Process Monitoring as a Mean to Ensure Quality and to Increase Productivity in Robotized GMA Short Arc Welding

X. Xie
Lund University, Lund, Sweden

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The concepts of quality assurance and productivity have been studied in this article. Based on the analysis of the electrical data of welding arc, a process monitoring system has been developed to monitor GMA short arc welding to ensure weld quality and to increase welding productivity. This article deals with only the welding of thin mild steel plates.

1. INTRODUCTION

Quality and productivity have become very important concepts in modern manufacturing activities. In robotized gas metal arc (GMA) welding, the following three aspects are important for quality assurance and for improved productivity. the first aspect is to develop an optimal welding procedure before the welding production starts. The second is to monitor and adaptively control the welding process to counteract disturbances that occur during the welding operation. The third is to diagnose the causes of weld defects and to take measures to quickly remove the quality disturbances when a weld defect results.

With the increased demand on productivity, quality and variety of products, flexible unmanned production systems are increasingly needed. In arc welding, the use of robots integerated with flexible positioners has greatly contributed to the flexiblity of welding productions.

In small batch production, the time consumed in developing a welding procedure or welding parameters significantly affects the productivity. This time should be reduced in order to increase the productivity, which implies that computer-aided planning of welding procedure or welding parameters is needed.

Disturbances during production must be quickly identified and removed, or automatically compensated in order to avoid weld defects. Quality monitoring and adaptive control of the arc welding process is therefore a pre-requisite of quality assurance in unmanned welding production.

2. THE CONCEPT OF WELD QUALITY

If a weldment is to have the required reliability throughout its life, it must have a sufficient level of quality of fitness for purpose. Here it must be noted that quality is not a fixed property of a weldment. Quality is a relative term, depending upon the function the weldment is intended to serve and upon the required life of the weldment. In another word, a weldment may have different levels of quality for different service requirements.

In practice, weld quality is verified by nondestructive examination, where the weld is examined in regard to size, shape, contours and other features. The acceptance standards for the welds are generally related to the method of nondestructive examination. Welds that do not satisfy the acceptance standard are classified as defective.

Many standards relating to weld quality do not govern product usage and leave maintenance of the fabricated product to the user. It is the user who must modify, amplify, or impose additional weld quality standards during maintenance activities to ensure that the product continues to function properly.

The determination of quality requirement for a weldment involves, therefore, design, fabrication and operating and maintenance considerations, which means that each weldment should be:

- Adequately designed to meet the intended service for the required life.

- Fabricated with specified materials and in accordance with the design concepts.
- Operated and maintained properly.

Specifying excessive quality can lead to high cost with no benefit, while low quality weldments lead to high maintenance costs and excessive loss of service. Thus, quality levels may be permitted to vary among different weldments and individual welds, depending on service conditions and requirements.

3. WELDING PRODUCTIVITY

Any type of production must be efficient. The efficiency of production or productivity can be measured by the time consumed in fabricating certain units of products. The shorter the time, the higher is the productivity. Of relevance, the following three factors are important for the welding productivity.

- time consumed in developing welding procedure.
- welding speed.
- time consumed in repairing defective welds.

A welding procedure is mainly developed by trials. This method is time consuming. This time can significantly affect the productivity in small batch production. The development of a welding procedure often requires much knowledge about the base material, welding process, quality requirements etc. The more expert knowledge one has in this field, the more efficient the development of welding procedure will be. Therefore, artificial intelligence has recently been introduced into this field to assist the procedure developer and thus to improve the efficiency.

The highest possible welding speed should be used, which is obvious. However, it often occurs that the welding procedures or welding parameters used in manual welding are transferred into robotized welding production without any adjustment. This can cause considerable loss of welding productivity since a robot arm can move the welding torch much faster and smoother than a human welder can.

Productivity decreases with increased defective welds, which implies that improved quality assurance systems will increase productivity.

4. QUALITY ASSURANCE

To ensure weld quality requires that we have both knowledge and control of the factors influencing the quality during production. Generally there are five major factors influencing the quality in robotized welding, Fig. 1.

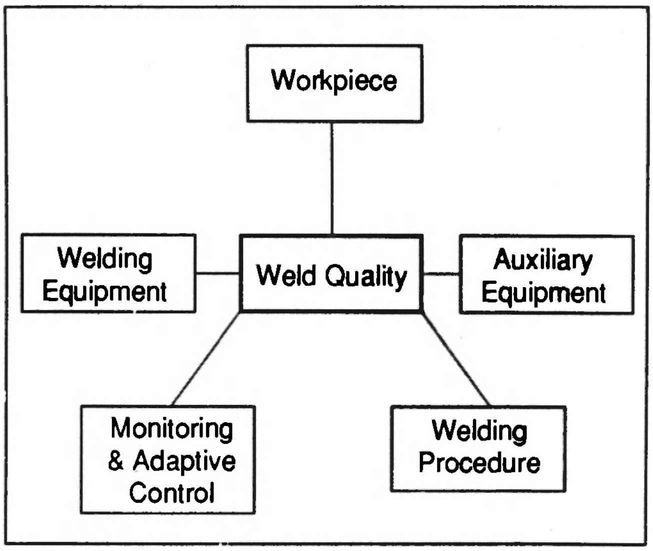

Fig. 1. *Factors influencing welding quality in robotized arc welding.*

The principal variables regarding workpiece, workpiece handling, welding equipment and welding parameters are listed in the following.

- Process Variables
  - — Static and dynamic characteristics of welding power source.
  - — Wire Composition.
  - — Wire diameter - current density.
  - — Shielding gas composition.
  - — Arrangement of assembly.
  - — Welding Position.
  - — Joint preparations - geometric variables.
  - — Preheat and interpass temperatures and condition.
  - — Welding sequence.
  - — Tacking and clamping arrangement.
  - — Joint pre-set (predistortion).
  - — Joint precision (repitition of robot + tolerance of position of the part + tolerance of tacking + joint preparation tolerance).
  - — Deviation of arc - magnetic deflection.
  - — Surface preparation - before welding.
- Welding Parameters
  - — Primary Parameters
    - * Wire feed rate (or Welding Current).
    - * Welding voltage.
    - * Welding speed.
  - — Secondary Parameters
    - * Electrode angle - advance attitude.
    - * Electrode angle - transverse attitude.
    - * Contact tip to workpiece distance or "Stick-out".
    - * Flow of shielding gas.

For MAG welding, a power source static characteristic of constant potential is used. The dynamic characteristic has a profound influence on welding properties. In conventional power sources, the dynamic properties are usually determined by the inductance and resistance in the welding circuit and there are a few conditions available. In modern power sources, the dynamic properties are normally predetermined for various welding conditions. The wire composition determines the mechanical properties of the welds and is chosen according to the chemical composition of the material to be welded. There are many commercially available welding wires. Wire of 0.8 mm in diameter is the most often used in thin plate welding. The composition of shielding gas affects welding properties. In welding of non-alloyed and low-alloyed mild steel, shielding gas 80% Ar/20% CO_2 is widely used. Welding position can influence welding speed and quality. The flat welding position should be used if possible. With a robotic welding system integrated with a flexible positioner, flat welding position can be obtained for many applications. Preheat and inter-pass temperature is not necessary for welding of thin plates. The surface condition, e.g. grease, rust on the surface, can influence process stability and cause weld defects. Deviation of welding arc seldom occurs in GMA welding since the arc length is very short in short arc welding. Welding sequence may be important since it can affect joint fit-up through the mechanism of thermal deformation. The welding sequence should be carefully chosen to minimize the effect of thermal deformation. Tacking and clamping arrangements should also be chosen carefully to minimize the effect of thermal deformation of joint fit-up. The joint type is chosen according to the thickness of the plates to be welded: I- and V- joints are most common for thin plate welding. The choice of joint gap and its tolerance is very important since it can greatly affect welding results. The joint gap and its tolerance is specified by the designer. In robotized welding, 90% of factors contributing to success relate to joint fit-up conditions. Higher quality requirements on welds put greater demand on joint fit-up. Seam tracking systems should be used when the joint fit-up is difficult to ensure and weld quality demand is high.

The determination of welding parameters is a very important part of the welding procedure and is the main task of a welding engineer. The determination of welding parameters should be done with the respect to joint fit-up condition, quality requirement and productivity etc. Among the welding parameters, the primary parameters can very greatly for different applications, while the secondary parameters can be the same for many applications.

The advance angle of the wire electrode is normally within 15 degrees from the normal position to ensure the effect of shielding gas. This torch angle has no apparent influence on weld geometry. Normal torch position is normally used in the flat welding position. The distance between contact tip and workpiece should be as short as possible to minimize the deviation of wire electrode from the welding joint; 10-15 mm distance should be used for short arc welding. This distance can influence weld geometry since this variation will change the arc current and voltage. Decreased distance between contact tip and workpiece increases arc current and weld penetration. Shielding gas flow rate does not influence weld geometry, it affects only the shielding effect. Normally 10-20 l/mm is used in GMA (Gas-Metal-arc) welding. Excessive flow rate will deteriorate the shielding effect by causing turbulent flow of the shielding gas.

The most important part in the determination of welding parameters is to choose the primary welding parameters. Here it should be noted that welding current is often not a preset parameter, it is mainly determined by wire feed rate, which is a preset parameter. Among the primary welding parameters, wire feed rate and welding voltage are the parameters determining the process stability. A stable welding arc is a prerequisite of a successful welding application. To achieve a stable short arc, the combination of wire feed rate (or current) and voltage must be optimized. The optimal combination between were feed rate and voltage may be different for welding power sources with different static and dynamic characteristics. Welding speed is the parameter affecting productivity. The higher the welding speed used, the higher productivity is achieved.

Process monitoring and adaptive control are particularly important in fully mechanized welding, for quality assurance. The factors affecting weld quality must be monitored during production so that when a parameter is disturbed to such a degree that the weld quality is risked the production should be stopped. A monitoring system should be able to help the operator to locate the disturbance so that correct counteracting measures can be taken to quickly remove the quality disturbance. In a more advanced welding system, the system should be adaptively controlled, which means that when a quality disturbance occurs the system can automatically adjust itself to counteract or remove the disturbance.

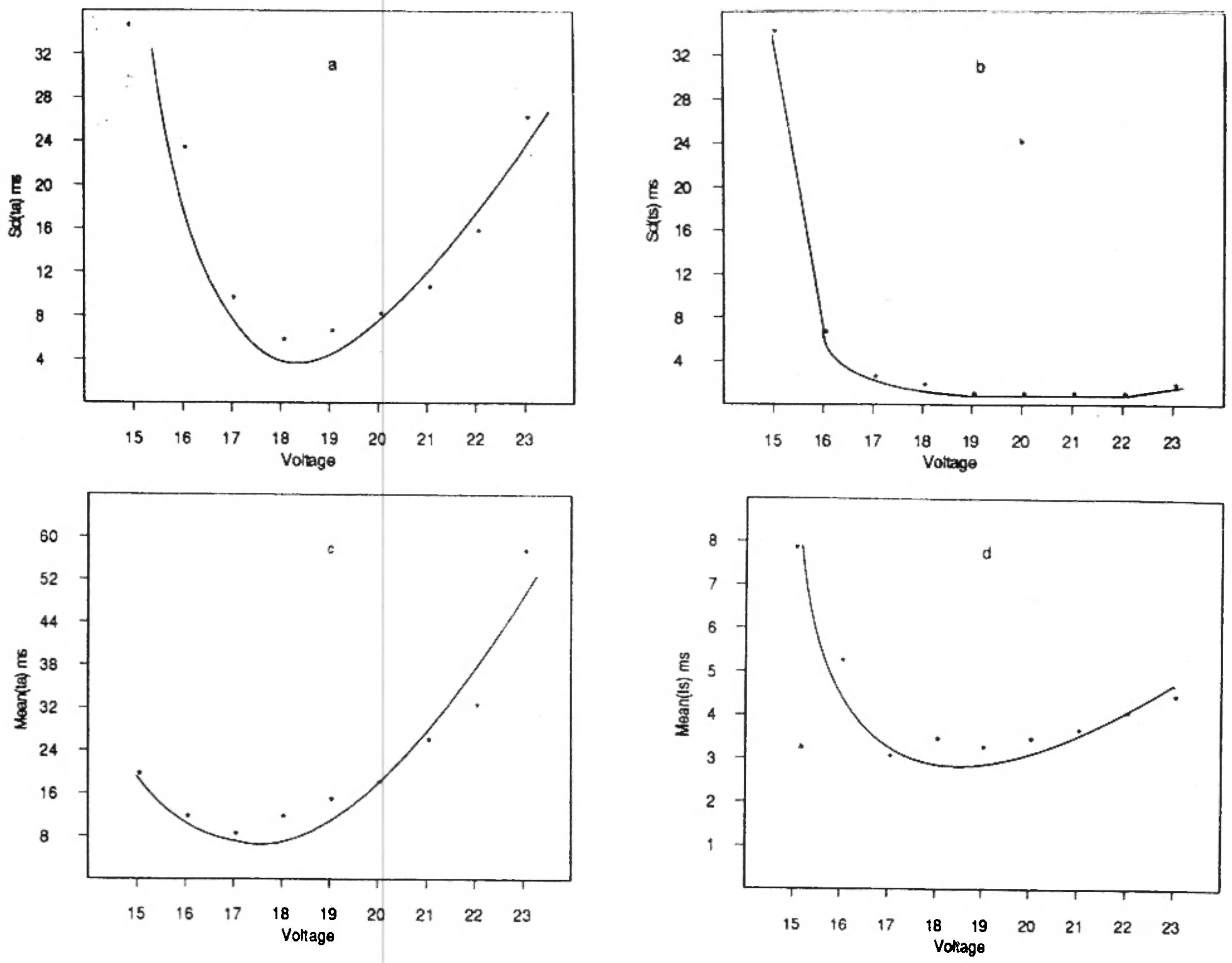

Fig. 2. *Standard deviation of arcing time, Sd(ta), is a parameter to assess arc stability. The influence of welding voltage on the standard deviation of arcing time (a) and short-circuiting time (b), as well as on the mean of arcing time (c) and short-circuiting time (d).*

5. DEVELOPING A PROCESS MONITORING SYSTEM

5.1 Experiments

At Lund University an advanced computer-based data acquisition system has been developed, which allows that the electric data of a welding arc can be sampled at a frequency up to 70 KHz. In our tests, a sample rate of 4KHz was used. The sampled data is stored in the computer memory for later processing and analysis. The data analysis program was developed in Pascal and run on an IBM PS/2. It has the following main functions:

- Display current and voltage waveforms.
- Make histograms of various parameters.
- Plot various parameters against each other.
- Calculate statistical values of various parameters.

The main welding equipments used were:

- six-axis arc welding robot ABB 2000.
- two axis positioner ESAB Orbit 500.
- transistorized welding power supply ESAB LAK 500R with synergic control.

The workpieces were mild steel, and the welds were made in form of bead-on-plate. The wire electrode used was solid wire type ESAB OK Autrod 12.51 diameter 1 mm and the shielding gas was 80% Ar/ 20%CO_2 with a flow rate of 12 1/min. The variables during the experiment were wire feed rate (or current), welding voltage and welding speed. All the other parameters were kept constant.

5.2 Process Analysis

For an ideally stable welding arc, the waveforms of arc current and voltage should be possible to be subdivided into a number of repeated cycles of exactly the same type. In another word, the standard deviations of arcing time and short-circuiting time should be equal to zero.

Figure 2 shows the standard deviations and mean of arcing time (t_a) and short-circuiting time (t_s) as a function of welding voltage, where the welding arc was visually observed to be most stable at a voltage of 18 volts. When voltage was below 17 volts, the arc was unstable with metal spatter, and the instability became worse with decreased welding voltage: the arc was more frequently extinguished and a greater amount of metal spatter was caused when the voltage decreased. The extinction of a welding arc can be explained by the following. When the voltage is not sufficient the wire tip is little melted. When a solid wire tip contacts the workpiece, the heating of the electrode tip proceeds slowly and covers a large length of the wire; further electrode melting is accompanied by an explosion, causing a large gap between the electrode and the workpiece so that the arc cannot immediately ignite.

When the voltage was above 21 volts, the arc was also unstable with metal spatter, but the instability was vary different from the instability with a voltage below 17 volts. The arcing time was long and droplets transferred were large. The metal spatter was mainly caused by the large droplet transfer. The arc was never observed to be extinguished.

From Fig. 2 it can be seen that the standard deviation of arcing time reaches a minimum at 18 volts. The mean of arcing time first decreases with welding voltage and then increases after 17 volts. The reason that the mean increases with voltage below 17 volts is explained in the following. The arcing time is here defined as the time period between the preceding short-circuit and the next one. This time is determined by the wire feed speed and the gap between the electrode and the workpiece. Since when the voltage was 17 volts, the extinction of the arc due to large gap between the electrode and workpiece increased with decreased voltage, it is apparent that the mean arcing time will be increased. When the voltage was above 17 volts, the arc was never extinguished and the arc length was regulated by the voltage. Increased voltage will increase the arc length, i.e. the gap between the electrode and workpiece, and thus increase the mean arcing time.

The standard deviation of short-circuiting time decreases rapidly at first and then keeps almost constant after the welding arc becomes stable. The mean of short-circuiting time is almost constant between 17 and 20 volts.

From the above analysis it should be concluded that the standard deviation of arcing time is a parameter indicating the stability of a welding arc.

This result can be used in developing the optimal combination of wire feed rate and welding voltage to ensure a stable welding arc.

Here it must be noted that a statistical value like standard deviation describes only an event as a whole. The standard deviation of arcing time cannot tell when and where an instability occurs and the cause of the instability. It is however important to know where and when an arc instability occurs and what is the cause.

If we plot arcing time against short-circuiting time, see Fig. 3, the above goal can be reached. If we compare Fig. 3c with Fig. 3d, where the arc was very stable for Fig. 3d and for Fig. 3c only slight instability was observed, it can be found in Fig. 3d all the short-circuiting times are less than 8 ms while in Fig. 3c a few short-circuiting times are longer than 8 ms. If we compare Fig. 3c with Fig. 3b, where the arc stability was worse for Fig. 3b than Fig. 3c and the arc was occasionally extinguished in Fig. 3b, it can be found that the number of short circuiting times longer than 8 ms has been increased. The following conclusions can therefore be drawn:

- 8 ms is a critical time for the stability of short-circuiting metal transfer.
- When short-circuiting lasts longer than 8 ms, an instability may occur.
- When short-circuiting lasts less than 8 ms, instability is not likely to occur.

If we compare Fig. 3b with Fig. 3a, where the arc was very unstable and was frequently extinguished in Fig. 3a, it can be found that the number of short-circuiting times longer than 30 ms has been greatly increased. It can also be observed that such a long short-circuiting period is often followed by long arcing times, indicating that a large gap was caused between that electrode and the workpiece. When the current and voltage waveforms were checked, it was found that during these long arcing times the arc was often not burning, but extinguished. Therefore, the following conclusions can be drawn:

- 30 ms is another critical time for short-circuiting metal transfer stability.
- When short-circuiting lasts longer than 30 ms, the arc may be extinguished.
- When a short-circuiting lasts less than 30 ms, the arc is not likely to be extinguished.

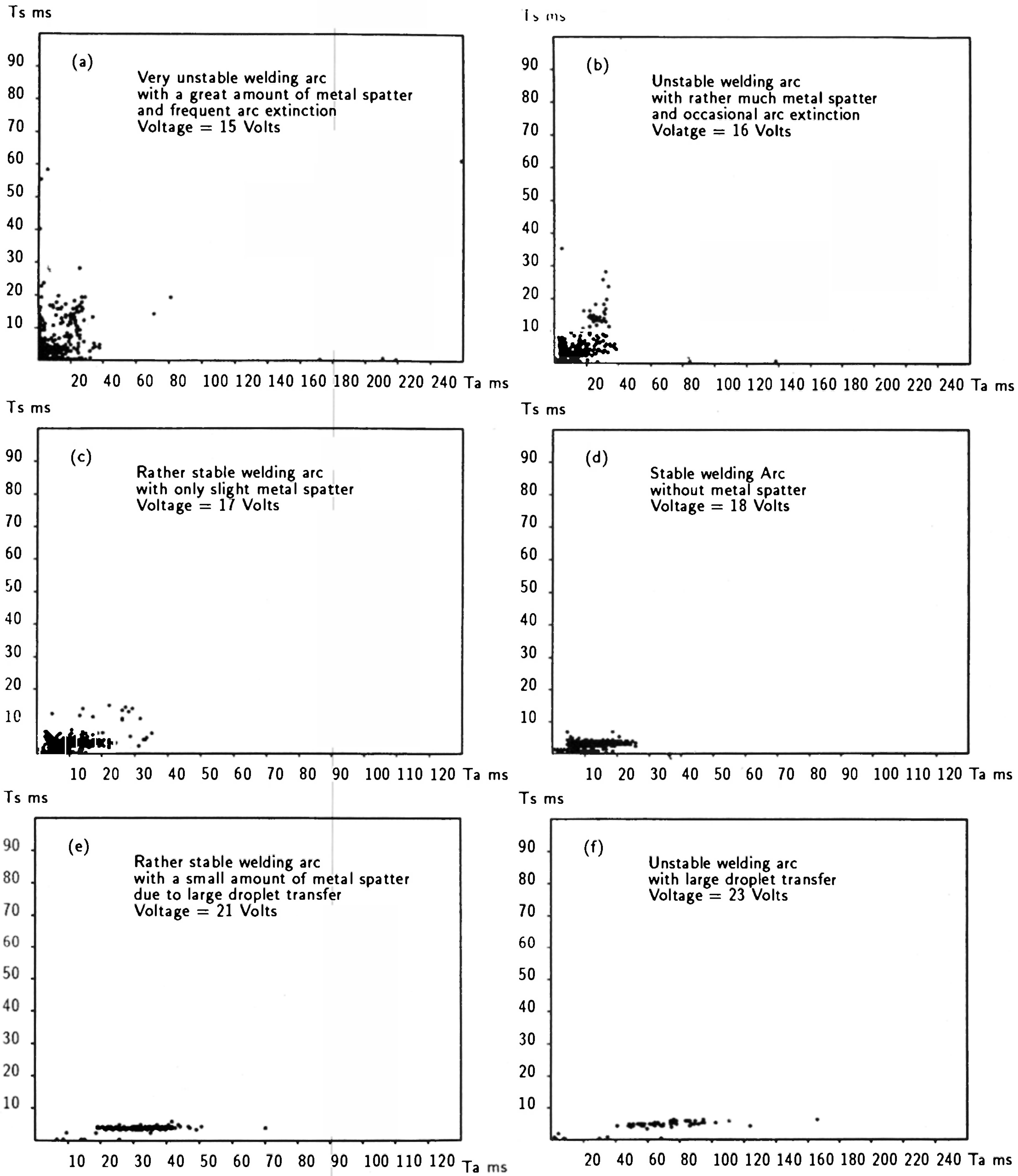

Fig. 3. *Plotting arcing time (ta) vs. short-circuiting time (ts) is a method to reveal arc characteristics. The successive form of ta-ts distribution and the change of arc characteristics when the welding voltage increases from 15 (a) to 23 volts (f).*

If we compare Fig. 3d, 3e and 3f, it is immediately found that when the welding voltage is above the optimal voltage (i.e. 18 volts in our case), no short-circuiting lasts longer than 8 ms, but the arcing times becomes longer with increased welding voltage. For Fig. 3f the arc stability was worse than 3e: larger droplet transfer droplet transfer and more metal spatter were observed. In Fig. 3d no arcing time is longer than 45 ms, while in Fig. 3e some arcing times are longer than 45 ms and in Fig. 3f the number of arcing time is increased. Therefore, 45 ms of arcing time can be chosen in our case as an indicator for large droplet transfer.

To sum up, the following conclusions can be made according to the above analysis:

- The distribution of arcing and short-circuiting times can reveal the characteristics of a welding arc.
- When short-circuiting lasts longer than 8 ms, an instability is probable.
- When short-circuiting lasts longer than 30 ms, the arc is likely to be extinguished.
- The cause of long short-circuiting period is insufficient welding voltage.
- With a welding voltage equal or greater than the optimal, no short-circuiting lasts longer than 8 ms.
- When welding voltage is greater than the optimal, if an arcing period lasts than 45 ms, instability due to large droplet transfer is likely to occur.

5.3 Process Monitoring

A computer program has been developed in Pascal to monitor various parameters of a welding arc and to evaluate the stability of a welding arc. The parameters monitored are:

— heat input per unit length of weld.
— average arc voltage and current per unit length of weld.

The evaluation of arc stability includes:

— locating where an instability probably occurs.
— locating where the arc is extinguished.
— identifying the probable cause of the arc instability.

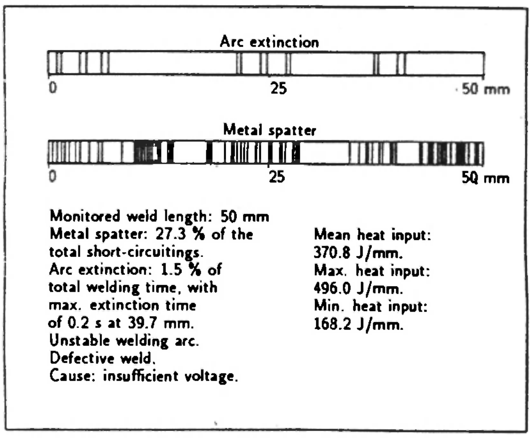

Fig. 4. *The information shown by the monitoring system*

The heat input is defined in the system as:

$$h = \int_0^{1/v} i * u dt$$

where
h - heat input (J/mm)
i - welding current (Amp)
u - welding voltage (Volt)
v - welding speed (mm/s)
t - time (s)

The average voltage and current are defined as:

$$\bar{u} = \int_0^{1/v} u dt \text{ when } u > 12 \text{ volts and } i \neq 0$$

$$\bar{i} = \int_0^{1/v} i dt \text{ when } u > 12 \text{ volts and } \neq 0$$

were $\bar{u}$ and $\bar{i}$ are respectively the average arc voltage average arc current per unit length of weld.

The evaluation of arc stability is based the analysis of the preceding section, but the location of arc extinction is done according the criterion that arc current i is zero. Fig. 4 shows the result of a monitoring.

6. PROCESS MONITORING AS A TOOL FOR QUALITY ASSURANCE AND FOR IMPROVED PRODUCTIVITY

6.1 Determination of Optimal Combination of Wire Feed Rate (or Current) and Welding Voltage

As discussed in the section process analysis the standard deviation of arcing time is a parameter indicating arc stability. Figure 5 illustrates the relationship

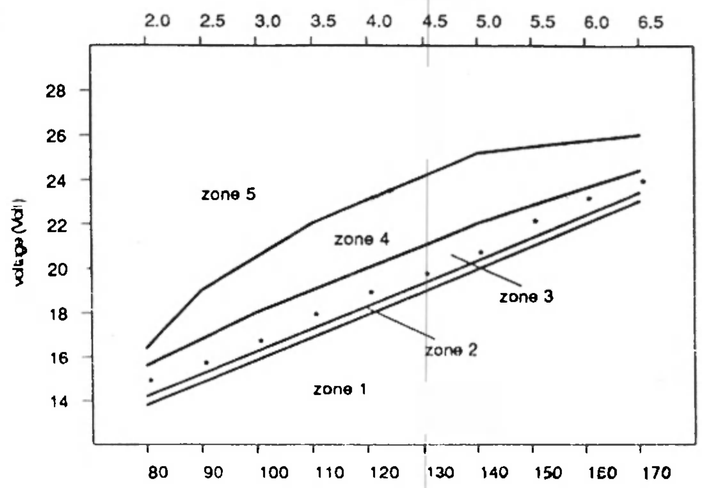

Fig. 5. *The influence of welding voltage and current on arc stability*

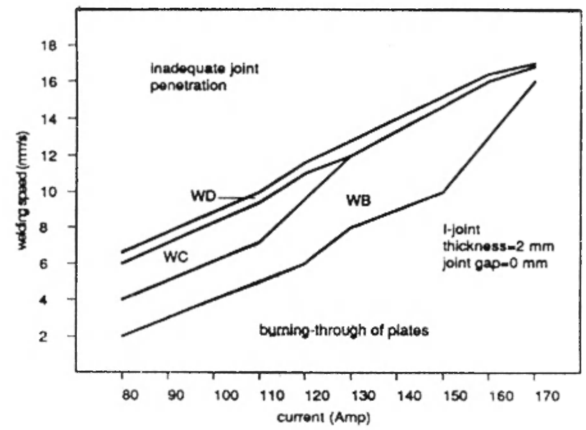

Fig. 6. *Quality class as a function of current and welding speed in welding of I-joint with joint gap = 0 and thickness = 2 mm*

between wire feed rate, welding voltage and arc stability for wire feed rate, welding voltage and arc stability for wire feed rate between 2 and 6.5 m/min, where (*) indicates the optimal welding voltage according to the standard deviation of arcing time.

Within the tested range of wire feed rate, there exists a minimum voltage for each wire feed rate, below which the welding arc is unstable, with much metal spatter and the arc is frequently extinguished (zone 1). This critical voltage increases with increased wire feed rate. When the voltage is about one or two volts above the minimum value, the arc stability was observed to be best (zone 3). It can be seen that the optimal voltages determined be the analysis of the standard deviation of arcing times agrees well with this observation. When the combinations of wire feed rate and voltage are within zone 2 the arc is stable, but occasional instability with metal spatter of small size can occur. In zone 4, the arc stability is a little deteriorated; metal transfer frequency is lower than in zone 3 and the size of transferring metal drops are larger. In zone 5, the metal transfer frequency is rather low and the sizes of transferring metal drops are further increased. The irregularity of arcing times increases with increased metal drop size or voltage, thus deteriorating the smoothness of weld dead surface. In this zone, more metal spatter of large size occurs. When the voltage is about 7-9 volts above the critical voltage, the arc length becomes so large that the burning of electrode wire onto the contact tip frequently occurs.

To sum up, the relationship between wire feed rate (or current), voltage and arc stability can be described by table 1.

Table 1. A summary of the relationship between welding current), voltage and arc stability (ref. Fig. 5).

Zone	Welding Arc
1	very unstable, frequently extinguished
2	occasionally unstable
3	stable
4	unstable

From Fig. 5 it can be seen that the optimal combination of wire feed rate (or current) and voltage can be linearly expressed by:

$$U = 0.08 \,.\, I + 8.4 \qquad (1)$$

where
U - programmed voltage (Volt)
I - programmed current = 80 to 170 Amp, or

$$U = 1.6 \,.\, w + 10.8$$

where
w - wire feed rate = 2.0 to 6.5 m/min.

When wire feed rate and voltage satisfy this relationship, the arc is free of metal spatter and the metal transfer is regular. Thus the heat generation of the arc or heat input to the joint is also regular.

This above equations and the information contained in Fig.5 can be put into an expert system.

6.2 Determination of Optimal Welding Speed

Figure 6 shows the the weld quality as a function of welding speed and welding current for MAG welding

BACK TO THE BASIC — GMA WELDING PROCESS

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The GMAW (Gas Metal Arc Welding) process uses the heat generated by an electric arc to fuse the joint area. The arcs formed between the tip of a consumable, continuously fed filler wire and the work-piece and the entire arc area is shielded by an inert gas. The principle of operation is illustrated in Fig. 1.

Terminology

GMAW is the preferred terminology for this process in the USA and is becoming more widely accepted over the terms 'MIG' or 'MAG' welding as it is more specific and leads to less ambiguity. MIG (metal Inert Gas) welding technically uses a totally inert gas shield, e.g. argon, whereas MAG (metal Active Gas) indicates that the shielding gas contains active constituents, e.g. carbon dioxide or oxygen. The process is sometimes called CO_2 welding or semi-automatic welding. In these Training Modules the process will be referred to as GMAW.

FUNDAMENTALS
Equipment requirements

The basic arrangement of the GMAW welding system is shown in Fig. 2 and consists of

- a welding power source,
- a wire feed unit, and
- a torch.

For the GMAW process, a power source with a direct

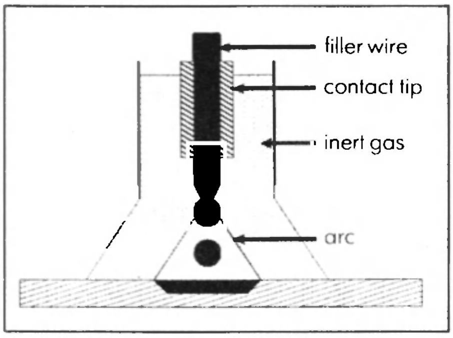

Figure 1. The principle of GMAW operation.

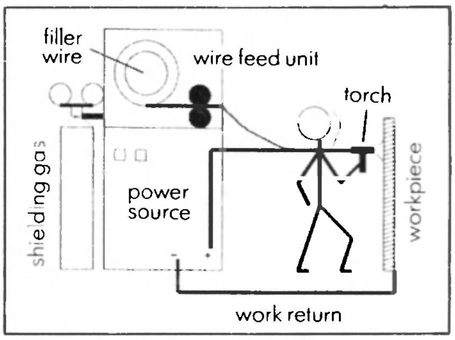

Figure 2. The basic arrangement of the GMAW welding system.

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of I-joints of 2 mm with 0 mm joint gap. The welding voltage used was chosen according to the equation established in the previous section.

As can be seen, for each current or wire feed rate, there exists a minimum welding speed. With a welding speed less than this critical speed, the plate is burned through. The burning-through is caused by excessive heat input, which increases with decreased welding speed. This critical welding speed increases with increased current.

When welding speed is above the critical speed, no burning-through of plate occurs, but the height of the weld root decreases with increased welding speed. When welding speed exceeds a certain value, the heat input becomes insufficient to melt through the plates and a defect - inadequate joint penetration - is caused.

From the Fig. 6 it can be seen that when the current is 170 Amp, maximum welding speed is achieved, but the weld quality is sensitive to the variation of welding speed or heat input. A small variation of heat input can result in defective welds. Therefore, in this case the monitoring of the heat input during welding is neccesary in order to achieve high welding speed and to ensure weld quality.

Back to the Basic — GMA Welding Process

— *Continued from page 21*

current (DC) output is used and the filler wire is normally connected to the positive output terminal. The wire feed unit feeds the wire from a spool, through the torch, to the arc at a predetermined and accurately controlled speed. Both the consumable filler wire and the shielding gas are directed into the arc area by the torch, and the welding current is transferred to the wire by means of a copper alloy contact tip as shown in fig 1.

Consumables

The consumables for the GMAW process include the shielding gas and the filler wire. The shielding gas protects the weld area from atmospheric contamination but also has a significant effect on the stability of the process, fusion characteristics and weld bead shape. Argon and helium, inert gases, may be used for some materials (eg aluminium and copper alloys) but active gases containing oxygen and carbon dioxide are often used to give improved operating characteristics particularly with ferrous materials.

The filler wire used for GMAW welding is supplied as a solid wire. The diameter is usually in the range 0.6 mm to 3.2 mm and the chemical composition is similar to that of the material being welded.

Operating modes

The characteristics of the GMAW process depend on the mode of metal transfer from the electrode to the weld pool. The common modes of transfer are usually classified as shown in fig 3.

Free fight transfer occurs when the material crosses the arc in the form of droplets, whereas in dip transfer the arc is extinguished at regular intervals when the filler wire comes into contact with the weld pool.

Free flight modes

Globular transfer occurs at low currents and may be found when steel wires are used in a carbon dioxide shield. It is typified by the formation of very large droplets which are detached from the end of the wire by gravity (fig. 4a). Transfer is often irregular and unstable, and large amounts of spatter are produced.

If the welding current is increased and an argon based gas is used, the droplet size decreases until the droplet diameter is similar to that of the filler wire (fig.4b). The frequency of transfer is increased and the arc is stable with low spatter levels. This type of is called spray. Although the current at which it occurs varies with wire composition, wire diameter and shielding gas it is normally found above 200 amps.

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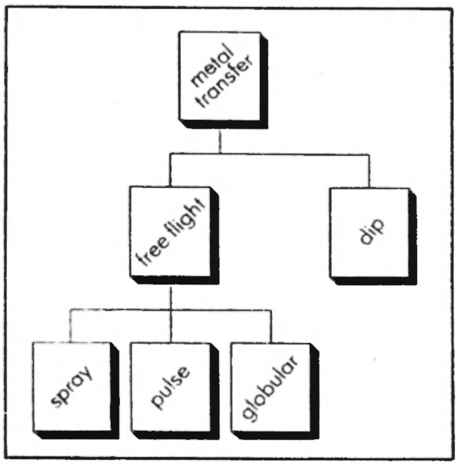

Fig. 3. *The common modes of metal transfer in GMAW.*