the field where the expertise of TIG welding had accumulated over many years. Thus, metallurgists from the metallurgy department and welding engineers from the welding development department were interviewed. This was supplemented with the information available in relevant codes and standards, internal reports and previously generated welding procedures.

Both structured and unstructured techniques for interviews were used as appropriate. Initial progress in eliciting knowledge from functional experts was comparatively straight forward. After a number of sessions, each of which lasted approximately for 45 minutes, one reached an impasse whereby the expert felt he had explained the subject thoroughly; any further questioning would be just a repetition. A tape recorder was used to record the interviews. In structured interviews precise questions had to be addressed to the welding specialist to extract the knowledge and the reasoning criteria. The following are examples of some questions:

"What is your first action when you receive a client's requirements?"

"How do you perform the Welding Procedure search?"

"If you did not find a similar procedure, what will your action be?"

"What are the questions which you ask yourself when you start and generate a welding procedure?"

"What are the sources of knowledge you used?"

"What will your decision be if you do not know this piece of information?"

"Can you explain how you determine the minimum preheat temperature for these particular parent metals?"

"On what basis did you select this value?"

"Do you consider any other factors?"

"How critical is this factor?"

"To what extent do you rely on standards?"

"Do you have in-house standards?"

"At what stage do you need to seek information from the Welding Development Department?"

"Do you have any documented information?"

"If tube 1 material is low carbon steel and tube 2 material is high alloy steel - What is the weld metal specification?"

In many cases the answer itself creates another direction of the dialogue. Indeed, at one level it was true that a full picture of the domain had been obtained, but it was of a shallow and qualitative nature without the underlying reasoning being caught. The second phase took place when the prototype had been developed. This phase included such aspects as adding more rules and details about the reasoning in each rule, etc. In order to make the process of acquiring the knowledge efficient and fruitful, a decision tree was constructed and a procedure generation document was also created.

During the process of acquiring the knowledge the following areas were identified as potential outcomes of the welding procedure that could be generated by the expert system

- Minimum preheat temperature determination.
- Post weld heat treatment identification.
- Filler metal selection.
- Welding conditions determination.

It was found that the knowledge acquisition process was much more difficult than expected. This difficulty was mainly due to the fact that in many cases, metallurgists and welding engineers not only use their common sense to solve problems but also they have different concerns about the initial specification. Furthermore, clearly knowledge acquisition is a difficult process and is hindered as much by lack of understanding of the subject by the knowledge engineer as by "hard and fast" data supplied by the welding engineer and/or the metallurgist.

4.2 *Designing and Developing the Knowledge Base*

In order to be able to formulate the knowledge base, it is important to analyze the welding procedure development tasks from the information processing point of view. The flow of welding procedure information usually starts when a client sends the company a contract that contained the initial specification. Both the metallurgist and the welding engineer need to analyze and interpret the initial specification and decide on the welding process and other relevant information. Therefore the flow of information can be classified into two consecutive phases:

1. Data acquisition at the beginning of considering the welding procedure and the final report interpretation at the end.
2. Adopting the governing knowledge and rules (decision-making phase).

4.2.1 *The system knowledge bases design*

At the model formulation stage it was apparent that a wide variety of knowledge and information of an interactive nature are involved covering such facets as metallurgical aspects, manufacturing aspects, geometrical aspects, etc. It was thus decided to construct the knowledge base in the form of modules; each module holding a self-contained area of expertise. This modularity allowed the developer to update, add or even replace any of these modular contents subject to requirements imposed by later developments.

Every single knowledge base comprised a number of rules. Each rule was built and compiled individually. Then another rule was built, compiled and linked to the first rule. When a number of rules were created they were tested through the knowledge process session. During the knowledge process the inferencing mechanism can be traced and the rules status can be observed through the graphic interface. Therefore, the necessary amendments or changes have been traced and modified. This process is continued until different knowledge bases are built. The linking between these knowledge bases has been achieved by using the Load and UnLoad commands in the knowledge base structure.

The block diagram of the complete model of The system is presented in Figure (3). The functioning knowledge bases are the system managers. They provide the user with the option to select, among other choices, the material and dimensions of the tubes. From this model, other knowledge bases from the core model can be loaded, consulted and left for another knowledge base. At the end of each consultation the user is given the choice to display, print or save the welding procedure specification report before ending the session.

4.2.2 *The development of a knowledge-base*

a) Rules:

The basic structure of the rule in the present system was

```
IF      Condition
AND     Condition
THEN    Hypothesis
AND     Actions
```

For example,

```
IF   workpiece_configuration is tube
AND  wall_thickness <= 10 mm
AND  outer_diameter <= 60 mm
THEN welding_process
DO TRUE rotating tube TIG
```

In the above rule, checks are made for all the conditions mentioned in the left hand side. If the conditions are fulfilled, i.e. true, it sets the hypothesis to true and the set of actions in the right hand side will be executed.

b) Objects:

The building tool is object-oriented in nature with facilities for classes, object methods, and inheritance.

Groups of objects can also be categorized into classes. An example of the structure of an object is as follows:

name: tubes
classes: hollow_cross_section, materials
subobjects: tube_1, tube_2
properties: wall_thick, outer_diameter, material

Through a combination of rules and objects, a variety of methods for representing an expert's knowledge enable the System Developers to overcome the complexity and diversity of the welding domain.

c) *Knowledge processing:*

Full control has been achieved on the reasoning mechanism through the four methods of inferencing on rules: backward chaining, forward chaining, semantic gates and context links. Figure (4) shows the display on computer screen for a rule network during the reasoning process. In reality, two different colors were used for rules and icons attached to each rule to represent the different status of rules, i.e. rules under investigation, rules that have been fired etc.

4.3 Testing and Refining the Knowledge Base

Towards the completion of the development of the system knowledge base, visits to some industrially collaborating establishments were conducted aiming at testing and refining the knowledge base. During this visit a number of welding engineers and metallurgists were interviewed and asked to give their comments and suggestions on the developed system. Most of these comments were centered around the sequence of the questions asked by the system and their relevance to each person. These suggestions were then collated and inserted to enhance the system performance.

5. SYSTEM CONSULTATION

An example of binding the knowledge base with the runtime will now be presented and a session on system consultation will be demonstrated. Results of some typical tests carried out on the expert system are also presented. These results concern the core model, i.e. core knowledge bases. The significance of the results has been evaluated by comparing them with those produced conventionally.

A typical consultation to the system undergoes three main sessions:

- User's identification data.
- Initial specifications.
- Welding Procedure Specification Report.

1. *User's identification data*

The system starts its session by checking the user familiarity with the system, offering a list of supporting information asking for the user's profession and name: metallurgist, welding engineer, welding designer or welder. This is done to evaluate the user's experience. At the end of this knowledge base the opening menu, appears to enable the system to know the user's requirement.

2. *Initial specifications*

After identifying the user's data the next step is to identify the initial specification of the client. The initial specifications include information about the tubes wall thickness and outer diameters, the first and second tube material and the reference standard code as shown in Figure 5(a). A material list is displayed to enable the user to select the first tube material and once a material is selected, the next screen shows the details of that material, as shown in Figure 5(b).

3. *Welding procedure specification report*

At the end of the consultation the final report file is executed and the results invoked and displayed. During this session the system will open a file and reserve data for the generated welding procedure. The user must provide the system with a unique welding procedure reference number. The system also enables the end-user to display, save or print the final report.

The outline of the welding procedure final report was designed to have a formal format similar to that producible in practical situations. The basic welding information is reported with a line drawing sketch of the weld preparation. Figure 6 is a printout of the weld procedure report produced by the system

6. SYSTEM VALIDATION

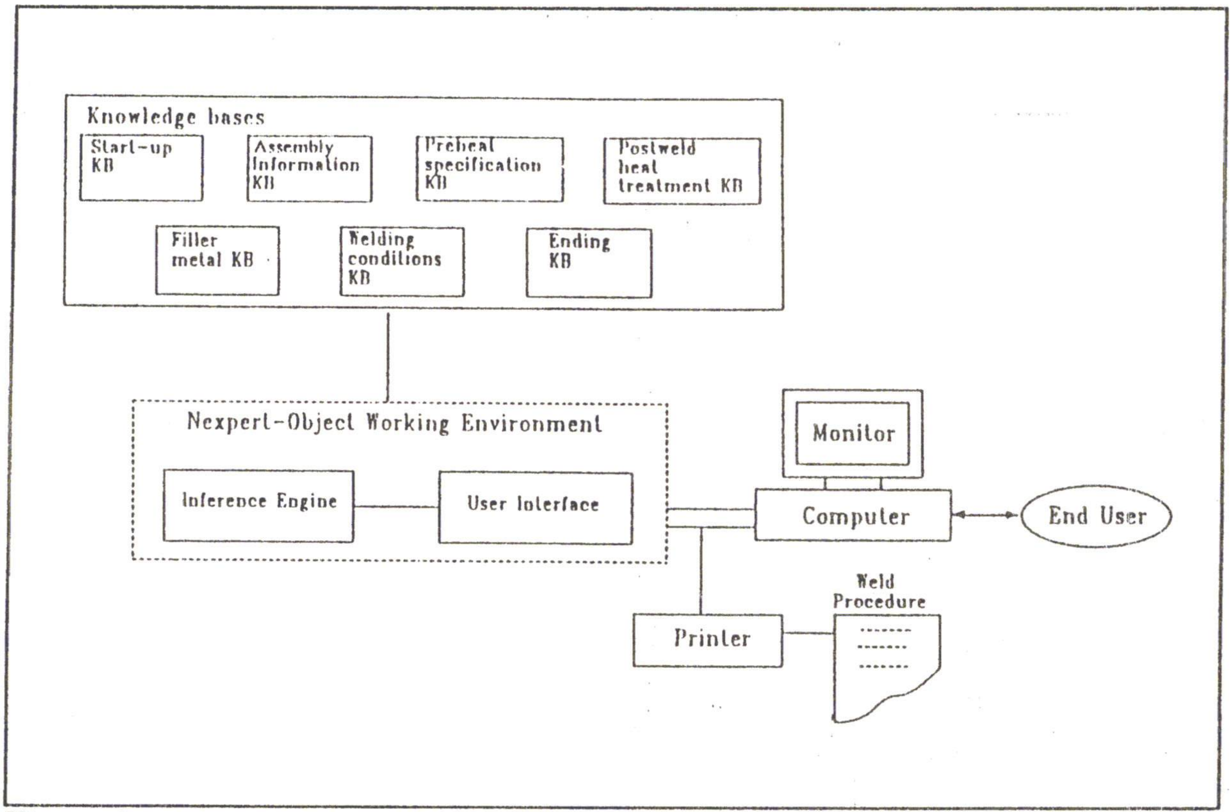


Figure 3 The layout of the expert system for rotating tube TIG welding

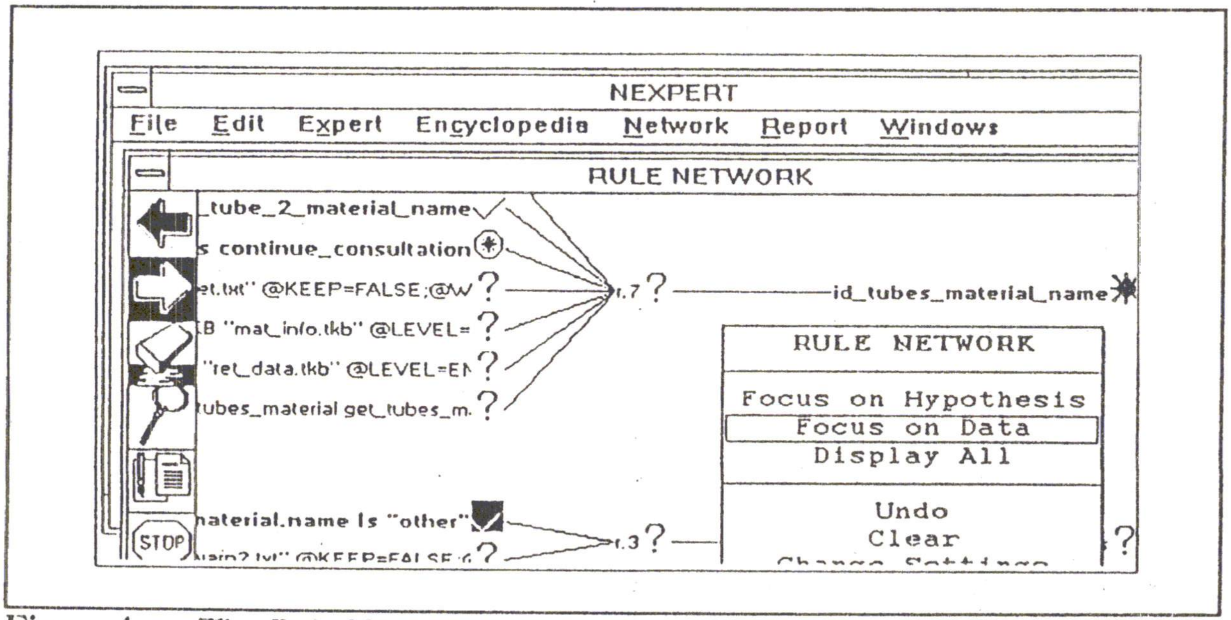
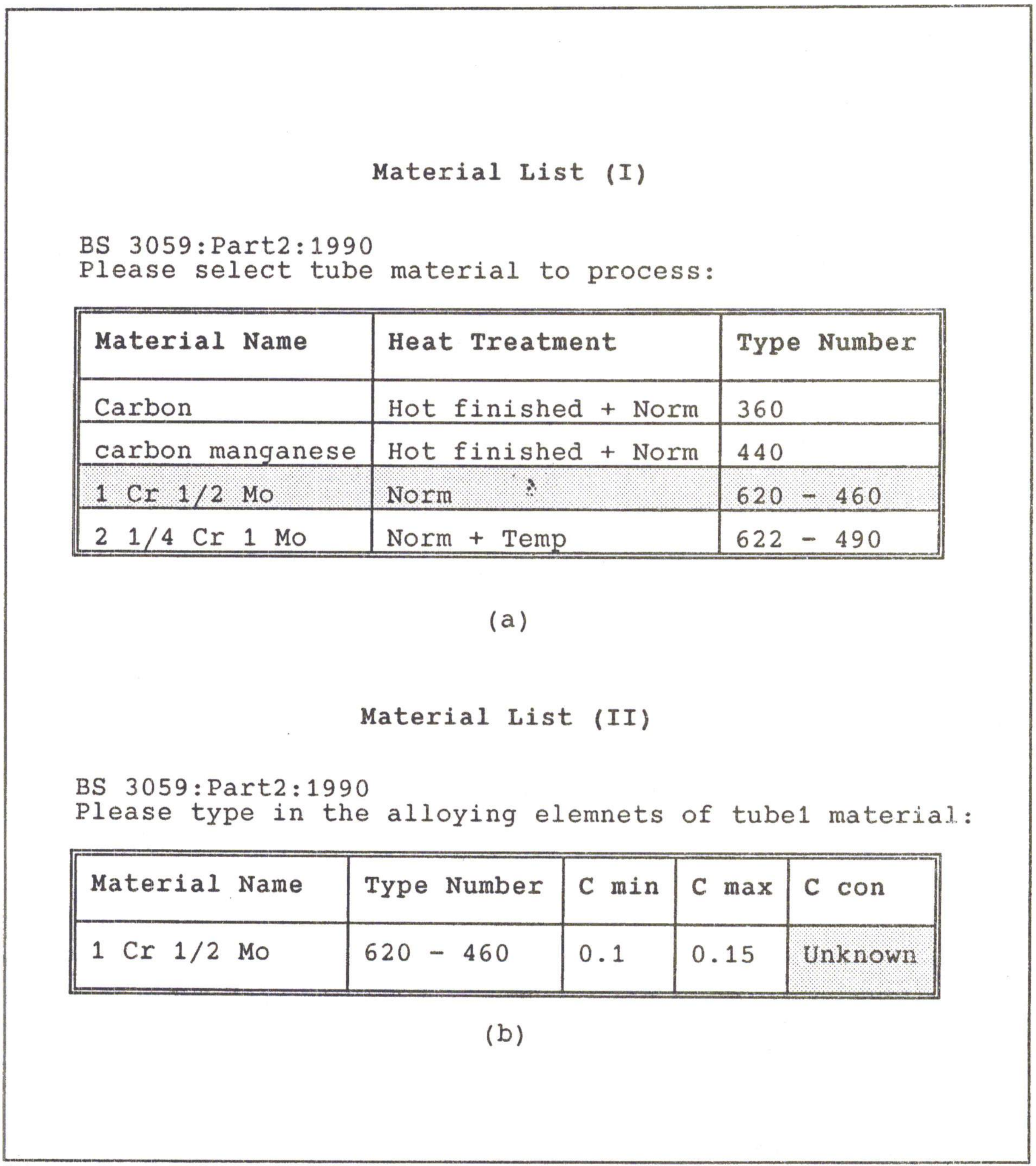


Figure 4 The Rule Network during the reasoning session



Material List (I)

BS 3059:Part2:1990
Please select tube material to process:

Material Name	**Heat Treatment**	**Type Number**
Carbon	Hot finished + Norm	360
carbon manganese	Hot finished + Norm	440
1 Cr 1/2 Mo	Norm	620 - 460
2 1/4 Cr 1 Mo	Norm + Temp	622 - 490

(a)

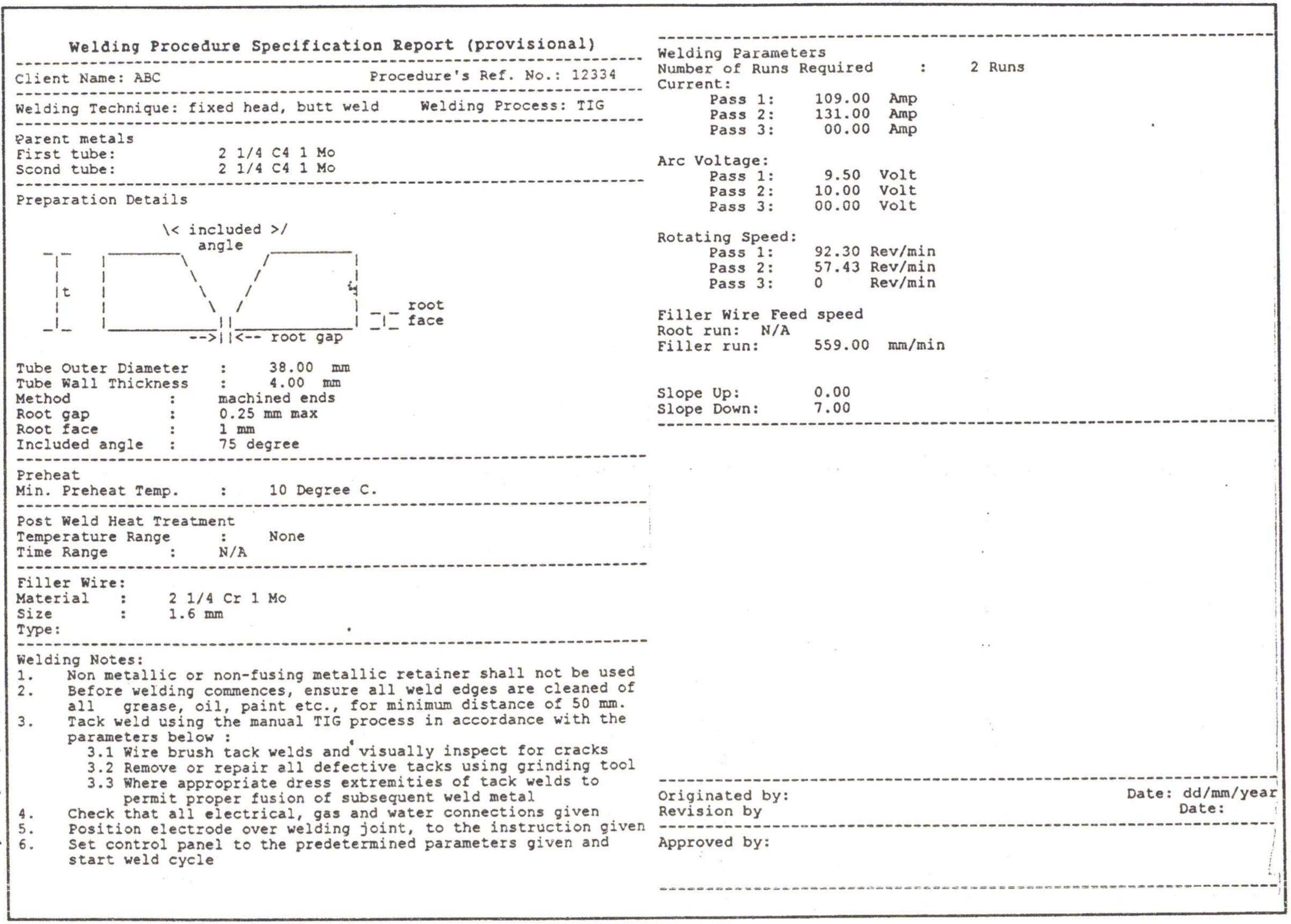
Material List (II)

BS 3059:Part2:1990
Please type in the alloying elemnets of tube1 material:

Material Name	**Type Number**	**C min**	**C max**	**C con**
1 Cr 1/2 Mo	620 - 460	0.1	0.15	Unknown

(b)

Figure 5 Menu for selection tube material (a), display of material chemical composition (b)



```
        Welding Procedure Specification Report (provisional)
---------------------------------------------------------------------
Client Name: ABC                            Procedure's Ref. No.: 12334
---------------------------------------------------------------------
Welding Technique: fixed head, butt weld     Welding Process: TIG
---------------------------------------------------------------------
Parent metals
First tube:             2 1/4 C4 1 Mo
Scond tube:             2 1/4 C4 1 Mo
---------------------------------------------------------------------
Preparation Details

                 \< included >/
                      angle
  _ _    __________          __________
   |    |          \        /          |
   |t   |           \      /           |
   |    |            \    /            |   _ _  root
  _|_   |_____________||  |____________|   _|_  face
                   -->||<-- root gap

Tube Outer Diameter   :     38.00  mm
Tube Wall Thickness   :     4.00   mm
Method            :    machined ends
Root gap          :    0.25 mm max
Root face         :    1 mm
Included angle    :    75 degree
---------------------------------------------------------------------
Preheat
Min. Preheat Temp.    :     10 Degree C.
---------------------------------------------------------------------
Post Weld Heat Treatment
Temperature Range     :     None
Time Range        :    N/A
---------------------------------------------------------------------
Filler Wire:
Material    :    2 1/4 Cr 1 Mo
Size        :    1.6 mm
Type:
---------------------------------------------------------------------
Welding Notes:
1.    Non metallic or non-fusing metallic retainer shall not be used
2.    Before welding commences, ensure all weld edges are cleaned of
      all   grease, oil, paint etc., for minimum distance of 50 mm.
3.    Tack weld using the manual TIG process in accordance with the
      parameters below :
        3.1 Wire brush tack welds and visually inspect for cracks
        3.2 Remove or repair all defective tacks using grinding tool
        3.3 Where appropriate dress extremities of tack welds to
            permit proper fusion of subsequent weld metal
4.    Check that all electrical, gas and water connections given
5.    Position electrode over welding joint, to the instruction given
6.    Set control panel to the predetermined parameters given and
      start weld cycle
```

```
---------------------------------------------------------------------
Welding Parameters
Number of Runs Required      :      2 Runs
Current:
         Pass 1:     109.00  Amp
         Pass 2:     131.00  Amp
         Pass 3:      00.00  Amp

Arc Voltage:
         Pass 1:       9.50  Volt
         Pass 2:      10.00  Volt
         Pass 3:      00.00  Volt

Rotating Speed:
         Pass 1:     92.30 Rev/min
         Pass 2:     57.43 Rev/min
         Pass 3:     0     Rev/min

Filler Wire Feed speed
Root run:   N/A
Filler run:          559.00   mm/min

Slope Up:            0.00
Slope Down:          7.00
---------------------------------------------------------------------




---------------------------------------------------------------------
Originated by:                                      Date: dd/mm/year
Revision by                                              Date:
---------------------------------------------------------------------
Approved by:

---------------------------------------------------------------------
```

Figure 6   A typical printout of the welding procedure produced by developed expert system

Two types of evaluations were carried out to validate the system knowledge bases and its results, i.e. welding procedure specifications. The first evaluation was carried out by consulting the system at a given initial specification and comparing the obtained welding procedure specifications with those produced conventionally and documented in the collaborating welding body. This involved validation on three testing conditions, as follows

	Test Condition(1)	Test Condition(2)	Test Condition(3)
Base material	2 1/4 Cr1Mo	Low carbon steel	1Cr 1/2 Mo
Tube wall thickness	5.6 mm	5.0 mm	4.0 mm
Tube outer diameter	57.0 mm	38.0 mm	63.5 mm

Tables (1), (2) and (3) contain a comparison of test results for the welding procedures produced by conventional methods and through the expert system.

From the results shown in Tables (1), (2) and (3) it is evident that welding procedure specifications produced by the system are very much similar to those produced conventionally. A clear example can be sited in the welding conditions such as the welding current, the rotating speed and the wire feed rate during the different phases of welding. Some discrepancies between the two procedure have been noticed, assumptions that have been made during the knowledge acquisition phase for the unknown which is attributable to some "less accurate" variables.

Many other welding cases where there was no approved welding procedures the expert's opinion of these procedures as generated by the present system was that its results were so close to what they would really expect. However, it is a common practice that generated welding procedures need further assessment to determine the expert system capability of producing reliable specifications.

The second evaluation took place at the industrial collaborating establishment. These tests were carried out by asking the welding engineers to give their views on the system generated procedures, particularly where there was no previous approved procedures as for the case in hand.

7. CONCLUSIONS

The development of an expert system for the rotating tube TIG welding has been investigated. The system was built to handle a variety of useful materials that included carbon, carbon manganese steels, low alloy steels and high alloy steels (with particular reference to materials listed in B.S. 3059: Part 2: 1990). It covers tube wall thicknesses in the range from 2.8 mm to 10.44 mm, and outer diameter in the range from 38 mm to 76 mm.

The following are the main conclusions:

1. An expert system can have a significant potential in optimizing the performance of metallurgists and welding engineers through the assistance it provides in their decision making process. The incorporation of metallurgists' and welding engineers' expertise in the system eliminates the impact that results from job transfers or lack of expertise.
2. The critical investigation and evaluation of the developed expert system shows it being capable to offer the the following advantages:
    - Significant reductions in the process planning time required to generate welding procedures. In typical conditions the system generated a welding procedure in full within 240 seconds.
    - Formulation of more consistent and accurate plans by incorporating multiple sources of expertise.
    - Compensation for skill shortages in planning departments by capturing and encapsulating the knowledge of experts.
    - Ease of use without probable misinterpretations.
    - Readily understood output on a standard formatted sheet.
    - Potentially significant contributions towards factory automation by automating the process of generating welding procedures.

The developed system can be broadened to cover extended ranges of material types, tube wall thicknesses and diameters. Also, the knowledge bases can be extended both horizontally and vertically. Horizontal extension comprises adding more modules, while vertical extension comprises deepening the developed knowledge base content in terms of technical data.

Table 1 Results summary of Test 1

Results	Conventional method	The system
Min. preheat temperature:	10 deg C	10 deg C
Post weld heat treatment:	Not required	Not required
filler material:	Type A33	2 1/4C4 1Mo
No of weld runs:	2 orbit weld	2 runs
Rotation Speed		
pass 1 :	96 sec/rev	92.30 sec/rev
Pass 2 :	96 sec/rev	57.43 sec/rev
Pass 3 :	0 sec/rev	0 sec/rev
Wire Feed Unit		
Wire Feed Speed:		
Root run	180 mm/min	N/A
Filler run	560 mm/min	660 mm/min
Wire Feed Delay:	0 sec	0 sec
Wire Feed Duration:	770 degree	740 degree
Arc Voltage Control		
Pass 1:	9.5 volt	9.5 volt
Pass 2:	9.5 volt	10.0 volt
Pass 3:	0 volt	0.0 volt
Arc Oscillation Device		
Frequency:	1.66 Hz	1.66 Hz
Amplitude:		
Pass 1:	10 gauss	40 gauss
Pass 2:	10 gauss	62 gauss
Pass 3:	00 gauss	00 gauss
Welding Program		
Current:		
Pass 1:	110 amp	109.27 amp
Pass 2:	123 amp	131.00 amp
Pass 3:	0 amp	0.0 amp
Slope Up	0	0
Slope down	7	7

Table 2 Results summary of Test 2

Results	Conventional method	The system
Min. preheat temperature:	10 deg C	10 deg C
Post weld heat treatment:	Not required	Not required
filler material:	Type A18	carbon steel
No of weld runs:	3 orbit weld	3 runs
Rotation Speed		
Pass 1 :	144 sec/rev	141.80 sec/rev
Pass 2 :	82 sec/rev	81.19 sec/rev
Pass 3 :	82 sec/rev	81.19 sec/rev
Wire Feed Speed:		
Root run	180 mm/min	N/A
Filler run	600 mm/min	660 mm/min
Wire Feed Delay:	0 sec	0 sec
Wire Feed Duration:	1080 degree	1100 degree
Arc Voltage Control		
Pass 1:	9.5 volt	9.5 volt
Pass 2:	9.5 volt	9.5 volt
Pass 3:	10.0 volt	10.0 volt
Arc Oscillation Device		
Frequency:	1.66 Hz	1.66 Hz
Amplitude:		
Pass 1:	30 gauss	40 gauss
Pass 2:	50 gauss	62 gauss
Pass 3:	100 gauss	99 gauss
Welding Program		
Current:		
Pass 1:	136 amp	132.00 amp
Pass 2:	150 amp	156.00 amp
Pass 3:	160 amp	166.00 amp
Slope Up	0	0
Slope down	5	6.24

Table 3 Results summary of Test 3

Results	Conventional method	The system
Min. preheat temperature:	10 deg C	10 deg C
Post weld heat treatment:	630-670 degree	630-670 degree
filler material:	Type A32	1Cr 1/2Mo
No of weld runs:	2 orbit weld	2 runs
Rotation Speed		
Pass 1 :	164 sec/rev	168.65 sec/rev
Pass 2 :	89 sec/rev	94.66 sec/rev
Pass 3 :	0 sec/rev	0 sec/rev
Wire Feed Speed:		
Root run	178 mm/min	N/A
Filler run	712 mm/min	559.00 mm/min
Wire Feed Delay:	0 sec	0 sec
Wire Feed Duration:	770 degree	740 degree
Arc Voltage Control		
Pass 1:	9.5 volt	9.5 volt
Pass 2:	10.0 volt	10.0 volt
Pass 3:	10.0 volt	0.0 volt
Arc Oscillation Device		
Frequency:	1.66 Hz	1.66 Hz
Amplitude:		
Pass 1:	20 gauss	40 gauss
Pass 2:	100 gauss	62 gauss
Pass 3:		00 gauss
Welding Program		
Current:		
Pass 1:	112 amp	101.00 amp
Pass 2:	138 amp	123.00 amp
Pass 3:	0 amp	0.0 amp
Slope Up	0	0
Slope down		11.24

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