Chapter 12

Visual Analysis of Welding Processes

Yoji Ogawa

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/53519

1. Introduction

Fusion welding process is very convenient method to join metal structures. It plays the most important role on industrial production. The process itself is quite simple. The generated heat sources such as arc and/or laser melt the limited parts of work pieces to be joined, and the joint zone is unified after solidification of melting metal in the groove. However fusion welding process contains much interesting research targets(Ogawa,2011). For example, metal contains many elements those thermal properties are quite different. The surface is oxidized. When the concentrated heat source strikes on the metal surface, some elements are evaporating away from the original work piece. If the shielding is insufficient, some amount of hydrogen and oxygen invades into the hot metal. Hydrogen reduces mechanical property of the structure. And quick re-solidification produces quite different structure compared to the original base metal which was qualified by thermal refining process. Usual fusion welding process contains four phases such as solid, liquid, gas and plasma. Plasma is quite hot, maximum temperature exceeds 10,000K. The temperature of metal in solid phase to be joined is normally in room temperature. The temperature of molten pool in the base metal is raised up more than melting point. But, this temperature is about 3,000K or less. Then the temperature gap between liquid parts and plasma is tremendous. The physical reactions in those regions include many unknown factors(Zacharia & David,1993). These reactions occur in quite small area about one centimetre cubic space. Therefor the moving speed of target in observing area is quite high. This is the main reason why high-speed imaging technique is necessary on visual analyssis of fusion welding processes. Almost all of welding processes are carried out in factories on the earth. However, some welding processes must be carried out in deep water or in space. These are another interesting area to study.

INTECH
open science | open minds

© 2012 Ogawa, licensee InTech. This is an open access chapter distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

2. Basics on imaging for fusion welding phenomena

2.1. General instruction for Gas Tungsten Arc Welding process

Basic concepts to study arc welding process had been constructed before 1970s(Pattee et al.,1973). The most useful signals to understand arc welding process is arc voltage and current. However, these two electrical signals are insufficient to understand actual process. Then, high-speed filming technique was introduced. The most important matter to get reasonable image of arc welding process is how to eliminate the meaningless light from the process. Very strong light is radiated from the arc. This strong light protects to observe actual welding procedure.

Figure 1 shows a fundamental concept of Gas Tungsten Arc welding (GTAW) process. GTAW is one of the simplest of fusion welding process. Electrons emitted from tungsten cathode impinge a base metal. Some parts of argon atoms, those are normal inactive shielding gas to avoid oxidation of molten metal, ionize in an arc column. The arc column is a channel of current between cathode and anode, and it includes the same number of ions and electrons. The strong light is radiated by recombination reaction with ions and electrons. Understanding of current density distribution is important to know thermal transportation, and the distribution of this radiation suggests the temperature of arc column. The GTAW process is materialized by the tight energy balance among the cathode, arc column and weld pool. And there exist very complicated physical and chemical reactions in each region.

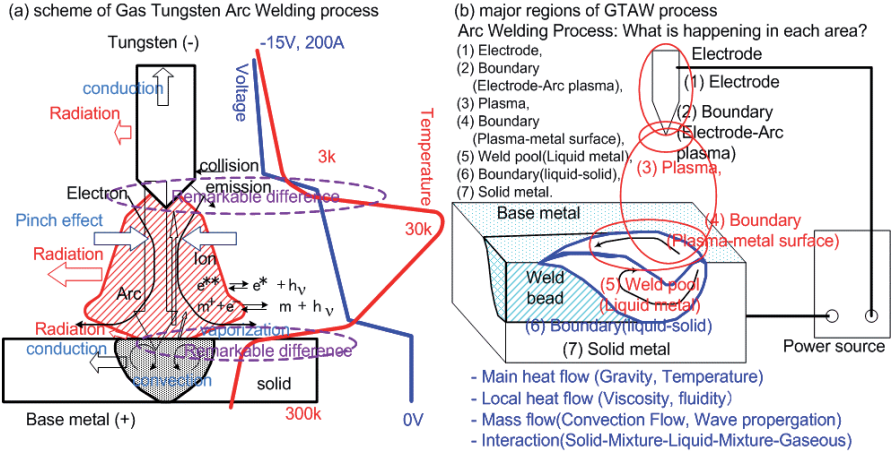


Figure 1. Scheme of Gas Tungsten Arc Welding(GTAW) process.

Figure 1(b) shows the main typical regions of interests during GTAW process. There are three major zones such as base metal, arc column and the tungsten electrode. The base metal has three different regions. They are melting zone, solid zone and boundary between solid

and liquid. The boundary zone is the most important on metallurgical point of view. Crystal structure in boundary becomes large, and the mechanical property of the metal changes as a result. Some defects like blowhole or undercut occur in this region. A melting area as called weld pool is complicated. Electrons and atoms hit on the molten surface, and some atoms invade into the pool. A surface of the base metal in front of the pool contains much oxide. The melted oxide also invades on the pool. Many physical and chemical reactions occur on and in the pool. Rapid liquid metal flow also occurs on and in the pool.

The tungsten electrode is expected as a non-consumable cathode. The cathode is mainly heated by Joule heating by current passing through the electrode. The surface of the cathode is heated by collision of atoms and ions from the outer space, and the top area, which called cathode spot, is cooled by electron emission. Normal tungsten electrode contains a few per cents of thorium oxide to improve emission ability. Thorium oxide on the cathode surface evaporates during arc process. A cool surface of the electrode is normally oxidized. And tungsten oxide is much easier to melt and evaporate compared to pure tungsten, then some amount of tungsten oxide, 3 or more millimetres from the top, melt and move toward the top where the arc generates. And the temperature near the top is hot enough to evaporate the invading tungsten oxide. Evaporated tungsten oxide is easy to dissociate to tungsten and oxygen. A temperature of middle region between the top and the area where tungsten oxide evaporates is cool enough to crystallize the impinged tungsten atom from the outer space. Very complicated physical and chemical reactions are occurred on the cathode surface. A microscopic observation is required because normal diameter of the tungsten electrode is 1.6-3.2mm.

The arc column existing between cathode and anode is hot enough where ionization, dissociation, and recombination frequently occur. Particles in this region are heated and forced by electro-magnetic field. Much power is conducted to the work piece by moving electrons. Some power is lost to open air by radiation and conduction. Arc light is the radiation loss of arc, and the frequency distribution of radiation has important information of arc characteristics. It contains temperature distribution information in arc column. The approximate power of arc radiation is very strong, and it protects precise observation of cathode and anode surfaces. The energy transfer from the arc is crucial in the weld pool formation. And the energy transfer due to convection becomes important in the weld pool compared to heat conduction. Total thermal radiations from the weld pool and solid surface are very weak compared to arc light. How to observe actual motion in and on the weld pool under luminous arc column is the issue to study(Shaw,1975; Inoue,1981; Ogawa,2011) .

2.2. How to get good image

2.2.1. Spatial effect

Figure 2 shows basic principles to show spatial effect of arc light. Suitable selections of exposure time, diaphragm and filtering set-up of camera are essential to get high quality image. An external light is usually used to improve image quality of target which has a strong light source in it. When the arc region is very small as shown in figure 2(a), normal

light source is enough. When the arc region becomes large as shown in figure 2(b), stronger light source is required to get clear image of the whole apparatus. Some halation occurs on and near the arc. However, the arc region is also small enough to get clear image of experimental set-up. When the arc region becomes larger as shown in figure 2(c), normal light source is insufficient because arc radiation is quite high. The size of this figure is normally used for observation of high speed imaging. We need some special technique to improve image quality. Details of how to get high quality image of fusion welding process are described in section 3.

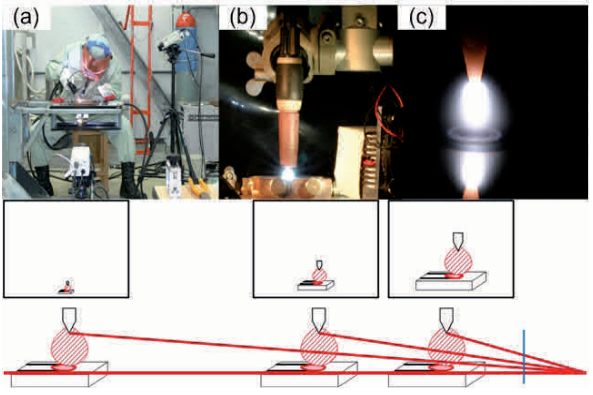


Figure 2. Size effect on image quality.

2.2.2. Fundamentals of high speed imaging

High speed video camera is a digital processor with huge memory. Captured high speed image data are processed as digital data inside of the camera. Depth of the captured data in the camera is normally 10 to 14bits. However, data depth of output image/movie is normally less than 8bits to fit normal picture/movie standards. Objects in three dimensional space are captured onto two dimensional digital data. Many two dimensional data sets are stored time by time as shown in figure 3(a). In case of monochrome camera, only one colour information on each pixel is stored. In case of colour camera, it captures three kinds of colour information on each pixel. They are red, green and blue. The arc light itself contains from ultra violet to infrared regions. Normal colour camera is set to fit human eyes, so light which is out of visible range of human eyes are avoided. But, ultra violet and infrared lights from arc are so strong compared to normal scene, so it affects the colour tone of the captured image(Ogawa,2008).

When the camera condition is set to get clear arc image, almost all back ground become black as shown in figure 2(c). One simple solution to capture clear background image is using a strong external light. Another good solution is using narrow banded interference filter which protects arc light and pass the light from back ground. Spectroscopic data is also useful to understand arc characteristics. Factors of interest to understand arc welding

process are three dimensional space information, wavelength information and temporal variations as shown in figure 3(b). Dynamic range of camera device or data depth of image is also important factors for precise analysis.

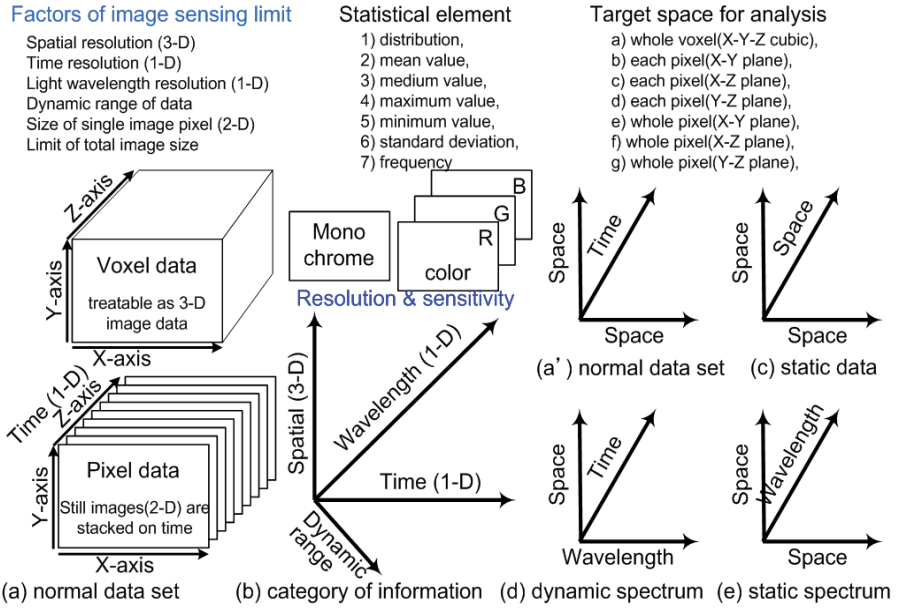


Figure 3. Data structures of high speed imaging.

The image of object just on the focal plane is clear, and the brightness of captured data is higher than those from out of focus position. When the objects is static, range information can be detected by changing the camera position or focal distance as shown in figure 3(c). Spectroscopic imaging is also important to understand the process behaviour as shown in figure 3(d). If the object is stable and constant, static spectrum information can be detected as shown in figure 3(e). Two dimensional digital data of each still images are stacked time by time in case of high speed imaging. The data itself can be treated as voxel data as shown in figure 3. Then statistical analysis becomes possible, and it becomes easy to choose numerous points of view to analyse the whole process. This is the remarkable benefit of high speed imaging to study on welding process.

2.2.3. Non-linearity on brightness

However, we need careful selection and understanding of observation conditions. Usual camera is fabricated to fit human sense. Figure 4 shows effects of exposure time on data brightness. The same static object is captured by different exposure time. One important fact to realize is an effect of dark noise. Some special camera has special cooling system for sensor device to avoid dark noise. However normal high speed camera has no special

cooling system, then some dark noise is added on the data. And the values are affected by temperature and exposure time. Another important fact is special fitting process on too bright objects. There are no linearity in the highest range as shown in figure 5. Halation is protected by this process, and the picture looks very clear. However, quantitative analysis cannot guaranteed. The relation of actual brightness on object and captured data value depends on camera. One typical relation is shown in figure 5. When we try to use high speed camera for quantitative analysis like detecting temperatures, we need precise correction of several different temperature object before actual observation.

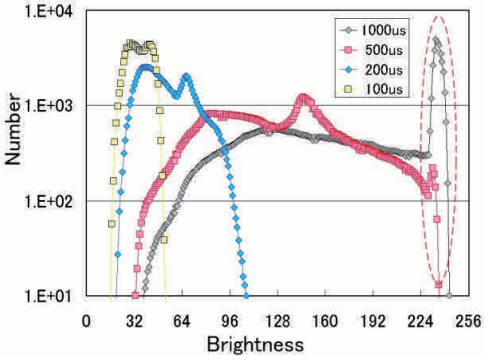


Figure 4. Effect of exposure time on brightness distribution of data.

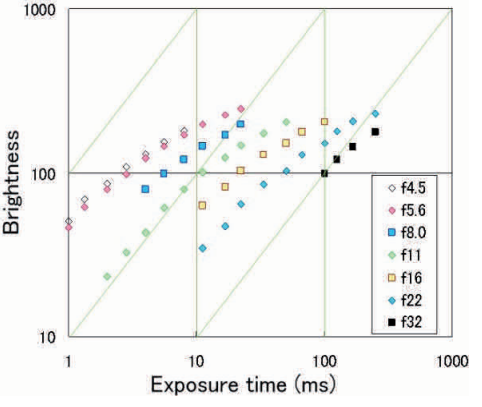


Figure 5. Typical relation between actual brightness of objects and data value.

2.3. Radiation effect

Surface conditions of a molten pool and a solid metal are quite different. The surface of the molten pool is smooth like mirror, because of surface tension, and a light illuminated on the molten pool reflects totally to the geometrical direction. On the contrary, solid surface has rough surface, and the light illuminated on the solid surface is scattered to wide directions.

This is an important difference for imaging of arc phenomena. Another important difference is radiation efficiency by surface condition. Radiation from oxides is greater than that from pure surface.

One of the major purposes of an imaging of arc is to provide a monochromatic two dimensional image from a polychromatic object. Optical frequency distribution at appropriate point has important information on arc temperatures at that point, such as electron temperature, atom temperature and ion temperature. Normal colour picture is a mapping of colour information from three dimensional scene on to a two dimensional frame. In case of normal picture of arc column, one point of the picture contains integrated intensity information in depth and integrated intensity on wavelength information. A single colour picture which means a picture at appropriate wavelength, as called monochromatic photography, and/or emission spectroscopy which measures information on wavelength distribution at appropriate point are required to estimate the temperature at that point. They are two dimensional data, and each point has information of intensity. The situations are also a matter of time. Static or quasi-static phenomena is not usual for arc welding processes, they usually changes time by time. So the time domain analysis is also required. Time domain information is easily recorded as time series of two dimensional data as shown in figure 3.

The intensity of the data show integrated values across the depth of the space. The image density measurements, as integrated intensity in depth, are input data for the Abel Integral Equation. Radiance (at each wavelength) is obtained as a function of position. The local ratio of radiances for two spectral lines then yields the temperature as a function of position. Monochromatic imaging also has more direct value. Arc light is an exponential function of radiation temperature. Total power of radiation is more than 1000 times of thermal radiation from molten metal. This is the major difficulty to get clear image and weld pool simultaneously. The highest value of radiation is estimated by Wien's law. The highest radiation just near the boiling temperature of iron is in near infrared region between 950 and 1000nm. And radiation from arc at this region is low enough to get clear image of the molten metal. Following formula are used to calculate temperature from image.

$$E_\lambda = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/kT^\lambda}-1} \qquad (1)$$
$$h = 6.6256\times10^{-34}\ Js \quad (\text{Planck's Constant})$$

$$E = \sigma T^4 \quad (\text{Stefan-Boltzmann's Law}) \qquad (2)$$
$$\sigma = 5.67\times10^{-8}\ Jm^{-2}s^{-1}\deg^{-4} \quad (\text{Stefan-Boltzmann's Constant})$$

$$\lambda_m T = 2.898\times10^{-3}\ m\ \deg \quad (\text{Wien's Transition Law}) \qquad (3)$$

$$I = A\,T^2\exp(-e\phi/kT) \quad (\text{Richardson's Theory}) \qquad (4)$$
$$e\phi = \text{work function}$$
$$k = 1.387\times10^{-23}\ JK^{-1} \quad (\text{Boltzmann's Constant})$$

2.4. Spectroscopic and monochromatic imaging

Figure 6 shows examples of argon arc images on mild steel and SUS304 stainless steel. Left hand-side pictures are over exposure images. Information of arc column is saturated, but image of cathode is clear. Weld pool and base metal can be detected. In right hand-side pictures, exposure time is too short to identify whole cathode surface, but plasma shape and metal vapour from the weld pool can be recognized. The pictures on middle part are suitable camera condition to recognize whole parts.

One good way to improve image quality is using circumferential filter of narrow band. Figure 7 shows the effect of band-pass filter on arc images. Figure 7(a) shows normal colour image, which reduce the intensity of all wavelength by ND(Neutral Density) filter. Images of different wavelength are quite different, but all of each image are captured in the same welding condition.

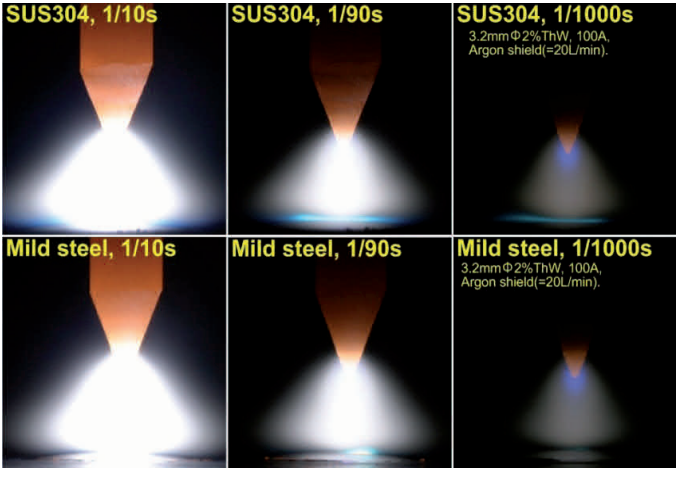


Figure 6. Example of argon arc image on metal plates.

The spectroscopic measurement of plasma condition is essential to understand plasma temperature. Plasma temperature is a key element to understand energy and mass balances in arc welding process. The problem for spectroscopic study on arc welding process is existence of metal vapour from work piece and electrode. Ionization potential of metal is much less than shielding gas. The metal vapour influences not only on ionization of plasma but also an energy transfer in boundary regions between plasma and electrodes. A grating monochromator is usually used to record spectra from representative arcs. Radiation strength is a function of wavelength depends on particle temperature. Typical line spectra due to transition of energy level indicate probabilistic number of temperature. In case of argon shielded arc, suitable lines in the Ar I (neutral) and Ar II (singly ionized) spectra are identified, measured and used to determine mean temperature of the species from the Saha's equation, Boltzmann distribution and the radiation law, by the two line method. The

ratio of typical two spectra indicates the temperature, and this method is a good way to reduce measuring error caused by measuring device such as transmission loss of lens and sensitivity of sensor device.

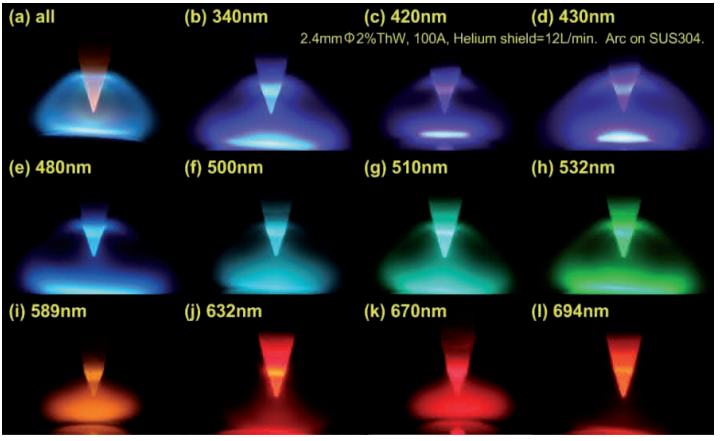


Figure 7. Example of single colour images.

The tendency is the same for thermometry. A monochromatic imaging is used to identify the measuring point of spectroscopy, and it is also used to identify spatial distribution of radiation. Spectroscopy by a prism is the simplest way to measure an interaction between radiation and matter as a function of wavelength, but resolution is much less compared to the grating monochromator. Figure 7 shows typical colour images, single colour images and spectroscopic images for several shielding gases. A single colour image at 694nm and spectroscopic image along the central line of the torch centre are captured by the same lens simultaneously. Image through the lens is divided by a prism. One half of light is passing through the band-pass filter of 694nm. The other half image is passing through the special prism which is called Imspector, and it reaches to the sensing device. Monochrome sensing devices are used for both cameras. Spectroscopic images are shown by pseudo colour system to identify the quantitative differences. Helium has a few spectra, so it can be used to identify the actual wavelength on horizontal position. Sensitivity of the image sensor is affected by wavelength. Normally, it is the highest between 500nm to 700nm range. The sensitivity over 900nm is one fourth of visible range or less. The sensitivity in the short wavelength less than 400nm is also low. Reduction loss of lens is affected by the wavelength also. Therefor precise quantitative comparison is difficult without correction of sensitivity and resolution. However, qualitative consideration becomes easy by spectroscopic imaging.

Dynamic ranges of data depth and optical frequency range are the most important factors to use measurement. A dynamic range in computer vision means data depth, and common data depth is 8 bits. The data depth of 8 bits is completely small for optical diagnostic. It usually requires more than 12 bits. Another important dynamic range is sensitivity of the solid imaging devices such as CCD (Charge Coupled Device) and CMOS (Complementary

Metal Oxide Semiconductor). Normal dynamic range of CCD camera is about 10^3. This value is much less for accurate measurements. A CMOS camera with specially tuned electronic device for sensitivity as a wide dynamic range of $10^{10\text{-}12}$ is available to use. However data depth is still a major matter to protect scientific use. Practical methods to use a solid devices for imaging are (1) using an well designed optical filter, (2) controlling the shutter timing and duration, (3) using a wide dynamic sensor, and (4) correction of image data those taken under different capture conditions as shutter speed, iris, and different neutral density filters.

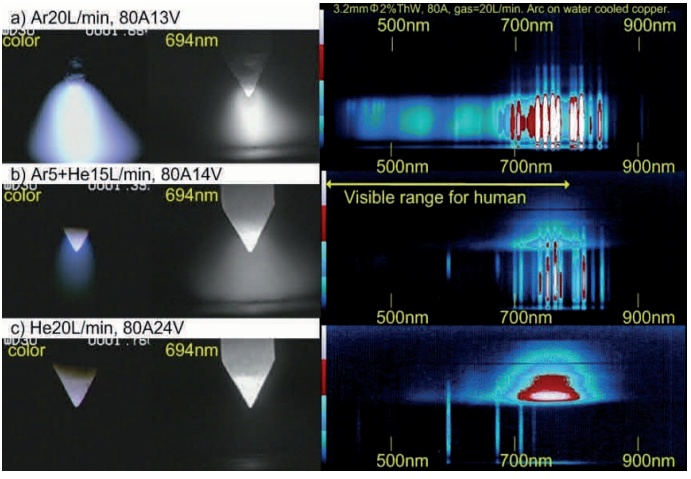


Figure 8. Effect of gas contents on arc plasma condition.

3. Observation of transient response

3.1. Observation of meta-stable stage of arc ignition

Argon and helium are usually used in GTAW process. Much smut covers on and around the welding bead in case of helium arc welding. This is a quite simple evident of metal vaporization during arc welding. Metal has much less ionization potential compared to argon or helium. Therefore, effects of metal vapours on arc properties and subsequently on weld bead configuration have been studied since 1950s(Pattee, 1973). Emission spectroscopy and monochromatic imaging were used to determine the prominent metal species present and distribution in arcs.

Temperatures of base metal and tungsten electrode are the same as room temperature until welding process is starting. Temperatures of base metal and tungsten electrode are quickly raised high. However they have some amount of heat capacity, so there are time rags to be stable temperatures. High speed video is a good tool to capture the dynamic behaviour. But, it is not so good to show movies to understand the dynamic behaviour. Capturing the video finishes very short time. But watching the captured movie takes a quite long time. Showing

the behaviour of dynamic response is another problem. Showing picture cue in time order is one answer, but numbers of pictures to show and time step are difficult to decide. Using streaking image on important location is good answer to understand the dynamic behaviour at glance as shown in figure 9. Vertical line on the centre line of the electrode is drawn by time. The top time chart shows the dynamic behaviour of centre line between arc start and 15seconds later. The behaviour at first 1 seconds changes much. It takes about 4-5 seconds to be a stable condition. The second top picture shows the detail behaviour of transient state. The third and the fourth pictures show the behaviour of the horizontal lines at cathode tip and 0.5mm below the cathode tip. These pictures show the behaviour of plasma behaviour. These streak images are good way to understand time response qualitatively. The pictures shown on the right are single colour pictures at 694nm. They are taken simultaneously. Taking pictures of different wavelength is a good way to consider actual behaviour of the process. When the cathode becomes stable condition, upper range of the cathode becomes brighter. Tungsten oxide on the surface becomes wet in this region, because temperature of the tungsten electrode becomes high enough to melt tungsten oxide on and near the surface. This high speed image shows from arc ignition to stable stage. However, video rate and image resolution are insufficient to understand actual dynamic behaviour.

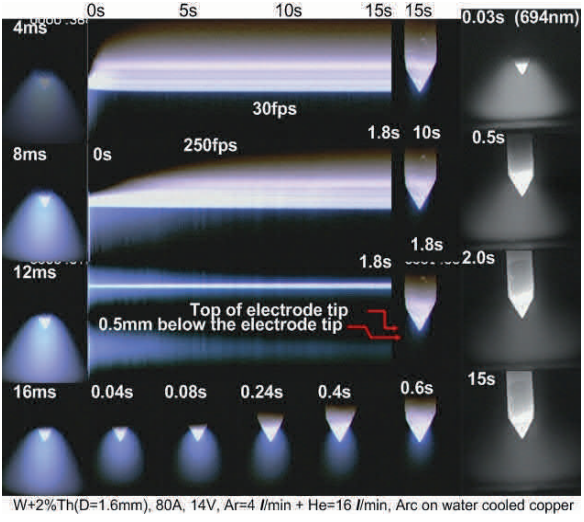


Figure 9. Typical example of GTAW at arc ignition stage.

3.2. Qualitative methods to show transient phenomena

Figure 10 shows examples of ultra-high speed pictures taken at 54k frames per seconds (fps). A picture before No.1 is absolutely in black. There is a big change between No.1 and No.2 pictures. There is brown coloured channel between the electrode and the base metal in No.1 image. This brown colour, which envelops the electrode top, is brighter than the other area. And three bright spots are shown on the base metal. These three spots have blue

colour, which is a colour of recombination from metal vapour. One bright spot is remained in No.2 picture. Blue colour zone looks like aurora occupies almost all space between the electrode and the base metal. Brown coloured zone is disappeared. One bright spot appears on the upper place of the electrode. There is a drastic change on arc behaviour at the ignition moment. Using higher video rate is better to analyse in this arc ignition period, but this video rate is the highest in this space resolution (320x256pixels) of this high speed camera. Pictures among No.3 and No.12 look almost similar. This is another problem, when we consider the process from captured high speed video. Capturing times of ultra-high speed video is a few seconds, but it takes too much time to watch whole video. Much time to save the data into a hard disk is another troublesome issue. One solution to recognize typical transient behaviour is reconstructed the stacked images into streak image which contains important information of time response.

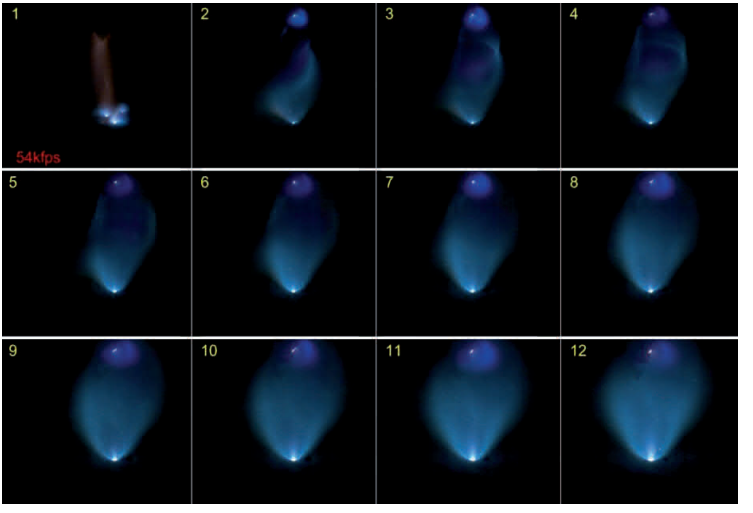


Figure 10. Time series of high speed video at arc ignition stage.

Figure 11 shows an example how to reconstruct the movie to a still picture. Left picture is a typical one shot at ignition stage. This is a typical case of arc ignition. Arc ignites in air, there is no shielding gas. Cathode and anode are easily oxidized, and their reactions produce much heat. Arc ignition in good shielding is shown in figure 12. Arc is very stable in this case, but some drastic behaviour occurs in first 5 ms.

The video rate of 250fps as shown in figure 9 is insufficient to understand actual arc ignition, because only two pictures in arc ignition stage can be captured in this video rate. Ultra high video rate as shown in figure 11 and 12 indicates that quite complicated response is appeared during first 5ms. High video rate is required for understanding of precise transient behaviour, but transient states of welding process happens only short time range. Welding process usually continues order of 10 to 100 minutes. And some unexpected

transient behaviour during steady condition also occurs in short time. Therefore, high speed video needs very huge memory size.

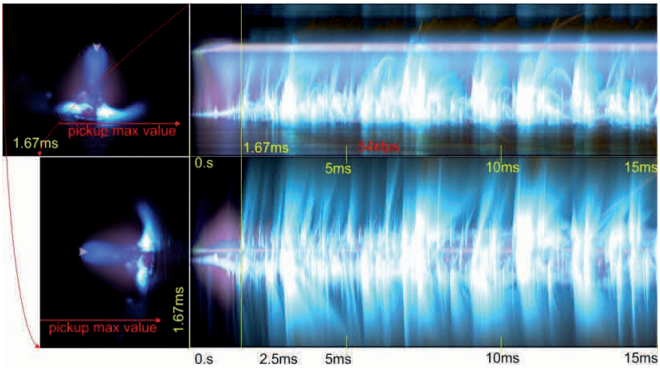


Figure 11. Example of time charts to recognize arc ignition stage in air.

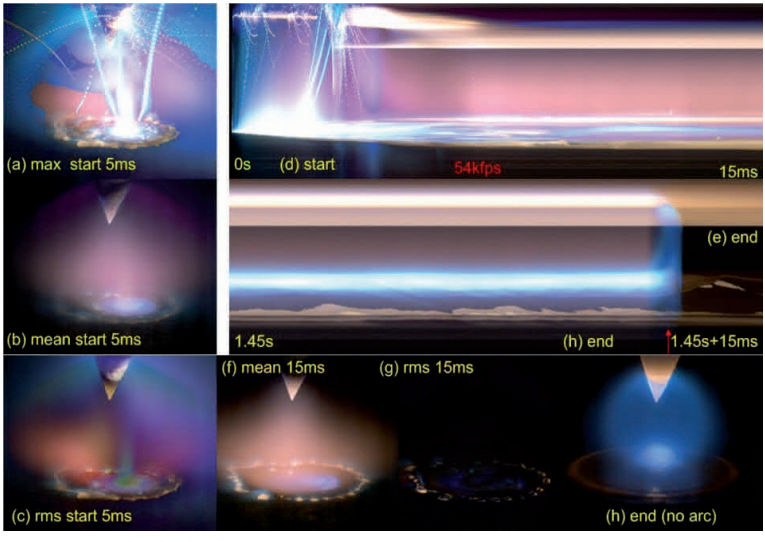


Figure 12. Methods to show process behaviour GTAW in helium shield.

Using statistical data on time axis is another good way to understand spatial behaviour. High speed camera captures many images in time series. Picking up the brightest value, mean value and/or deviation for each pixel gives us good information. Figure 12(a) shows the maximum value during arc ignition stage of 5ms. A whole time chart in this arc start duration along 15ms is shown in figure 12(d). The picture of maximum values gives us typical quantitative information on spatial behaviour. A locus of spatters indicates particle size, velocity and flying direction with its origin. Sizes and positions of anode and cathode

are apparently appeared as bright zone. A picture of mean value is almost the same as normal still picture. An image of standard deviation indicates the active regions. The image of maximum values emphasizes singular situation like sputtering. So, this image is useful to identify the place somewhat abnormal situation exists. On the other hand, image of standard deviation usually hides one time irregular event.

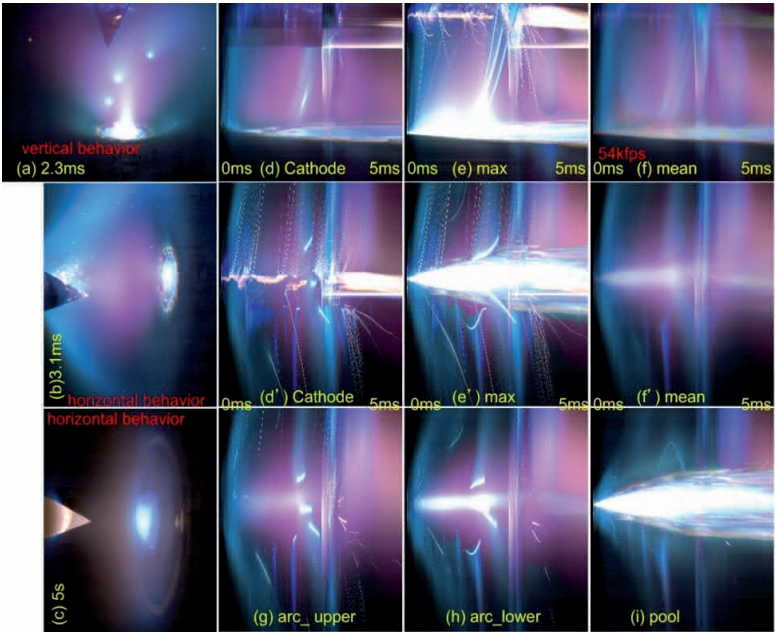


Figure 13. Examples of drawing methods to show time response.

Streak image is convenient for quick understanding of time response. And there are many points of view to get valuable information on time response as shown in figure 13. One is to check the typical line like centre line of the cathode as shown in figure 13(d). The arc process usually assumes as cylindrical symmetry, however this assumption is always wrong during arc ignition stage and improper welding condition. These conditions are main cases when we need the analysis by high speed camera. However, difference between the streak image of max value and it on the centre line suggests much good information for analysis. A streak image of mean value is also important to recognize global time response of the process. Vertical streak image is simple compared from the horizontal streak image. There are typical three different area such as the cathode region, plasma region and the anode region on the horizontal streak image. They are shown in figure 13(d', g, h and i), respectively. Pictures on typical moments are essentially important to understand the process. We can reconstruct the three dimensional behaviour of the process to use typical features of streak images in our brains. However, we need some other pictures for reconstruction of spatial features.

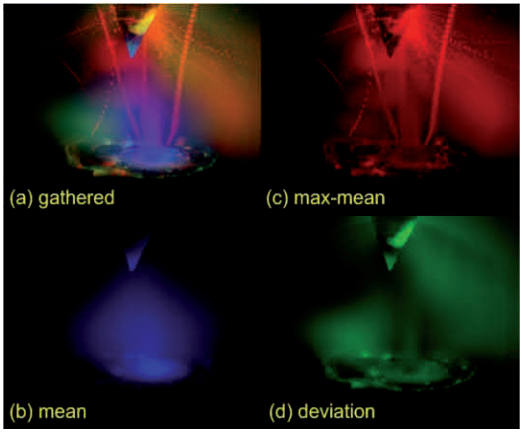


Figure 14. Examples of methods to show typical characters.

Figure 14 shows a synthotic image assembled different feature images. Figure 14(b) shows mean values of stacked images in blue colour. Figure 14(c) stresses one time feature in red, used values are maximum values minus mean value. Figure 14(d) shows deviation in green colour. Figure 14(a) is a gathered image among these three colours of different features. This kind of synthotic image which contains different feature helps to understand the spatial property at any periods. Discussions of this paragraph are somewhat sensitive or qualitative. Merit of using high speed camera is that captured huge data is digital, and quantitative analysis is expected in this field.

Figure 15 shows time response of unsuitable welding condition. Behaviour of arc ignition stage is almost the same as suitable condition. Because high frequency power source assists arc ignition. But current is too low to heat up the cathode temperature to keep steady arc. When the high frequency power is shut off, cathode spot (arc ignition area) becomes to move irregularly. It becomes stable from after 243ms of arc ignition. However, arc spot exists on the shoulder of the cathode. A single colour image of 957nm is captured in this case to get in good contrast to show arc and cathode spot. Reactions on cathode and anode are high-lighted in green, and reaction in plasma is high-lighted in red. Colour tone suggests the location of happening.

Colour image contains much information. But, colours captured by cameras have different characteristics. Captured image by usual colour camera is set to fit human sensitivity on natural scene. Radiation from arc has discrete line spectra. Therefore colour tone of captured arc image is very different by the makers and sensor kinds. We usually use (R,G,B) colour sets on pictures. Some cameras use (Y,U,V) colour system to proceed data in the camera. YUV colour system is reasonable on natural scene which has continuous property on colour frequency. Colour tones on arc welding process are different by camera kinds. Some good cameras have ability to correct colour tones, but it is very difficult to make the same colour tone from different cameras.

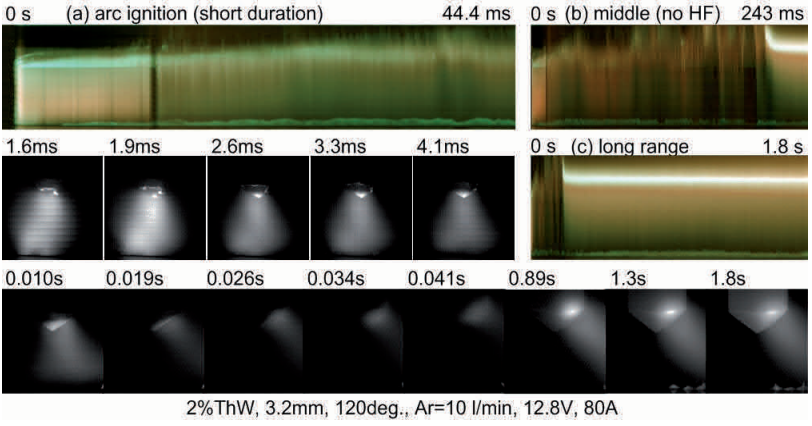


Figure 15. Examples of time response on not suitable cathode geometry.

3.3. Quantitative methods to show transient phenomena

Brightness is only apparent quantitative data at the first stage of analysis. Many quantitative elements such as cathode size and brightness distribution of cathode spot, maximum brightness of arc, arc area size, brightness distribution in arc, pool size, mean brightness of pool, metal flow speed on pool, etc.. The brightness is a good indicator to pick up unusual feature. One problem for analysis of captured data is a data depth. Normal data depth is 8bit, this means that digital range of brightness value is from 0 to 255. This data range is so small for actual arc welding process. When we focus the analysis in arc ignition period, brightness value of major target on this stage is less than those in steady state.

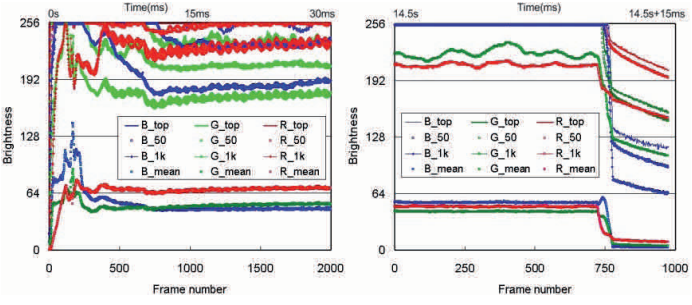


Figure 16. Time response of brightness in each frames.

Figure 16 shows the example of brightness values. This figure show maximum value(top), 50th value from the top, 1000th value from the top and mean values for each colour. Camera condition is set to get clear image of sputters during arc igniton period, so rather over exposure condition is used, and some data in bright area are saturated. Top 1000th data is appeared in the graph, and many of top 50th data also appeared in the figure. Data size of

this video is 320x256(=81,920elements), then top 1000th data means top 3% value. In this meaning, capturing condition of this figure is almost the best to understand on arc ignition stage. Figure 16 also shows brightness on the end stage. Brightness increases with time until being on the steady state. So, all top values are saturated. Radiation of plasma suddenly stops with arc expiration, however many hot particles remains in space. Radiation from hot metal vapour is only appeared on this ending stage as shown in figure 12(h), so mean value of blue is increased at this ending moment.

Mean value is low compared to top values, because it contains low values in dark back ground. Figure 17 shows the difference of mean level for total image and it on arc and relating area. Tendency of both data is almost the same except sensitivity on alteration. A power source uses inverter control at high frequency. Brightness of arc changes with this frequency, and the frequency is close to image capturing rate of 54kfps. So some interference occurs as beat plotted in figure 17(b). However area size of target is almost the same, so mean value for whole image has some sense. Spectroscopic high speed imaging is also carried out, but video rate is 2kfps. Time charts of horizontal distribution shows the difference. Radiation by recombination of atom is essential at arc ignition duration until ion produces.

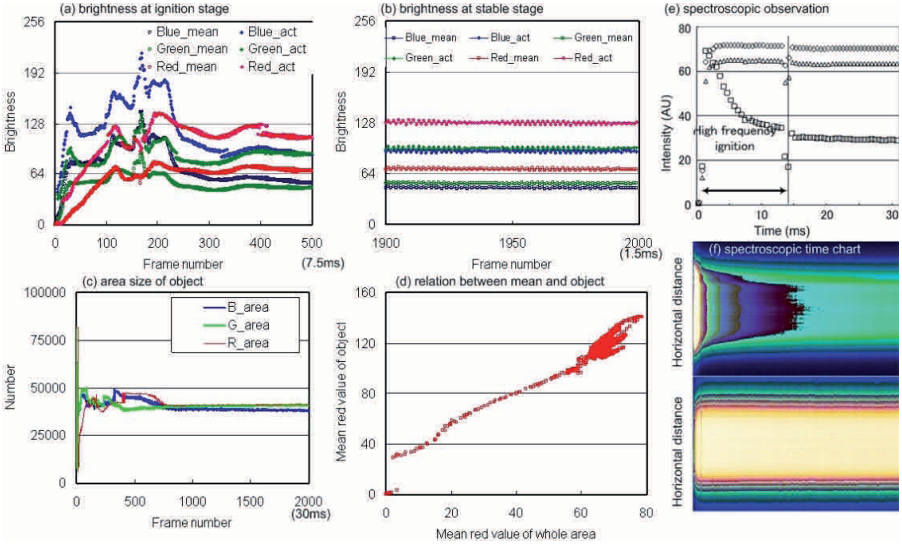


Figure 17. Examples of brightness characteristics.

Estimation of temperature on cathode and anode is important to understand welding process. Using thermal radiation value is good way to estimate temperature distribution even it usually over estimates the temperature by arc influence. Another way to estimate cathode temperature is using cathode spot area size. Electron density is a function of temperature, so estimation of mean temperature of cathode spot becomes possible when we count this area size from image. Figure 18 shows effect of gas contents on cathode

temperature. Cathode spot in argon is concentrated on tip. Spot area size increases with helium addition. Cathode spot size suddenly increases when helium content exceeds 25%. Cathode temperature becomes high with cathode size enlargement. This sudden change causes by cooling effect of electrode. When the cathode spot is small and it locates on the top, current passing through the cone shaped electrode is heated efficiently by concentrated current in the cone shaped electrode. Cooling effect acts also efficiently by conduction in the cone. When cathode spot is enlarged by helium addition in argon, heating efficiency decreases. Heating by hot helium collision onto the upper position of the electrode also increases.

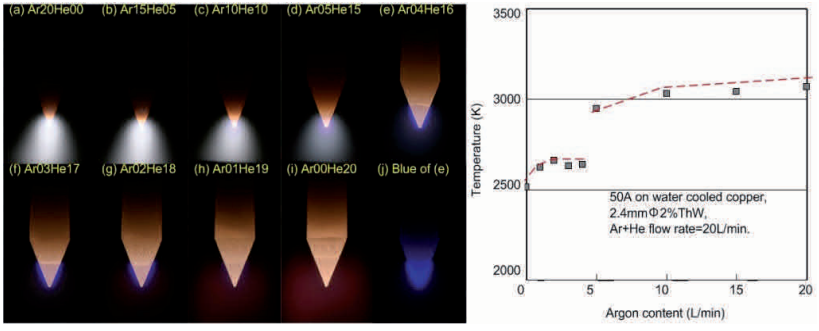


Figure 18. Effect of gas contents on arc behaviour.

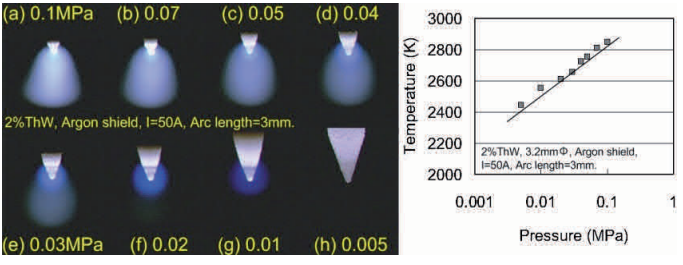


Figure 19. Effect of pressure on arc behaviour and electrode temperature.

Temperature change by ambient pressure is also estimated as shown in figure 19. Shielding gas is pure argon in this case, but argon is fulfilled in an experimental pressure chamber in this case. So, there is no flow of argon along the electrode, cooling action by shielding gas is not existed. And cooling system of cathode is different, those are reactions that cathode temperature at atmospheric condition is higher than the temperature shown in figure 18. Argon arc in low pressure looks like helium arc at atmospheric condition.

Figure 20 shows dynamic response of thermal radiation. Both electrodes are tungsten. Upper one is cathode, and lower one is anode. This movie is captured through interference filter of 532nm. Pseudo colour display is chosen to show brightness difference, because data depth of this high speed camera is 10bit. Much heat is lost by emission of electron at

cathode. Anode is heated by impingement of electrons. This is the reason why anode is much brighter than cathode. Figure 21 shows effects of wavelength on brightness. Upper pictures show original monochrome image, and lower pictures show pseudo colour image. Thermal radiation at short wavelength is much less compared to long wavelength, because the highest radiation occurs at about 950-1100nm. Capturing conditions are set in proper value for each wavelength. Brightness is also normalized, so contour line shows approximate brightness distribution.

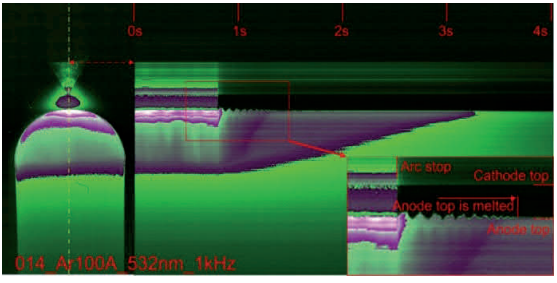


Figure 20. Dynamic response of thermal radiation.

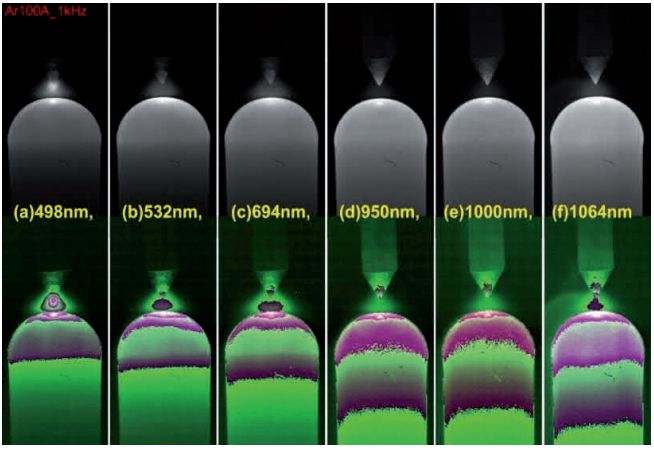


Figure 21. Effect of wavelength on radiation.

Estimation of temperature from brightness is simple method. But correction of obtained data is difficult. There are many unknown factors to correct. One simple way to correct the data is using the data at solidification area. Latent heat of solidification causes some typical feature around this area. When the brightness data is arranged as time chart, the same value continues at solidification stage as shown among point b and c in figure 22. Period between 'a' and 'b' is melting stage without arc influence. Dropped values from arc stage to no arc stage are about 1500 at point D, 1000 at point C and 750 at point A. These values are affected by radiation from arc. Point A is not melted. Solidification starts at b, and it ends at c when

almost all metal near the point c is solidified. Data during melting period, which is between 'a' and 'b', are almost the same. Brightness data increases when solidification starts, surface of solid state is rough and it is covered by oxide, so radiation efficiency is high than the liquid state. One problem is why brightness data at C and D are different. Time period during solidification is longer at Point D, this is reasonable because heat capacity on fat area is higher.

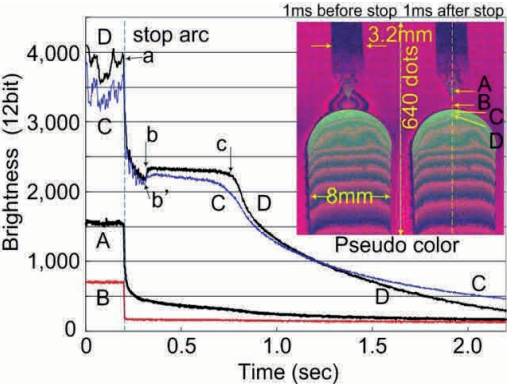


Figure 22. Measurement of surface temperature.

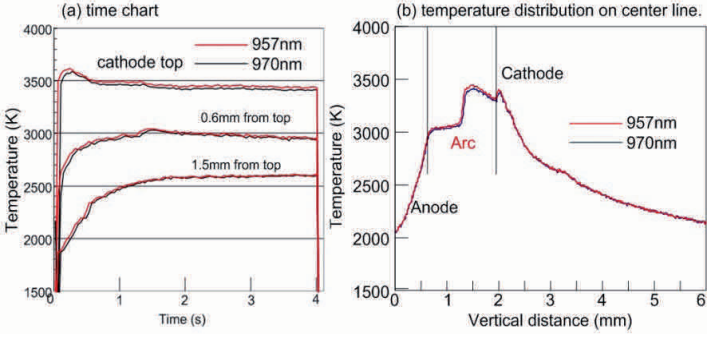


Figure 23. Example of single colour video for arc ignition stage.

Figure 23 shows temperature distribution calculated by brightness data. Argon is used as shielding gas in this case, and bead on plate welding is carried out. Used band-pass filters are 957nm and 970nm. Capturing condition is set to fit the brightness on tungsten electrode becomes just below the saturation. The reason why near wavelength is used is to estimate the influence from arc radiation. Calculated results for both cases are almost the same. Temperature at top position becomes high at early stage of arc ignition. The arc is concentrated at the top, therefor the temperature becomes high. Temperature becomes stable about 2 to 3 seconds later. Values of temperatures are higher compared to those as shown in figure18. Reasonable correction of brightness data is necessary.

Figure 24 shows temperature distribution of bottom surface of the welding pool. There is no affection by arc radiation, and boundary between liquid and solid is clearly recognized in this case. Melting temperature can be used to correct brightness data to temperature. Brightness on solid area is higher than that on solid area, therefore different fitting formula are used to determine the temperature value. Inside of red colour region is molten pool, and precise temperature distribution on welding pool is drawn in right. Upper picture shows early stage of welding, and lower one is the distribution in steady state. Length of welding pool becomes longer.

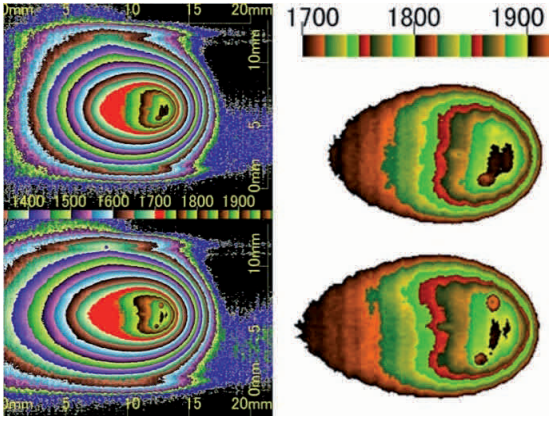


Figure 24. Pseudo colour image of temperature distribution.

4. Analysis of steady state

4.1. Effect of active flux on arc behaviour

Figure25 shows effect of active flux on behaviour of welding process. Upper pictures are captured on slant position. Lower pictures are capture in horizontal position to watch metal vapor on the pool. Major difference is size of anode area. Anode area for normal welding is wide. Anode area for active flux is narrow, and some vapor jet is shown on anode area. Next difference is position of metallic vapour color on the cathode. Metal vapour in arc decreases plasma temperature, because ionization potential of metal is much lower than argon and helium. And metal vapour is fully ionized in arc. Metal ion moves to cathode by electric field. Anode area for active flux is very narrow. This means that electron is constricted to this size, and almost all electrons impinge on this area. On the contrary, electron for normal case is wide spread to broad anode area.

Figure 26 shows the dynamic response of arc behaviour from normal area to an area where active flux is painted. Arc starts from left(normal area) to right(active flux area). Anode area on normal case is wide. When an welding pool reaches to active flux area, melted active flux invades on to the pool. And anode area is pushed to rear side by invaded flux layer. Upper pictures and lower pictures were captured by different maker's camera. A camera captured

images in figure 26 is also made by different maker. Cone angle of electrodes, and surface treatment, and captured date are, but welding condition and material are the same. Tones of colour are quite different for these pictures. Another difference between normal arc and active flux is pool behaviour. Front position of the pool becomes closer on active flux case. And there is no change on pool length, so pool end moves to rear on active flux. Vibration level increases on active flux, many small ripples are produced.

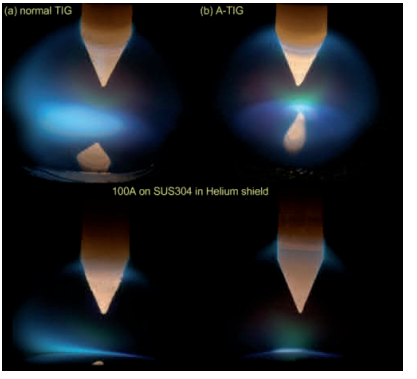


Figure 25. Effect of active flux on arc process.

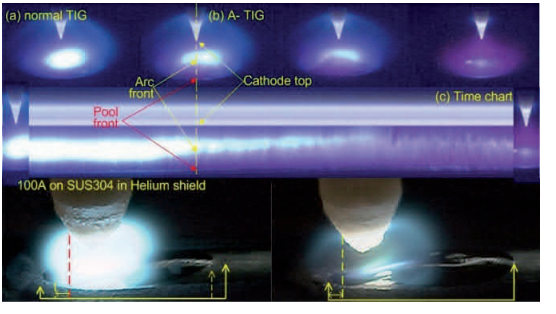


Figure 26. Effect of active flux on arc and pool behaviour.

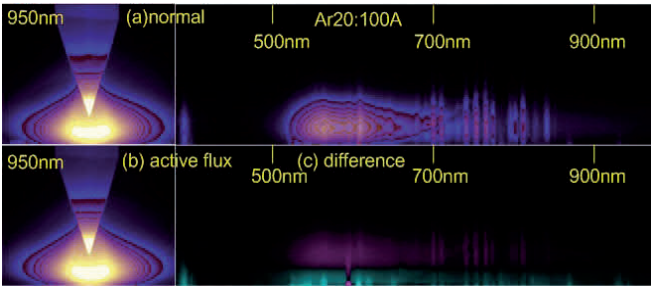


Figure 27. Effect of active flux on arc plasma.

Figure 27 shows typical pictures of plasma configuration and spectrum distribution in pseudo colour. Arc is generated in argon. Left pictures are single colour images at 950nm, which range has no strong spectra for argon, for normal stainless steel and stainless steel with active flux. These pictures are displayed in pseudo colour to intense the difference of both conditions. These are single colour images, and brighter point indicates higher temperature. Upper right picture shows spectrum distribution along central line of cathode for normal welding. Lower right picture shows the difference between normal case and active flux. The region where the brightness for normal plate is higher than it for active flux, displayed in green colour. Red colour shows the opposite case. The intensity shows amount of the difference of brightness. Radiation from normal plate near the molten pool is larger. On the contrary, the brightness for active flux is higher in the electrode surface and outer space of main plasma as shown in red colour. Radiation from active flux area near surface is very low.

Actual physical and chemical process acts on brightness. Brightness on cathode is low. It is difficult to recognize the difference to watch normal video by human eye. However there is some difference of frequency on space and/or time. Pseudo colour display is good method to show spatial difference as shown in figure 28(a,b). Small difference due to chemical reaction also can be extracted as shown in figure 28(c,d). Melted thorium oxide on electrode moves from upper side to top position. Behaviour of this chemical and physical reaction becomes visible by some numerical treatment. These reactions remain the evidence on the electrode. These evidence can be watched by SEM and EDM.

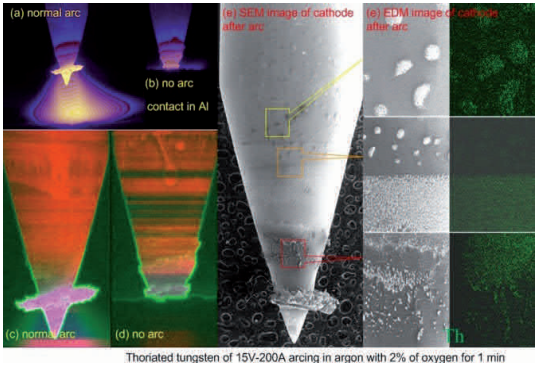


Figure 28. Effect of oxygen for reactions on cathode.

4.2. Effect of gravity on arc behaviour

Figure 29 shows effects of gravity on welding process. High speed video is captured by drop tower experiment. Height of free drop zone is 10m, and time duration of micro gravity is 1.3sec. This time period is short, but it is enough to detect transient motion from normal gravity condition to micro gravity condition. There is no time limit to continue welding process before drop trial. Shape of molten metal is clearly affected by gravity. There is no

apparent change on molten metal flow on the weld pool. However, inertial force acts on metal flow, and the time response of inertial force is unknown. Reconstruction period to balance static forces is finished in 10ms, and some vibration by overshoot motion remains around 10ms.

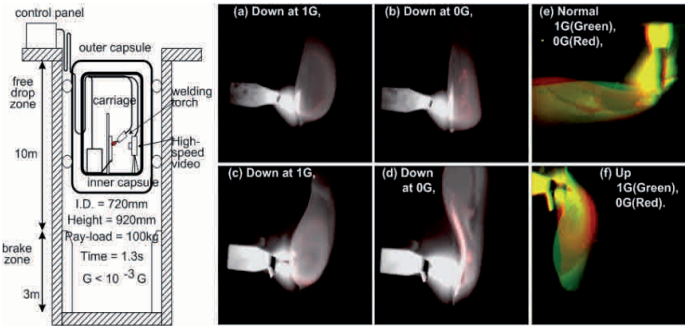


Figure 29. Results of drop tower experiment.

4.3. High speed imaging of metal transfer on GMAW process

High speed imaging of wire melting and droplet transfer phenomena have been carried out for long time. Silhouette imaging by using of strong external light was essential for observing metal transfer during Gas Metal Arc Welding (GMAW) process. GMAW process has some periodical vibration on metal transfer. Using band pass filters in near infrared wavelength becomes convenient because it contains information on temperature(Ogawa, 2004).

Figure 30 shows the typical metal transfer of GMA welding by interference filter of 950 nm without external lighting. Streak imaging is also useful to show dynamic behaviour. The reactions at the plasma/metal interface include oxygen removal at the anode and the discharge and pick-up of oxygen ions at the cathode. Figure 30 shows the reaction of oxygen invaded into the molten metal in the melted wire. A combination of invaded oxygen and carbon in wire makes carbon oxide gas. The gas is abruptly expanded by high temperature and exploded on the way to the work piece. Streak image shows points for spattering and unusual situation. Spatters are recognised as spike lines to the outsides from the wire centre, and the flying speed is recognised as its locus angle. Abrupt expansion of the droplet is recognised as an irregular knot. This scene is automatically detected by image processing of this figure. The merit of the high speed imaging system is that it uses digital data; therefore, effective analysis can proceed automatically(Ogawa et al., 2003).

A single colour video is a kind of thermal image, and it is presented in pseudo colour to emphasise the physical changes. Cathode spot exists in the first frame. The melting part at the top of the wire is growing, and the region between this melting part and the solid wire becomes slender. Current density of this slender portion becomes high, and temperature of this region increases quickly. Pinch force is also acted in this region. The combination of these forces drives to release the metal. Arc is soon generated between new tip and droplet

with some small spatters. This set of images gives a visual representation of transfer modes in GMAW.

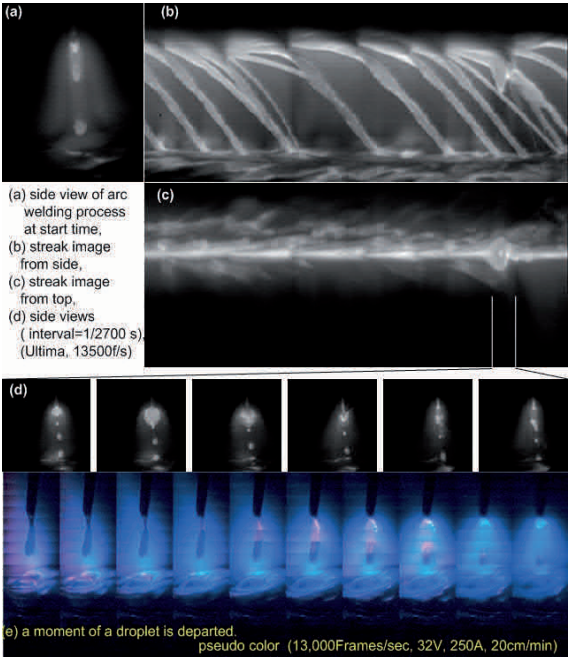


Figure 30. Time chart to pick up abnormal condition.

4.4. High speed imaging of Laser Welding process

Laser welding is very high speed welding method. Hybrid system such as Laser Arc hybrid and Laser Hot wire hybrid are often used to improve joining efficiency of large structures. Normal observation of arc welding process uses fixed torch system. Work piece moves during welding. High speed camera is heavy and big to carry on laser torch. When moving object is captured by fixed camera, object to watch moves in the scene as shown in figure 31(a). Reconstructing the scene as static torch system is easy as shown in figure 31(b). However, this system needs wide range of image size. Static coordinate observation system saves image size and/or improve spatial resolution as shown in figure 31(c).

Torch moving system has good points to present information on quality of whole welding result as shown in figure 32. These pictures are produced by using of histogram information. Lights have several infomations of their origin, and they appear in statistical features. Behaviours of arc, fume and sputters are apparently drawn by statistical features. Laser itself is invisible. But laser acts on fume and plume, and some statistical change appeares on its value. So laser channel can be shown from reconstructed image as shown in

figure 33. Figure 33 shows pseudo color display of mean value image, original mean image and deviation images, respectively. Laser beam channel is apparent in this figure.

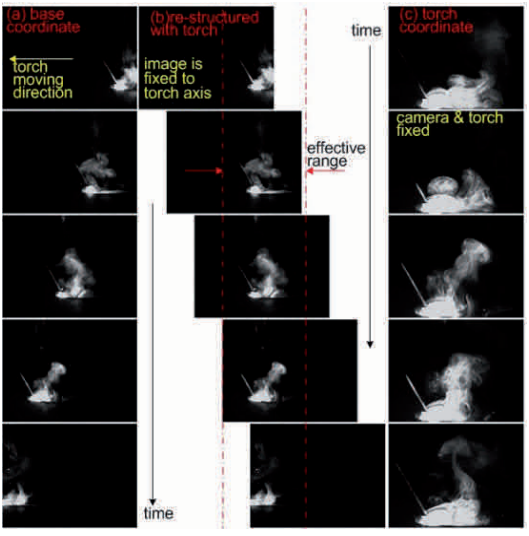


Figure 31. Comparison of coordinate system.

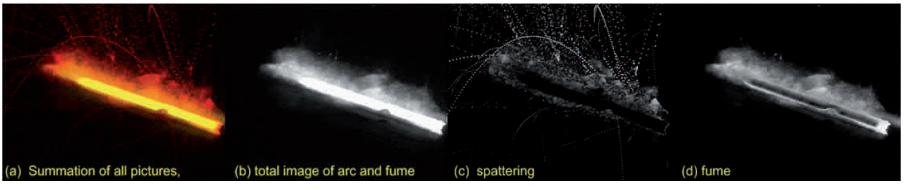


Figure 32. Exsample of imaging methods..

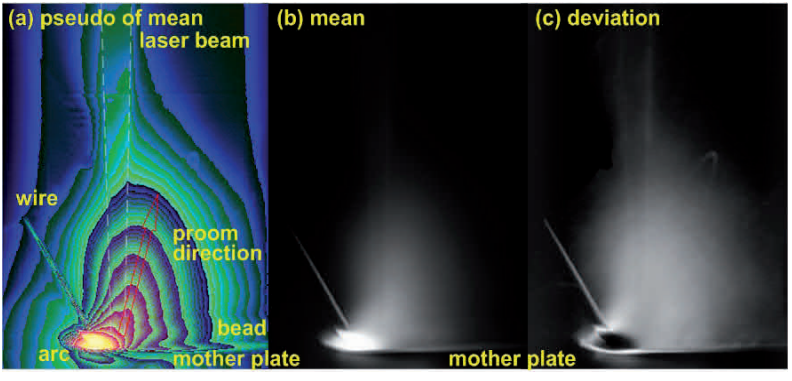


Figure 33. Statistical image of laser arc hybrid welding.

4.5. Monitoring and evaluation of GTAW process

Figure 34 shows a training system for weldrs of one side butt welding of thin stainless steel. This system uses four cameras to identify welder's skill. Welding trials are carried out by manual operation. A torch camera captures weld pool and arc. Camera 2 and 3 are fixed on carriage to capture surface and bottom situations of welded plate. Camera 4 is a fixed camera to observe welders motion. The camera 3 is the most important camera to identify the weld quality. This camera captures the conditon of bottom pool, and the system indicates analysed status of penetrated condition by sound on real time. Five tones are used to notice the actual condition to the welder. The welder can watch bottom situation by small LCD monitor inside the cover face. This monitor indicates only the image from camera 3. Voltage and current signals are also recorded and shown on the screen with colour. When the signal is out of suitable range, normal green colour changes to red. The collected data is stored in the data folder. In the same moment, a mentor of the welder tells to the welder about important points, and this voice is also recorded in the system. The welder can watch his own operation to select his data. Almost the same features are reproduced by the system with mentors indicated voice. Several reference information on mentors' operation and editorial videos are stored in the reference folder. The trainee can watch the reference video at any time. So he can learn his skill without any stress of actual welding operation. Another purpose of this system is to study relationship among voltage and amperage signals, torch camera image, and penetrated situation. Data of more than 200 welders of several welding companies were acquired to improve evaluation algorithm from torch camera image and electrical signals of manual welding. The same data on automatic welding operation are also acquired in various welding conditions. Evaluation of weld quality by one camera system becomes possible, when the feature of the welder was stored in the data base. One camera system is used on actual production process, and whole manual process is recorded to evaluate the quality of the products.

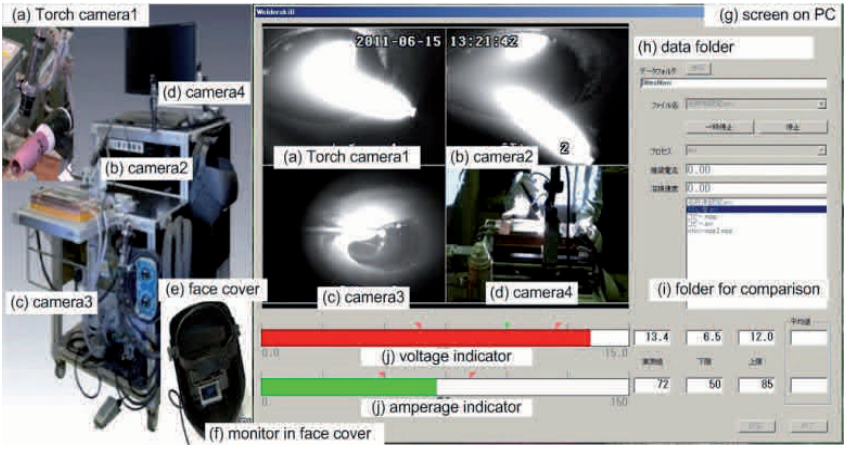


Figure 34. Training machine of GTA welders of one sided full penetration butt welding.

5. Conclusion

High speed imaging on welding process is a powerful tool to understand their nature. Deep knowledge on principle of target process is necessary to take and analyse succesfully. Some fundamental technique on high speed imaging are described in this paper.

Author details

Yoji Ogawa
Ogawa Giken Co.ltd. & AIST, Japan

6. References

Inoue, K. (1981) Image processing for on-line detection of weld process, Trans. JWRI, No.10, pp.13-18

Ogawa, Y. (2008) Accurate three dimensional measurement of arc welding phenomena, J. Soc. Instrum. Control Eng., Vol.47, pp.65-68 (in Japanese)

Ogawa, Y. (2011). High speed imaging technique Part 1, Science and Technology of Welding and Joining, Vol.16, No.1, pp.16-26

Pattee, H. E. et al. (1973). Effect of arc radiation and heat on welders, Welding Journal, Vol.52, pp.297-308

Shaw, C. B. Jr (1975). Diagnostic studies of the GTAW arc. Part 1. observational studies, Welding Journal, Vol.54, pp.33s-44s

Zacharia, T. & David, S.A. (1993). Mathematical Modeling of Weld Phenomena, Welding Journal, Vol.52, pp.3-23