REVIEW ARTICLE

An Overview of Arc Welding Control Systems

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Abstract: In this paper an overview of arc welding control systems is given. At first some basic physical background of the process is given. Then the two most important subtypes Gas tungsten arc welding (GTAW) and Gas metal arc welding (GMAW) are presented in some detail. In order to understand the logic of feedback control systems, the most essential control theory is outlined shortly. In the overview of control systems a feedback signal is used as a means of division. The analysis of recent research papers in the area has shown that recently image processing based control systems seem to be the most popular ones.

Keywords: arc welding, control, overview, GTAW, GMAW, TIG, MIG/MAG.

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1. Introduction

In general welding can be defined as a localized coalescence of metals or nonmetals (usually called weldpieces) produced either by heating them to the welding temperature, with or without the application of pressure, or by the application of pressure alone, with or without the use of additional filler metal. A schematic overview of the better known welding processes is shown in **Figure 1.** Although there are some 40 or so welding processes, only a few processes are really important [2]. One of the most important ones, if not the most important one, is arc welding. The term arc welding refers to a broad group of welding processes that employ an electric arc as the source of heat to melt and join metals. It is believed that in the entire metal fabrication industry, arc welding is the third largest group of processes, behind assembly and machining in metal fabrication industry [2].

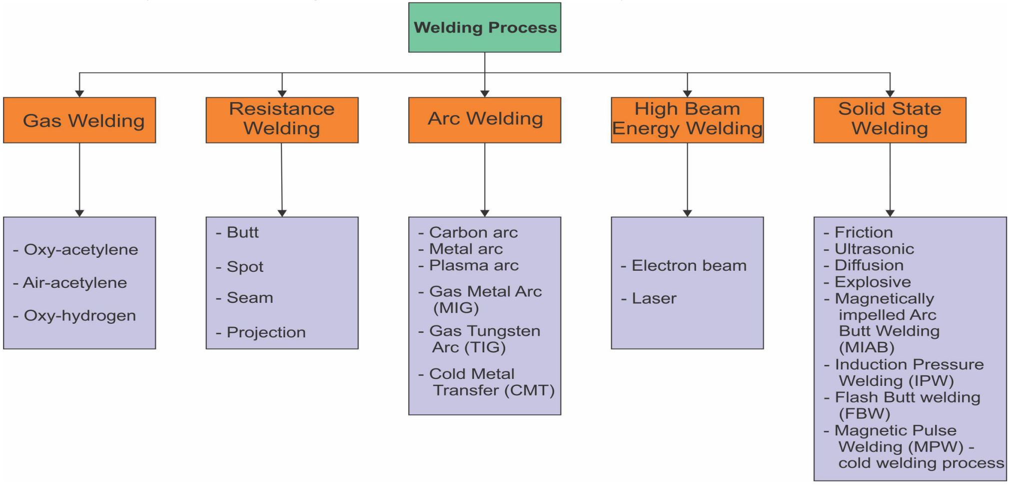

Figure 1. An overview of welding processes [1]

From the historical perspective the first type of welding was forge welding, where the weldpieces are first heated and then hammered or pressed together to remove slag and oxides and enable the bonding of the surfaces. An alternative is the so called fusion welding, where the heat input must be intense enough to locally melt the two

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weldpieces. In the case of a surface heat source the minimum rate of energy release per unit area P required to maintain a molten weld pool of radius r is approximately [3]:

$$P = \frac{AkT_m}{r} \tag{1}$$

where k is thermal conductivity, T_m is melting temperature and A is a factor dependent on welding speed, weld size and thermal diffusivity. The weld pool size is of course limited by practical considerations. The typical values are within 10-20 mm range, which for steels results in the required power density of around 107 $\frac{W}{m^2}$. As shown in **Figure 2** this is a typical value of power density provided by arc welding sources. This is one of the reasons for its widespread usage.

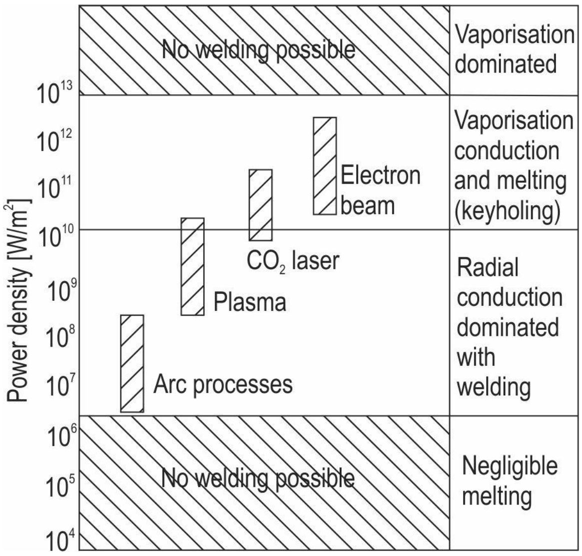

Figure 2. Power density for various welding processes [3]

An arc (see **Figure 3**) refers to strong electric fields that cause gas to induce an electric breakdown and continuous discharge of plasma [5]. Thus, a current passes through insulation media in a manner similar to air. A typical arc welding setup is shown in **Figure 4.** The welding current can be DC or AC and the electrode can be consumable or non-consumable. In many cases the welding region is protected by a shielding gas. A power source is also needed in order to get the voltage down to an appropriate value. Welding processes in general need lower voltages and higher currents. Advanced power sources are also capable of providing signals of various waveforms, which might be adjusted in real time based on some feedback signal. Power source related research is still very active [6], [5], [7]. There are several subtypes of arc welding, but only the two most common ones will be described in some detail.

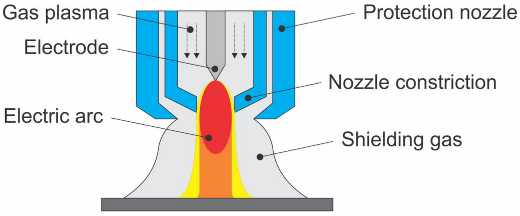

Figure 3. Arc plasma [1, 4]

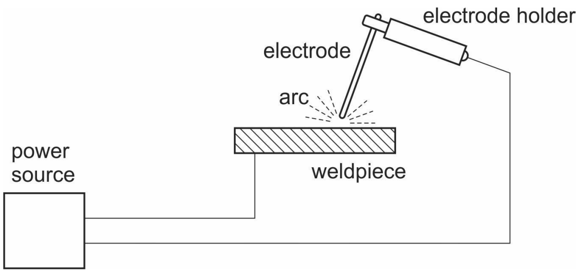

Figure 4. Schematic representation of arc welding

1.1 Gas tungsten arc welding

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding is a widely used high-quality, high-precision welding process. In TIG welding, an arc is established between a nonconsumable tungsten electrode and a metal that is heated and melted (see **Figure 5**). Filler wire may be added for the weld. The inert gas [9]:

1) shields the welding area from the air, preventing oxidation,
2) transfers heat from the electrode to metal, and
3) helps to start and maintain a stable arc (due to the low ionization potential)

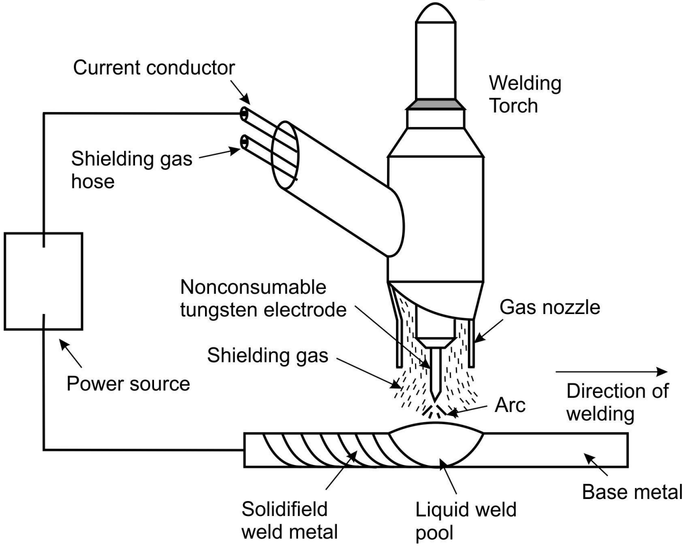

Figure 5. Schematic representation of GTAW (TIG) welding [8]

Although pure argon is the most common choice, shielding gas composition can also have effect on the resulting weld in some cases [10]. The process can be used for many types of materials in all welding positions, and it provides a concentrated, stable arc and a high-quality and neat weld deposit. Plasma arc welding (PAW) is an extension of GTAW characterized by a much higher arc energy density and higher plasma gas velocity due to the arc plasma being forced through a constricting nozzle [11].

1.2 Gas metal arc welding

Gas metal arc welding (GMAW) (sometimes also referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) welding) is widely applied in various industries because of its high productivity, flexibility, and low cost. It can be operated in semiautomatic and automatic modes and can be used particularly well in a high-volume production environment [12]. A typical setup is shown in **Figure 6.** In GMAW, there are three major modes of metal transfer from the electrode wire to the weld pool: globular transfer, spray transfer, and pulse transfer as shown in Figure 7 (some authors also define streaming transfer [14]). By using a pulse current, it is for example possible to achieve

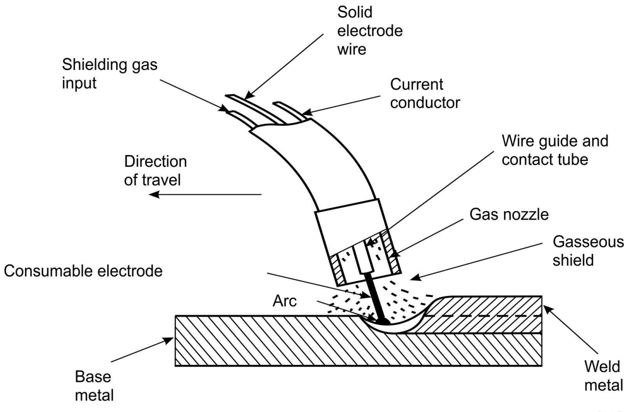

Figure 6. Schematic representation of GMAW (MIG/MAG) [13]

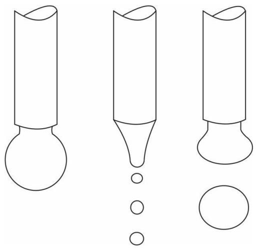

Figure 7. Metal transfer modes (globular, spray, pulse) [15]

a stable one drop per pulse mode and therefore a controllable metal transfer to the weldpiece [16]. The feedback control systems for this type of welding have already been proposed [17].

Despite being one of the most common arc welding processes, GMAW also has shortcomings. One is the fact that the same current is used to melt the wire and heat the material. That means, that by increasing the melting speed for higher productivity we also increases the base metal heat input resulting in increased distortion. To resolve this problem a modified approach called double-electrode GMAW or DE-GMAW has been proposed [18]. As each arc's magnetic field influences the other, the process is still being researched [19], [20].

2. Control system background

In control system theory, a system is usually presented by a block diagram as shown in Figure 8. In the case of arc welding the object is the welding process under consideration. The input vector **x** is composed of all the parameters that influence the process. These are welding voltage, distance between the electrode and the weldpiece, electrode geometry, wire feed rate (in GMAW), weldpiece thickness and composition, shielding gas flow and composition, etc. The components of the output vector y are all the characteristics of the resulting weld (weld strength, corrosion resistance, visual appearance, possible deformations etc.).

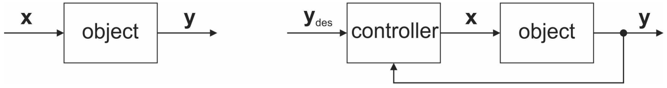

Figure 8. Open loop and close loop control system

The relationship between input and output can therefore at least in theory be given by some vector function f

$$\mathbf{y} = f(\mathbf{x}) \tag{2}$$

Although we cannot write down this function, experience tells us, that an appropriate combination of input parameters x, will usually (but not always) result in an acceptable output y. The problem lies in the fact that in some cases we lack experience or there are some signals, which we cannot monitor or control (the so called disturbances d). So, Eq. 2 can be rewritten into the following form:

$$\mathbf{y} = f(\mathbf{x}, \mathbf{d}) \tag{3}$$

The solution is the modification of the system from the so called open-loop form (left side of **Figure 8**) into the so called close-loop form (right side of **Figure 8**). In close loop form the output y is monitored (measured) and fed back to the controller. The controller compares the actual values y with the desired ones y_{des}. Based on this difference the input to the object is calculated in such a way that the difference between the actual values y and the desired ones y_{des} (the so called error signal) decreases or ideally equals zero. So the control algorithm programmed in the controller can be written in the following way:

$$\mathbf{x} = g(\mathbf{y}_{des} - \mathbf{y}) \tag{4}$$

Within the domain of arc welding related control systems by far the most common control algorithm is the so called PID control algorithm [21], [22], [23], [24]. The other commonly used control algorithms are based on fuzzy logic [25], [26], neural networks [27], [28], [29], sliding mode control [59] and others [30].

3. Arc welding control systems

From the control theory point of view, the main problem, when designing a control system is the fact, that most of the components of the output vector y in Eq. 3 cannot be measured. Weld strength, which is the most important, can for example only be determined by destructive testing after the weld is already made. Because of that, a lot of research is made based on some more or less easily measured signal, which however is correlated with good quality weld. Some of the most common systems will be discussed.

3.1 Seam tracking

Especially in robot arc welding applications it is very important for the welding system to follow the seam accurately. These types of arc welding control systems do not exactly fit into the idea presented in the preceding section, despite being a proper feedback control system. The main goal of seam tracking control system is the elimination of one disturbance (improper positioning of the electrode in relation to the weldpieces). There are various approaches in this group. Some researchers have for example used ultrasound [31], but the most common approach are image processing based control systems. An early example of such a system is shown in **Figure 9** [32]. The system uses structured laser light which reflects from the weld seam and forms an image in the image sensor. A typical image obtained by this method is shown in the right part of **Figure 9.** The lowest point in the image is very simple to determine by the most basic image processing algorithms. This setup is used often in recent research [33], [34]. A very similar seam tracking system on a mobile robot welding platform has also been developed [35]. Some recent solutions within this set don't even need a source of structured laser light anymore [36], [23]. Another approach[37] uses an asymmetry in the weld pool image in order to track the seam.

A system[38] is also given in this subsection despite not being a seam tracking system. It uses a linear CCD sensor to determine the type of weld joint.

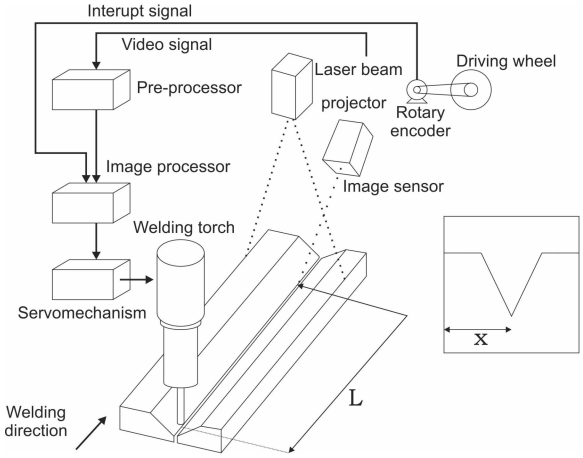

Figure 9. Seam tracking system [32]

3.2 Temperature measurement

The quality of a weld joint is strongly related to both the spatial distribution and temporal history of temperature in the weld region during the welding process. Therefore a control system which would be able to control the temperature would clearly be beneficial. Such a system, where temperature is being measured using a commercially available infrared pyrometer with a 3-mm target diameter focused on the trailing weld bead, 2.5 cm from the tip of the electrode is an example[39] shown in **Figure 10.** The manipulated variable is the welding voltage. A camera based system used for

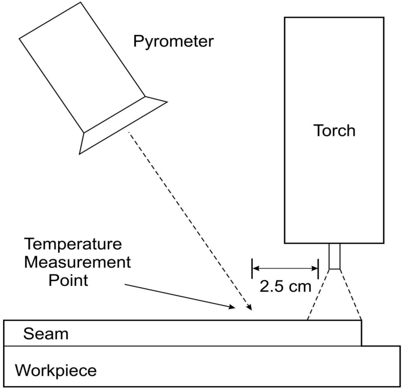

Figure 10. A possible temperature measurement setup [39]

that purpose has also already been developed [40]. Temperature measurements obtained with this system are within 10% of those measured by a calibrated two-color optical pyrometer despite the fact that an inexpensive and readily available video camera was used.

3.3 Image processing based control systems

The idea of image processing based arc welding control system lies in the fact that an experienced welder can judge the quality of welding process quite well. His main sense used in this task is vision. A typical setup of an early version of image processing based arc welding control system is shown schematically in **Figure 11** [41]. In this specific case the process under consideration is the GMAW. For image acquisition a monochrome CCD camera which is capable of obtaining 16bit resolution images of 256 x 256 pixel size. A typical image obtained in this way is shown in **Figure 12.** As camera is fixed to the torch, the position of the arc in the image tells us if the torch is either too high or too low. The system is also capable of determining the weld pool size. This is done by counting the number of pixels (and therefore area) with a certain brightness. When the brightness reaches the lowest level of the weld pool, the area typically increases more than 1.5 times. Therefore, it is possible to determine the weld pool area by counting the number of all the pixels that are brighter than the lowest level of the weld pool. Other (later) systems use similar setup for control purposes.

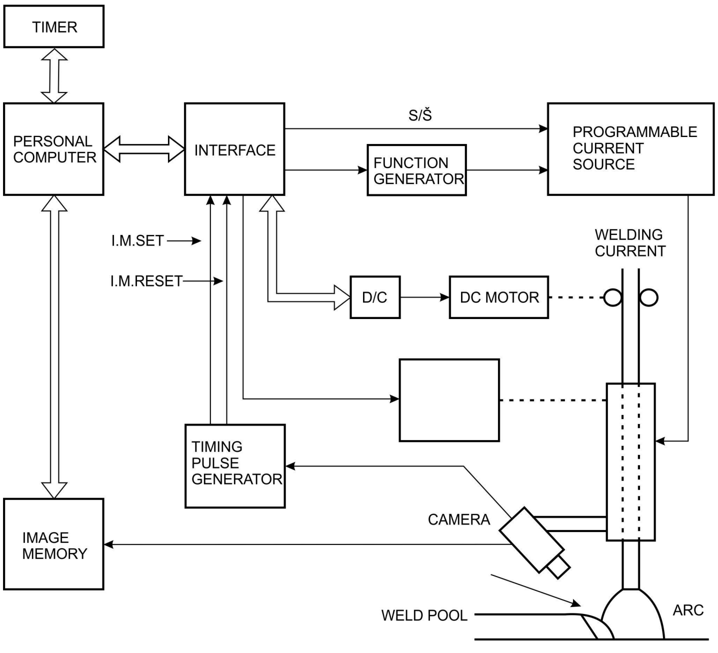

Figure 11. A typical setup of an early version of image processing based arc welding control system [41]

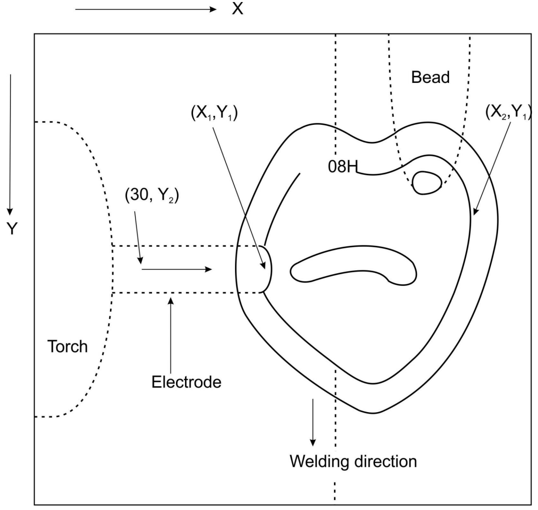

Figure 12. Image obtained from a system shown in Figure 11

A system uses a camera viewing the weld pool region at the 45° angle[42]. Contrary to the previous system, here a pulsed laser with a peak intensity that is much higher than the intensity of the arc light is used for illumination. The laser is projected on to the weld pool and its surrounding area. Because the weld pool surface is mirror-like, the projected laser light is specularly reflected from the surface of the weld pool. The corresponding image of the weld pool is therefore dark. But from the solid area surrounding the weld pool, the projected laser is diffusely reflected. The resultant image is bright. Thus, the weld pool can be very clearly viewed and estimated. Further development of this approach is given in the reference[43]. A problem of too bright images and therefore a need for a laser illumination can be eliminated if images at the right moment on the current wavefrom are taken [28]. A more advanced approach using a camera and filters with the application of active contours is presented in the reference[44]. Another interesting approach is outlined in the reference[45]. It is well known that the spectroscopic analysis of the plasma spectra produced during the welding process is a possible technique to monitor the quality of the resulting weld seams. The analysis of specific emission lines and the subsequent estimation of the electronic temperature profile offers a direct correlation between this parameter and the corresponding weld seams.

Systems using a structured laser light reflection (similar as in seam tracking) in order to determine the weld pool parameters are presented in the references[46], [47]. A more advanced system using a set of laser lines is shown in **Figure 13** [48]. Due to the change of the welding pool surface, the projected straight laser lines will be distorted differently. Accurately computing the equations of these laser lines is necessary for the subsequent weld pool shape estimation. A similar approach using a 20mW laser with variable focus in order to project a 19-by-19 dot matrix structured light pattern on the weld pool region is presented in the reference[8]. The measured characteristic parameters are then used to estimate the backside bead width. An adaptive neuro-fuzzy inference system (ANFIS) is used for this purpose. An even more advanced system is presented in the reference[49]. It uses three cameras and structured laser pattern to get an accurate reconstruction of weld pool.

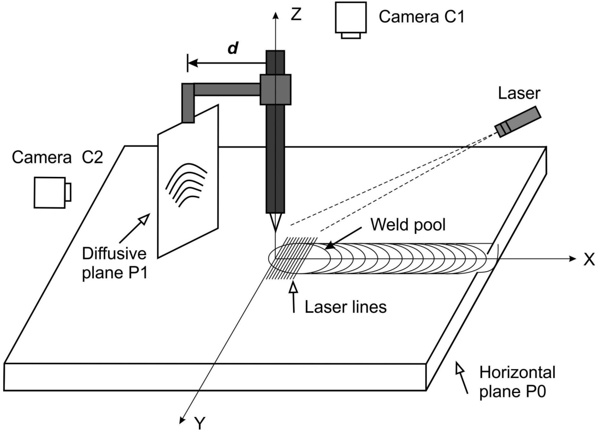

Figure 13. Weld pool observed by the reflection of structured

3.4 Arc Length based control systems

For most welding situations, it is desirable to keep the arc length constant to produce a high-quality weld [50]. The common method used is to keep the arc voltage constant. In order to explain the rationale behind the arc length control the power supply is converted into the equivalent RL circuit as [51]

$$U_p = L\frac{di}{dt} + Ri + U_a \tag{5}$$

where U_p is the voltage of the power source, L the inductance, R the resistance, i the welding current and U_a the arc voltage. The arc voltage is determined by equation [52]:

$$U_a = k_a l_a + k_p i + U_c \tag{6}$$

where l_a is the arc length, and k_a, k_p and U_c the parameters of the arc characteristics. This equation is an approximation as the voltage drop in the arc is still being researched [53]. The basic conclusion, which is however always valid, is that arc length can be controlled by arc voltage. This fact was for example used in a control system presented in the reference[50]. A special care is taken of arc ignition and arc termination. A GTAW feedback system in which the actual arc voltage is compared to the reference voltage and then the welding torch position is being controlled is presented in the reference[54]. An improved version of this approach using gain scheduling is detailed in the reference[55]. As parameter k_a in Eq. 6 is not really constant, an adaptive voltage control system is proposed in the reference[56] and a predictive functional controller based on ARMarkov model structure in the reference[30].

Optical systems used to determine the arc length have also been introduced. A precise system for arc length sensing in GTAW based on arc ligth spectrum is for example presented in the reference[57]. There are also systems based on acoustic signals. A real-time control of welding penetration during robotic GTAW dynamical process by audio sensing of arc length is presented in the reference[24].

3.5 Other systems

There are also some other interesting control systems. When arc welding is used in additive manufacturing, wire twisting is an important disturbance. An image processing system addressing this problem is presented in the reference[58]. A complex control system used for an arc welding based shaped metal deposition (SMD) system that is an innovative method for the manufacturing of metal objects is outlined in the reference[60]. Both visual and acoustic signals were taken in consideration for control purposes.

4. Conclusion

Arc welding might be considered as a mature joining process. The paper however showed that there is still an enormous amount of research going on in relation with arc welding control. This might be attributed to the fact that it is probably by far the most important welding process.

The main conclusion based on the conducted overview could easily be that machine vision / image processing based control systems are becoming the most hot topic. In arc welding control where process feedback is needed images may be required of the arc, weld pool, underbead, surface bead, or weld preparation. Observations of the arc length and electrode stickout can also give important information about the process. Arc intensity is also affected by various process parameters and disturbances. The weld pool also emits radiation in the visual part of the EM spectrum. As intensity levels are much lower than those emitted by the arc itself, it is often used to asses the weld quality. This is also attributed to the fact that this is where the weld strength comes from. So, it can be concluded that there are still many possibilities for future research in the area of arc welding control, especially control systems based on visual information, because the equipment needed is getting more an more inexpensive.

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