ROYAL INSTTITUE OF NAVAL ARCHITECTS
AUSTRALIAN BRANCH
WHYALLA SECTION

TECHNICAL MEETING

Members and visitors are invited to attend a Technical Meeting of the Whyalla Section of R.I.N.A. to be held at 8.00 p.m. on Monday, 30th. August, 1976 in the Theatrette of the South Australian Institute of Technology, Nicolson Avenue, Whyalla. At the Meeting two (2) papers will be presented as follows:-

(1) One Sided Welding
Presented by Mr. Nakatuma of I.H.I., Japan.

(2) Fumes Generated During Welding
Presented by Mr. Kobayashi of Kobe Steel, Japan.

Both speakers will be in Whyalla to deliver papers by the International Institute of Welders Annual Assembly 1976, being held in Sydney.

B.V. Chapman,
SECRETARY

Some Considerations About Fumes Generated in Arc Welding Processes

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SUMMARY

The mechanisms for the formation of arc welding fumes are considered. The compositions, shapes, and quantities of fumes are discussed in connection with the mechanisms. Fumes are mainly formed by vaporisation of the molten liquid at the tip of the electrode. The vapor is blown off into the air, suffered oxidation, and condensed rapidly into fine solid particles.

1. Introduction

Fumes inevitably generate during arc welding. Since welders are situated very near to the origin of the fumes, they cannot avoid inhalation of fumes to some extent. For that reason, attention has been paid recently to hygienic aspects of welding environment. In Japan, welding is one of the work regulated by the law of pneumoconiosis, and further, Japan Welding Engineering Society is going to establish standards for the method for measuring the concentration of fumes in welding environment, the method for analysis of fumes, the basis for controlling welding environment, and so on. Almost all of the foreign welding institutes or societies are also dealing with the problem of fumes. And the regulations for the welding environment is becoming more definite and severer in each country.

Under these circumstances, it is important to clarify the essential characteristics of fumes, in order not only to find reasonable methods in the fields but also to develop materials and equipments in the laboratory, for improving welding environments. From those point of view, this article reports on some considerations about the formation mechanisms and the characteristics of welding fumes, based on some experimental results and references.

2. Mechanisms of fume formation

Fumes are observed under electron microscope, as shown in Photo. 1, as agglomerates of extremely small spherical particles, about 0.1μ in diameter. The particles observed here can not be considered to originate in crushing of flux or in splashing of molten liquid. Accordingly, fumes should be considered to originate in high temperature vapor which is rapidly cooled and solidified into small solid particles, as it is the definition of the word "fume".

The origin of high temperature vapor which transforms into fumes seems to consist in the arc pole and its surroundings. From the surfaces of the tip of electrode, molten drops transferring in the arc, and the molten pool on the base plate, their own constituents may be vaporizing according to respective vapor pressures. Among these origin of vaporization, the molten pool on the base plate has lower temperature than other origins, and the amount of vapor is assumed to be comparatively less. It is going to be ascertained in our experiments that the contribution of the molten pool is not large. Heile et al.[1) have also considered about the formation mechanism of fumes. They have related that vapors from the tip of the electrode and the transferring molten drops are the controlling factor to fume formation. The amount of fumes have also been discussed in connection with the temperature, the holding time in the arc, and the surface area. As the condensation process is carried out in the air, metal vapor naturally suffers oxidation.

Observations on the a.c. arcs of manual metal arc welding by the method of high speed camera can show, as Photo. 2, phenomena of blowing off of high temperature vapor and condensation into fumes in every half cycle, if the photographing conditions are suitably selected. From the fact that the blowing off of high temperature vapor can be seen in every half cycle irrespective of existense of transferring drops, it is considered that the inside melting surface of the electrode tip or the drops adhering at the tip are the main origin of the high temperature vapor rather than the transferring drops. That is, there occurs violent vaporization at the tip of the electrode, and after blowing upon the molten pool with an arc-blow, the vapor is blown off into the air. Since arc-blows and blowing-offs can be observed in both plus and minus polarity of a.c., it may be suggested that the pressure arising at the tip of the electrode play some role in the phenomena of arc-blows.

Among the vapors blown off in the air, metal vapor is oxidized and condenses into fine particles having complex composition together with flux constituents. Since these processes proceed very rapidly, the particles are extremely fine in their size, and are spherical in their shape due to initial condensation in liquid form. The processes from liquid to solid are also very rapid. The crystals are imperfect excepting constituents of high crystalizing character. Fume particles, agglomerating into larger secondary particles, go up with accending current caused by high temperature of the arc, and diffuse into the air.

These are welding fumes.

3. Composition of fumes

Table 1 shows the examples of fume compositions generated by three coating types of manual metal arc welding electrodes, a solid wire for CO_2 welding, and a flux cored wire for non gas shielded welding.

Although manual metal arc welding electrodes consist of coatings only about 30% in weight, the constituents originated in the flux occupy almost 80% of fumes from lime and harmless lime type electrodes. Also in the case of non gas shielded welding, flux in wire is only about 20%, but flux constituents are above 80% in fume.

These facts show that, in these cases, the vaporization from molten flux is the controlling factor to fume formation. On the other hand, the fume from ilmenite electrode consists of about 50% iron oxide. The difference from the former case suggests that there are differences in arc phenomena (e.g. arc temperature) or melting state inside the melting tip of the electrode.

The composition of fume, of course, depends on the constitutions of coating, but the percentages of each element do not coincide between them. Considering that vaporizing process is a controlling process for fume formation, it is easily assumed that a component of high vapor pressure takes prior vaporization and concentrated into fume. Alkalis ($Na_2O + K_2O$) are included in the coating of lime electrode at most 5%, but in the fume they rise to 35%, and taking account the composition other than iron oxide alkalis occupy as much as 50% in it. Highly vaporizing alkalis are, in this case, excessively concentrated in the fume. On the other hand, the fume from ilmenite electrode has 13% of alkalis, or 25% of them in the composition other than iron oxide. Some differences in the process of fume formation can be infered also in these considerations.

The richness of alkalis in the fume from lime type electrode seems to be one of main cause of hazards, like headache, by inhalation of this kind of fume. Especially, potassium shall be payed attention due to its high vapor pressure and heterogeneity to human body. The harmless lime type electrode shown in Table 1 is designed to contain almost none of potassium, and together with the shapes of fume particles as described below, the electrode has succeeded in reducing hazards of lime type fumes.[2)]

In case of CO_2 arc welding with solid wire, iron oxide occupy 75% in its fume due to lack of flux. Silica and manganese oxide come from alloying elements in wire. Heile et al.[1)] have shown that the formation of SiO molecules, which have high vapor pressure, causes abnormally high percentage of silica in the fume.

In welding workshops, coated or adhered materials on the base plate must be taken into consideration. The cases can be given as common examples when coated steels with paint containing zinc, lead, or cadmium are welded. These elements all have high vapor pressures and high noxiousness. They can be concentrated in fumes even if they are on the base plate, and for that reason care must be taken about the quantities in the fumes and the concentrations in the air. Moreover, the fumes from coatings give surpluses in quantity. Tebbens et al. [3] have showed that the fumes by welding gulvanized steels contain as much as 65% zinc oxide.

The crystal components in fumes are then considered. They can be detected by x-ray diffraction if any crystals are formed in the process of rapid solidification and cooling. Photo. 3a shows the result of x-ray diffraction of ilmenite type fume, and only disordered crystal of Fe_3O_4 is detected. In a rapid cooling process of fine particles like fumes, only the component which is particularly susceptible to crystallize may be turned into crystal. Metallic components like manganese can exist as replacements of Fe atoms of Fe_3O_4, and silica can form glasses with alkalis and other elements. Honma et al.[4] have detected $MgAl_2O_4$ and γ-Al_2O_3 in the fumes by welding of aluminium alloys. These crystals have spinel type structures together with Fe_3O_4, and it is an interesting fact that the spinel type crystals are feasible to be formed in the case of fume formation.

Photos. 3b and 3c show the results of x-ray diffraction for the lime type fume and the non gas welding fume respectively. NaF and $KCaF_3$ are detected in the former, and MgO and CaF_2 in the latter. In the fumes containing alkalis, alkali earths, and fluorine, species of crystals may be able to anticipate.

4. Shapes and prticle sizes of fumes hanging in the air

Fumes hanging in the air form secondary particles by agglomeration of primary particles. The shapes and particle sizes of secondary particles vary according to the welding materials. Photo. 4 shows appearances of fumes observed by electron microscope, sampled by natural sedimentation. Lime type fumes have so small secondary particles and so dense agglomeration as to be difficult to distinguish the primary particles. Other fumes are roughly agglomerated in all cases so as to be able to distinguish the primary particles, and in addition the secondary particles are larger in size. The reason why the fume particle agglomerate seems to be that the surfaces of the primary particles are very active and the spinel type crystals have such characterestics. The fact that these fumes are more or less magnetic can be an useful information about the behavior of fumes after formation.

The dense agglomeration of lime type fumes may be resulted from their high sensitivity to moistre due to high content of potassium. They may absorb moisture in the air and suffer further agglomeration. Since the harmless lime type fumes have less sensitivity to moisture due to the least content of potassium, they may show agglomeration similar to ilmenite type fumes.

Heile et al.[1)] have determined the particle size distribution of fumes from CO_2 welding and non gas welding, and have obtained the mean particle size of 0.03μ and 0.12μ respectively. Also in Photos. 4d and 4e, it can be observed that the primary particles of CO_2 welding fumes are smaller and the non gas welding fumes larger. Manual welding fumes are medium size.

Fig.1 shows an example of particle size distribution of secondary particles by manual metal arc welding. Although there are some differences from Photo. 4 because of differences of sampling conditions, ilmenite type fumes have larger size than lime ones, and both of them have peaks near 1μ. Looking over other results, for example a result by cascade impactor[5], nearly 1μ particles are regarded to be a main part of fumes hanging in the air.

When a human body inhales some particulates in the air, it is said that larger particles are filtered out in air ways and do not reach into alveoli, and that smaller particles are inhaled into alveoli but again exhaled. Particles with intermediate size of 0.5μ- 5μ can be inhaled deep into alveoli and be deposited there. Attention should be payed to the fact that most fume particles have these intermediate sizes.

5. Amount of fumes

In order to set up a ventilating condition for a purpose of controlling welding environment, it is necessary to know about total fume amount at the origin of generation. Consideration should be taken in that case to the facts that amount of fumes changes according to the constitution of flux or welding conditions.

The difference in fume amount caused by the difference in coating is remarkably large, and the amount extends between 200 - 500 mg/min when conventional 4 mm electrodes are welded at 170A.[6] Experimentally, wider range of 100 - 1000 mg/min can be obtained under same conditions. The ZERODE series electrodes, which emit less fume than conventional electrodes, are developed upon exact comprehension of these facts. The constitution of the coating controls, as described above, the composition of the fume. Still more, it controls the amount of fume, indicating an important fact. The mechanisms supporting this fact are not yet fully explained, but some experiments are being carried out under consideration that the causes exist in the temperature of the arc and/or the vapor pressure of each constituent.

It is obvious that the amount of fumes differs according with the welding methods. Generally speaking, non-gas welding gives off most fumes due to a lack of shield gas, CO_2 arc welding and coated arc welding lie next, and MIG welding gives off less fumes than CO_2 welding because of shielding with inert gas. Submerged arc welding, arc being covered wholly with flux, emits almost no fume. Exceedingly less fume emission is observed in TIG welding, though higher temperature of the arc, because the electrode itself does not melt.

Differences according to welding conditions are also remarkable, even if under the same method and the same materials. Especially, the effect is obvious by welding current and welding voltage, and this is understood as a change of electrical energy supplied into the arc.[7] Accordingly, it is easy to understand when the product of current by voltage, or the apparent power of a.c., is related to the amount of fumes. When various types of 4mm electrodes, for example, are welded at 140, 170, and 200A, the relation can be shown as Fig. 2 between the amount of fumes and the apparent power. The amount increases almost proportionally to the power. The figure also shows that the differences between different coating type can not necessarily explained by the differences of arc voltages, when compared in the same current.

It is important in the research of fumes that different results can be obtained from different methods[5], not only about the amounts but also about compositions, shapes, and particle sizes. In case of measuring the amounts, particularly, biases or fluctuations are apt to arise owing to unavoidable factors as peculiarities of welders, characteristics of welding transformer, or weather conditions, and further unexpectable factors.

6. Conclusions

Nearly twenty years have passed since our laboratory had started the research on the fumes. In the course of the research, the social situation changes remarkably. The view into the fume becomes severer as an assailant to welding environments, and the sphere of the responsibility becomes clearer as a manufacturer of the origin. A theory has not yet been established about the effect of fumes on human body, and there are many fooms for investigation in the present stage due to the complex characteristics of fumes. Against the situation of suffering severer attention notwithstanding leaving much to know, conclusions have been drawn out rather inductively from many apparent facts. In order to expect progresses in the future, it is necessary to investigate the basic matters paying attention to the phenomenon of fume formation. This article has reported so far about the viewpoint on the first stage to the future investigations. The authors reflect on a fearless inference regardless of their ignorance, and they are expecting useful advices.

7. References

1) R.Heile and D.Hill:"Particulate fume generation in arc welding processes", Welding J., Vol.54, No.7 (1975) pp 201s-210s

2) K.Kawada and K.Iwano:"Experimental studies on the harmfullness of basic type welding electrodes and on their improvement" IIW Doc. VIII-197-64 (1964)

3) B.Tebbens and P.Drinker:"Ventilation in arc welding with coated electrodes", J.Ind.Hyg.Toxicol., Vol.23, No.322 (1941)

4) K.Honma, H.Yamaguchi, T.Yagami, and Y.Araki:"Industrial health aspects on the MIG welding of Al-alloys", IIW Doc. VIII-654-76 (1976)

5) American Welding Society :"The welding environment" (1973)

6) Y.Kimura, I.Ichihara, and M.Kobayashi:"Some quantitative evaluations of fumes generated from coated arc electrodes", IIW Doc. VIII-574-74 (1974)

7) M.Kobayashi, S.Maki, and T.Ohe:"Factors affecting the amount of fumes generated by manual metal arc welding", IIW Doc. VIII-670-76 (1976)

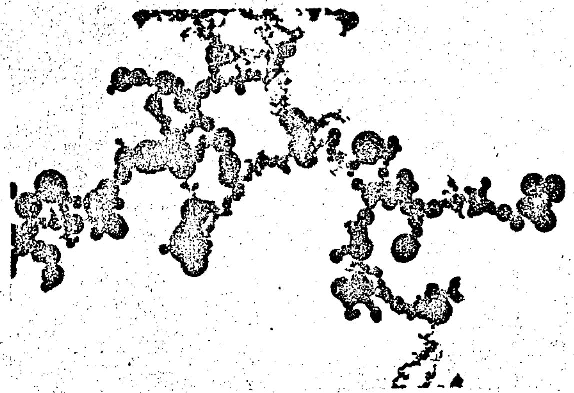


Photo. 1 Primary particles of welding fume and their aggromeration (x20,000)

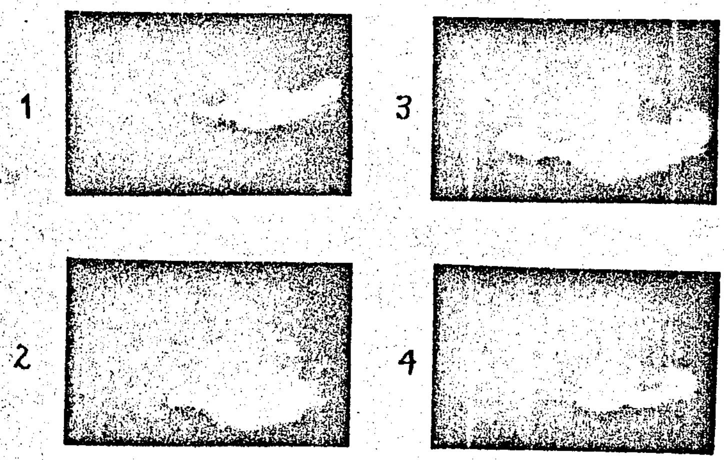
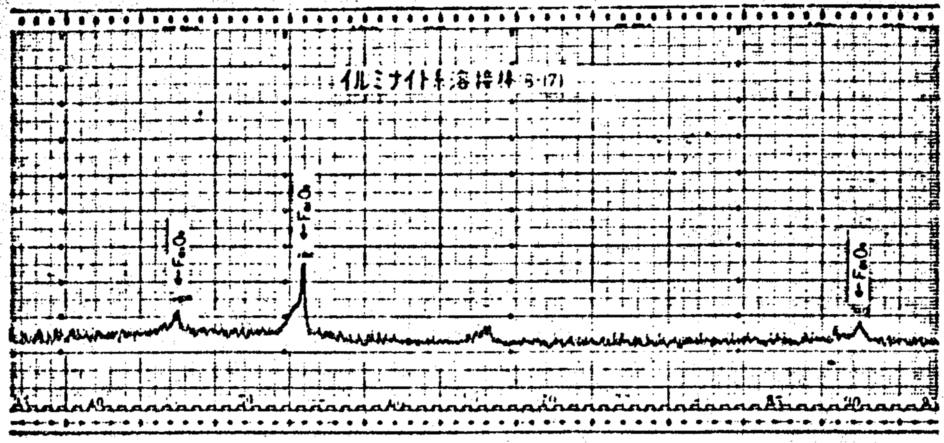


Photo.2 Blowing off of high temperature gas from welding arc

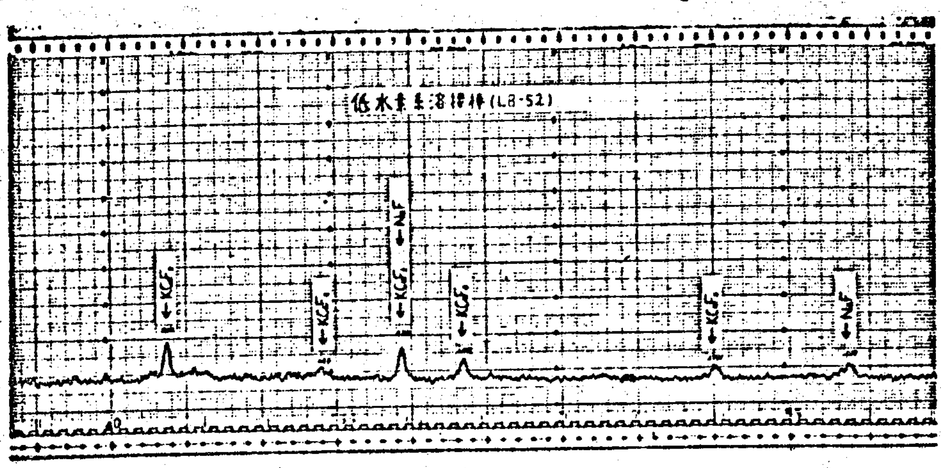
Table 1 Chemical composition of fumes (%)

Materials	Brand	Fe_2O_3	SiO_2	MnO	TiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	F
Lime	LB — 52	13.69	3.70	3.82	0.25	0.32	12.25	0.97	10.11	25.20	17.50
Harmless lime	LBM — 52	19.55	5.95	4.49	0.57	0.36	13.35	6.76	24.90	3.65	11.54
Ilmenite	B — 17	46.54	19.35	11.24	2.14	0.41	1.72	0.53	6.20	6.44	—
CO_2 welding	MG — 50	75.47	10.69	12.57	—	—	—	—	—	—	—
Non-gas welding	OW — 56	16.22	1.33	2.14	—	7.83	18.30	42.10	0.30	tr.	11.12

a. Ilmenite type



b. Lime type



c. Non-gas welding

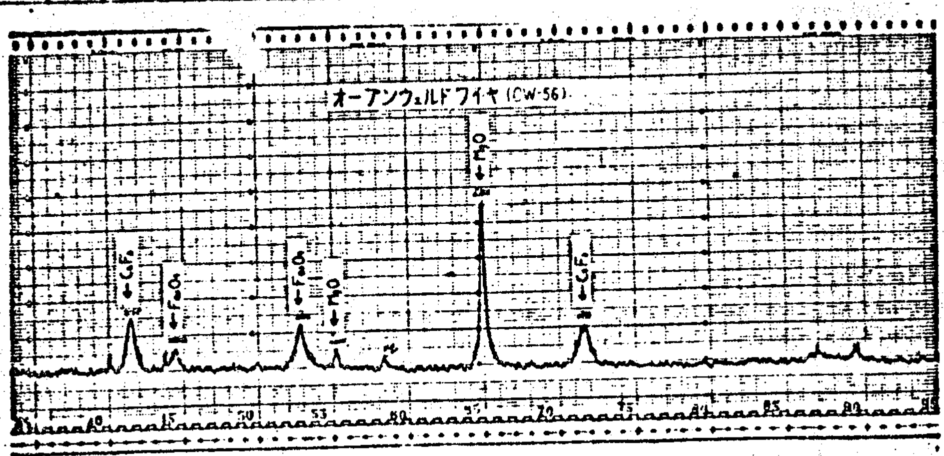
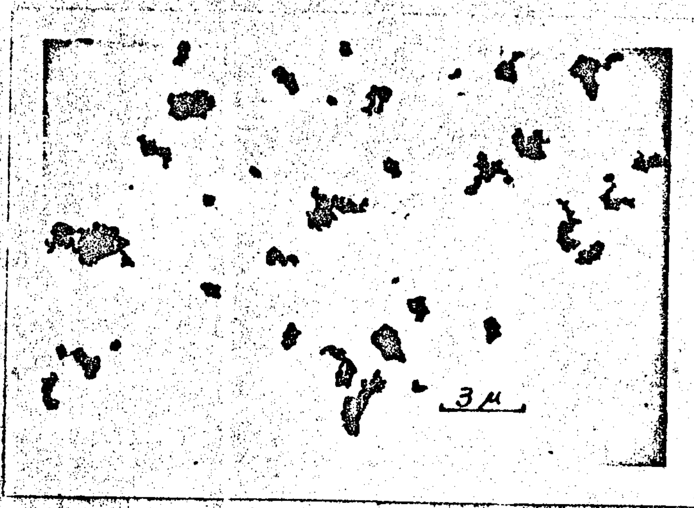
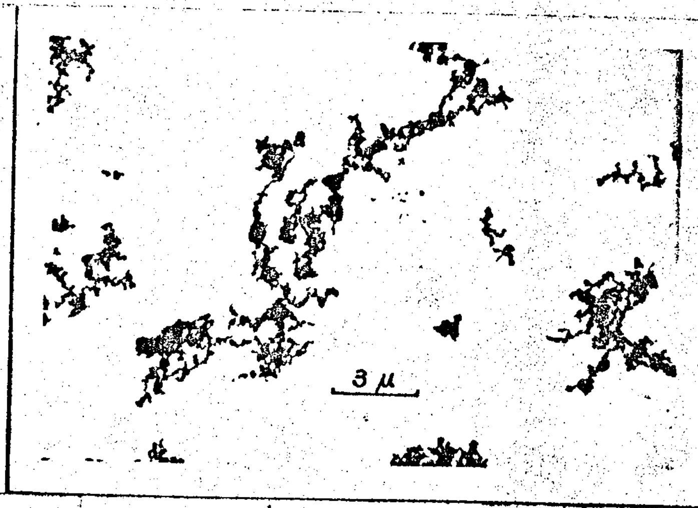


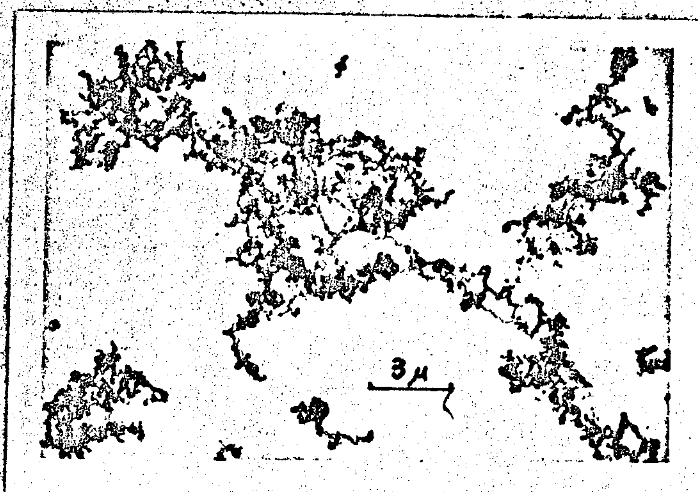
Photo.3 X-ray diffraction patterns of fumes



a. Lime type

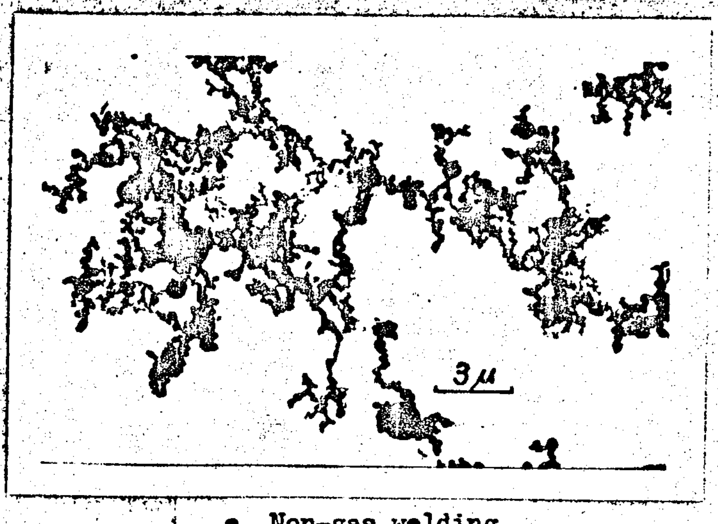


b. Harmless lime type



c. Ilmenite type

d. CO_2 welding



e. Non-gas welding

Photo.4 Secondary particles of fumes (x3,000)

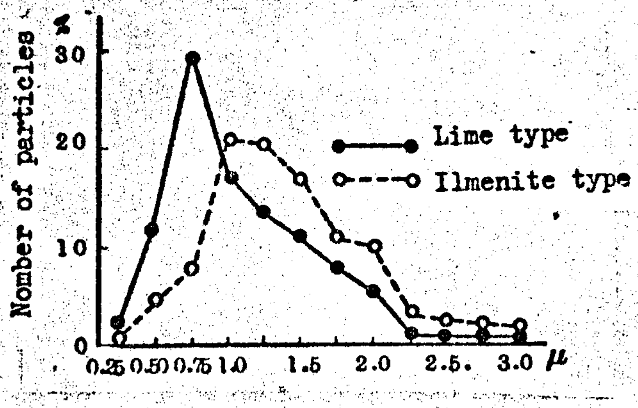


Fig.1 Particle size distributions of secondary particles

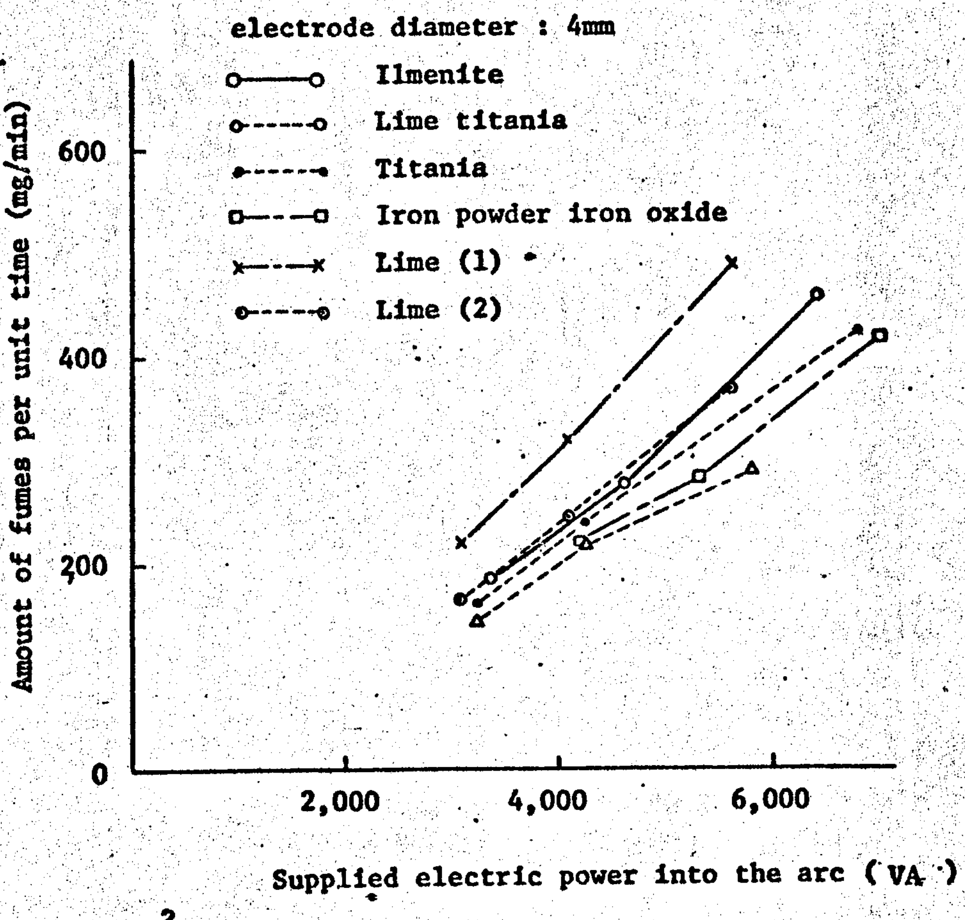


Fig. 2 Relation between amount of fumes and supplied electric power into the arc