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CONTINUOUS CASTING OF TITANIUM IN COLD CRUCIBLE

SYNOPSIS

The C.C.C.C. (cold crucible continuous casting) is a new process for the induction melting and casting of high melting point reactive materials. Continuous billet extraction can be carried out without the need for a slag, provided that the design is optimized and that the frequency and the transmitted power are adapted to suit the material to be melted.

The CEZUS plant enables the production of 150 mm diameter and several meters length billets. By melting titanium turnings, sound billets are obtained with a good surface quality, a fine solidification structure and a good control of the chemistry.

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1 - INTRODUCTION

Titanium, which melts at 1660°C, has a marked affinity for oxygen and carbon. So induction melting is a process which is difficult to apply to titanium, since reaction between the liquid metal and the refractory crucible lining (oxyde ceramic or graphite) leads to pollution of the titanium.

For several years, CEZUS, in collaboration with the CNRS MADYLAM laboratory has experimented with a new type of induction furnace which allows the clean melting of titanium. The main feature of this furnace is the crucible which is a cooled copper crucible, made up of a number of separate segments to promote electromagnetic coupling with the metallic charge.

This new process called C.C.C.C. (cold crucible continuous casting) (1) involves:

- continuous melting of the divided charge material or a consumable electrode.
- solidification of the liquid metal.
- continuous extraction of the solidified billet.

The system is designed to operate without slag, a significant improvement compared to the "Inductoslag ingot melting" process, developed in the past by the U.S. Bureau of Mines (2).

It avoids numerous difficulties such as slag supply to the crucible, volatilisation, furnace cleaning constraints, billet peeling requirements, etc ...

Another point is that device allows to reach very high temperatures and not only titanium but also zirconium, niobium and even molybdenum have been successfully melted.

2 - EXPERIMENTAL INSTALLATION

The CEZUS plant shown schematically in figure 1 comprises:

- a cooled double-walled stainless vessel,
- a charging system consisting of a stainless steel hopper, vibrators and a chute,
- a water-cooled segmented copper crucible,
- a cooled inductor,
- a mechanical billet extraction system.

The inductor is supplied by a medium frequency static generator. A pump unit enables a vacuum to be established in the furnace, and if required, it is possible to introduce an inert gas.

3 - MELTING OF TITANIUM TURNINGS

The cold crucible induction furnace has been used to melt titanium and titanium alloy turnings. The melting procedure is as follows.

- The hopper is filled with turnings.
- A titanium primer with a diameter slightly smaller than that of the crucible is installed to contain the initial liquid.
- The furnace and hopper are pumped down to 10^{-2} torr and then filled with argon.
- The operating frequency is set by selecting the value of the adjustment capacitor in accordance with the inductor characteristics.
- When the impedance has been adapted, the power is gradually transmitted to the charge until it melts, with

the formation of a dome. The power is then adjusted to maintain a fluid bath and to control the height of the dome.

- The supply of turnings and the simultaneous continuous extraction of the billet can then be started.
- Melting is stopped when the desired length of billet is attained.

4 - OPERATING PARAMETERS

It is important that a suitable operating frequency be selected for the melting process to proceed in a satisfactory manner. In fact, the choice depends on the effects required, since there are three coexisting frequency dependent phenomena:

- a thermal effect (maximum energy dissipation in the charge),
- a pressure effect, which determines the form of the free surface of the liquid metal,
- a stirring effect in the metal bath.

Each of these phenomena can be favoured at the expense of the others by adjusting the frequency. An optimum frequency can be shown to exist for each of the effects, and the three values are quite distinct.

The effect of frequency f is described by the dimensionless "screen parameter" $R\Omega$

$$R\Omega = \mu_o \sigma \Omega R^2$$

where: μ_o is the magnetic permeability of vacuum,
σ is the electrical conductivity of the material

at the melting temperature,

Ω is the frequency of the current in the inductor ($= 2\pi f$),

and R is the radius of the crucible.

$R\Omega$ can be shown to have the following characteristic values:

* 2: establishment of a plane free surface
* 25: optimum value for heating
* 40: optimum value for stirring.

The power transmitted is a second important parameter. It should be sufficient to melt the turnings, but must not produce too high a dome. In effect, it can be shown theoretically, and has been experimentally verified, that the dome height H is proportional to the magnetic field, and therefore to the power transmitted, through the relation:

$$H = B^2/2\mu_o l g$$

where: B is the magnetic field strength inside the crucible,

l is the density of the liquid metal,

g is the acceleration due to gravity.

5 - RESULTS

Billets of excellent surface quality are obtained when the frequency and transmitted power are optimised and stable with time. Figure 2 shows a 100 mm diameter billet obtained from TA6V turningsj the skin is smooth and crack-free. On the contrary, the cracked surface of a billet of the same alloy shown in figure 3 illustrates the effect of a poor choice of frequency.

Table 1 compares the chemical analysis obtained on TA6V billet with that of the initial turnings.

	Al (%)	V (%)	Fe (ppm)	Cu (ppm)	O (ppm)	N (ppm)	C (ppm)
Turnings	6.2	4.1	1500	<50	2200	130	250
Billet	6.2	4.0	1550	<50	2250	120	260

It can be seen that there is no increase in the oxygen and nitrogen contents, nor in that of copper, showing that the crucible has not been attacked. Furthermore, melting under argon prevents the loss of volatile elements such as aluminium.

As in any induction melting process, stirring is extremely vigorous, In consequence, in spite of the steep thermal gradients induced by the use of a cold crucible, fine equiaxed macrostructures can be obtained in alloys such as TA6V. In general, the solidification structures produced by this process are found to be much finer than those obtained with the conventional consumable electrode arc melting technique.

6 - CONCLUSIONS

The C.C.C.C. (cold crucible continuous casting) is a new process for the induction melting of high melting point reactive materials. Continuous billet extraction can be carried out without the need for a slag, provided that the design is optimized and that the frequency and the transmitted power are adapted to suit the material to be melted.

By melting turnings, it has been shown in the case of titanium and its alloys that sound billets can be obtained with a good surface quality, a fine solidification structure and a good control of the chemistry.

The CEZUS plant enables the production of 150 mm diameter and several meters length billets suitable for direct extrusion or rolling.

7 - ACKNOWLEDGMENTS:

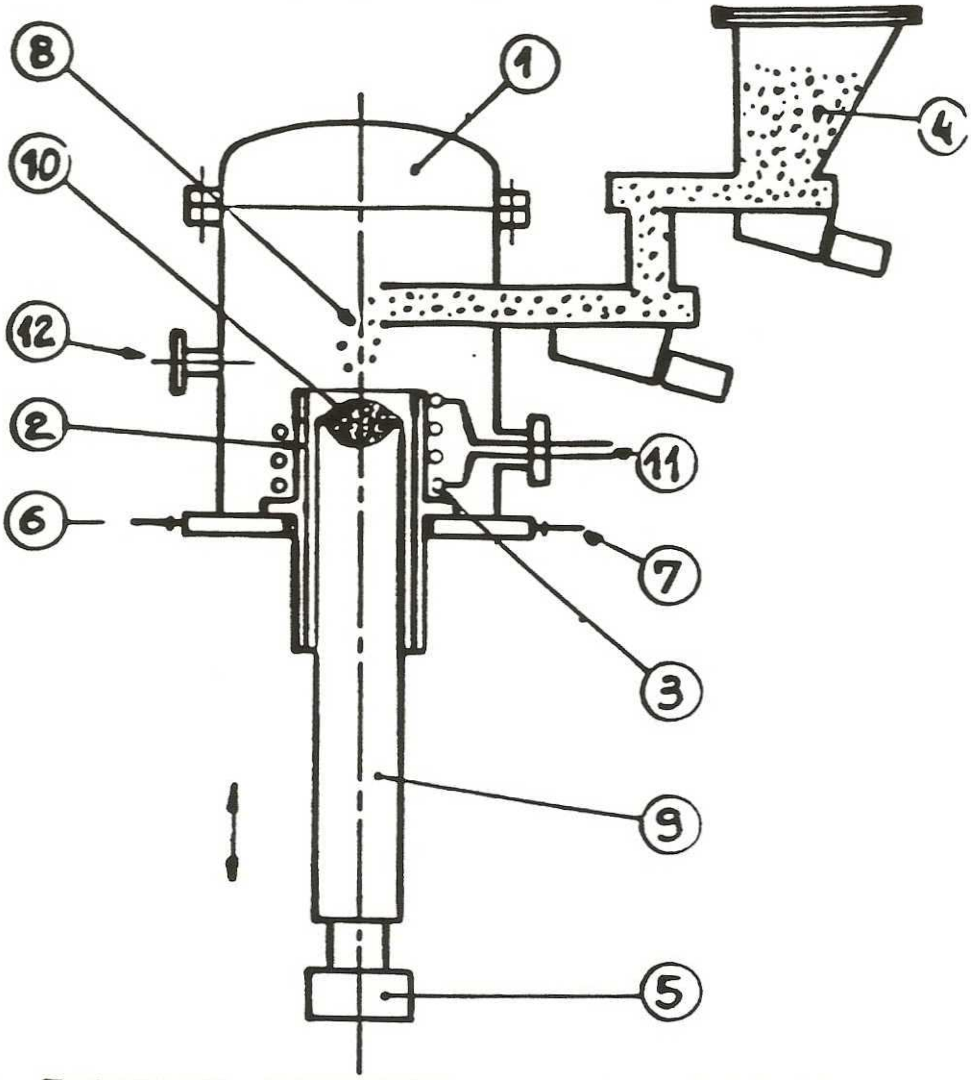
The authors wish to thank the AFME for partial support of this investigation.

8 - REFERENCES

(1) FRENCH PATENT N° 8700814
(2) P.G. CLITES, U.S. Bureau of Mines, (1982), Bulletin 673.

FIGURE 1

INDUCTION MELTING FURNACE



1_ FURNACE CHAMBER
2_ SEGMENTED CRUCIBLE
3_ COIL
4_ VIBRATING FEEDER
5_ INGOT WITHDRAWAL MECHANISM
6_ WATER INLET
7_ WATER OULET
8_ SCRAP
9_ INGOT
10_ POOL
11_ POWER CONNECTION
12_ TO VACUUM PUMP AND ARGON INLET

Figure 2

TA6V BILLET OBTAINED WITH THE C.C.C.C. PROCESS

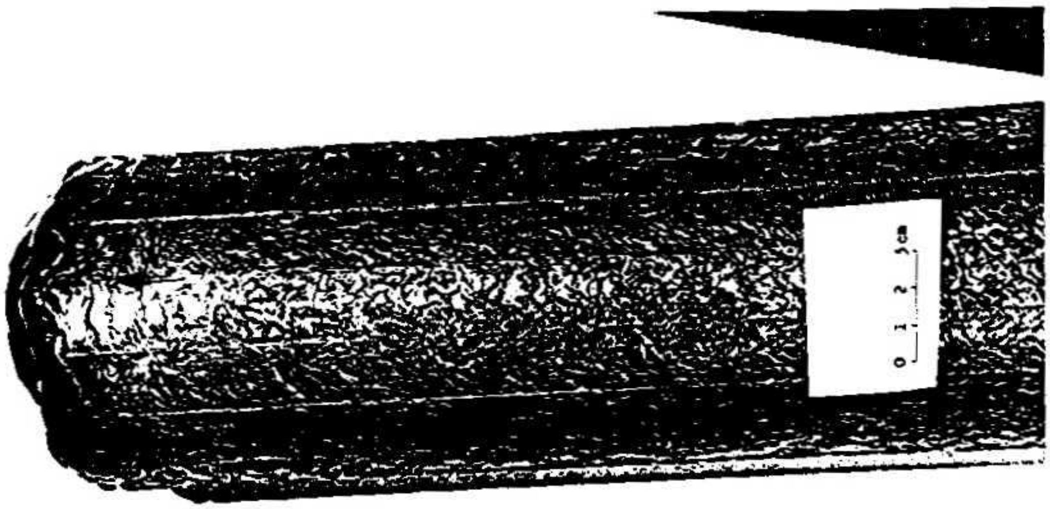
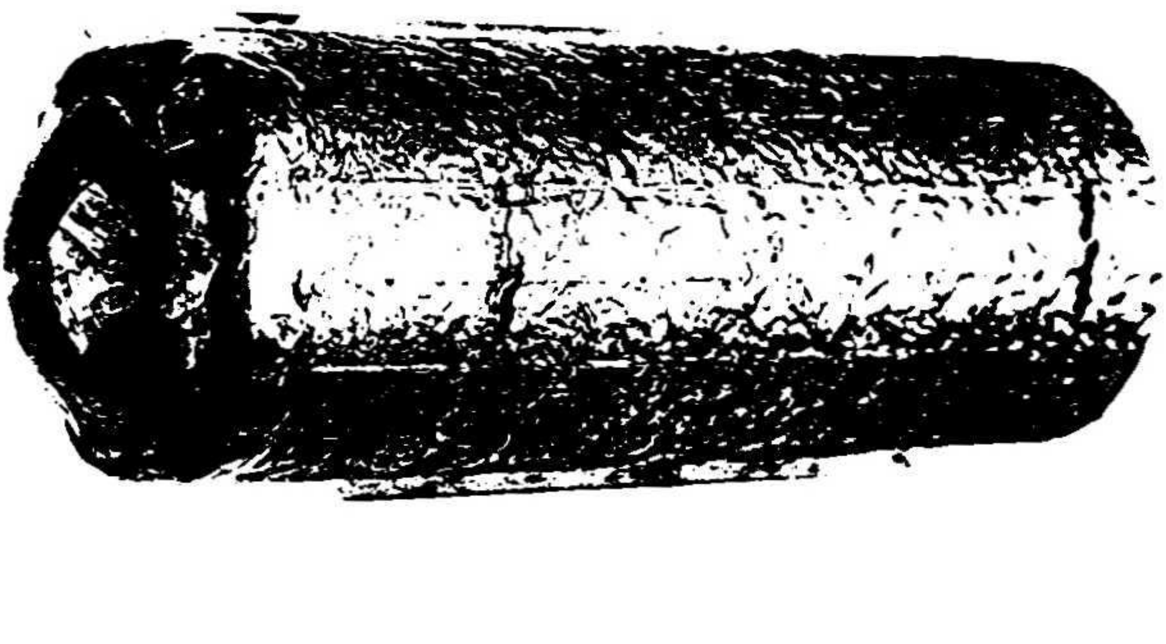


Figure 3

CRACKED TA6V BILLET DUE TO A POOR CHOICE OF FREQUENCY



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OF TITANIUM
IN COLD CRUCIBLE

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CONTENTS

INDUCTION MELTING
OF REFRACTORY AND
REACTIVE METALS

PROBLEM

CONVENTIONNAL INDUCTION MELTING IN REFRACTORY CRUCIBLE ===> THE MOLTEN METAL REACTS WITH THE CRUCIBLE AND IS CONTAMINATED.

IT IS THE CASE OF TITANIUM

SOLUTION

INDUCTION MELTING IN COLD CRUCIBLE

EARLY EXPERIMENTS :

US BUREAU OF MINES

" INDUCTOSLAG INGOT MELTING "
" INDUCTOSLAG CASTING "

WITH CAF_2 SLAG

COLD CRUCIBLE

CONTINUOUS CASTING

CEZUS AND MADYLAM HAVE DEVELOPPED AND PATENTED A NEW DESIGN CALLED C.C.C.C ALLOWING :

- THE CONTINUOUS MELTING OF RAW MATERIAL OR CONSUMMABLE ELECTRODE
- THE SOLIDIFICATION OF METAL
- THE CONTINUOUS WITH_DRAWING OF THE SOLIDIFIED BILLET.

WITHOUT SLAG ← → HIGH TEMPERATURES

DESCRIPTION
OF THE PILOT
PLANT

DIFFERENT PARTS

- FURNACE
- MECHANICAL PUMP + INERT GAS CIRCUIT
- COOLING CIRCUIT
- MEDIUM FREQUENCY STATIC GENERATOR 200 KW + CAPACITORS
- INFORMATIC SYSTEM FOR FURNACE CONTROL

FURNACE

- VERTICAL WATER COOLED CHAMBER
- FEEDING SYSTEM WITH A HOOPER AND VIBRATORS
- SEGMENTED, WATER COOLED, COPPER CRUCIBLE
- WATER COOLED INDUCTION COIL
- BILLET WITHDRAWAL MECHANISM

===> BILLET DIAMETER : 150 MM
LENGTH : SEVERAL METERS

MELTING OPERATION

. THE HOPPER IS FILLED WITH TURNINGS

. A TITANIUM PRIMER IS PLACED IN THE CRUCIBLE

. FURNACE AND HOPPER ARE PUMPED DOWN THEN FILLED WITH ARGON

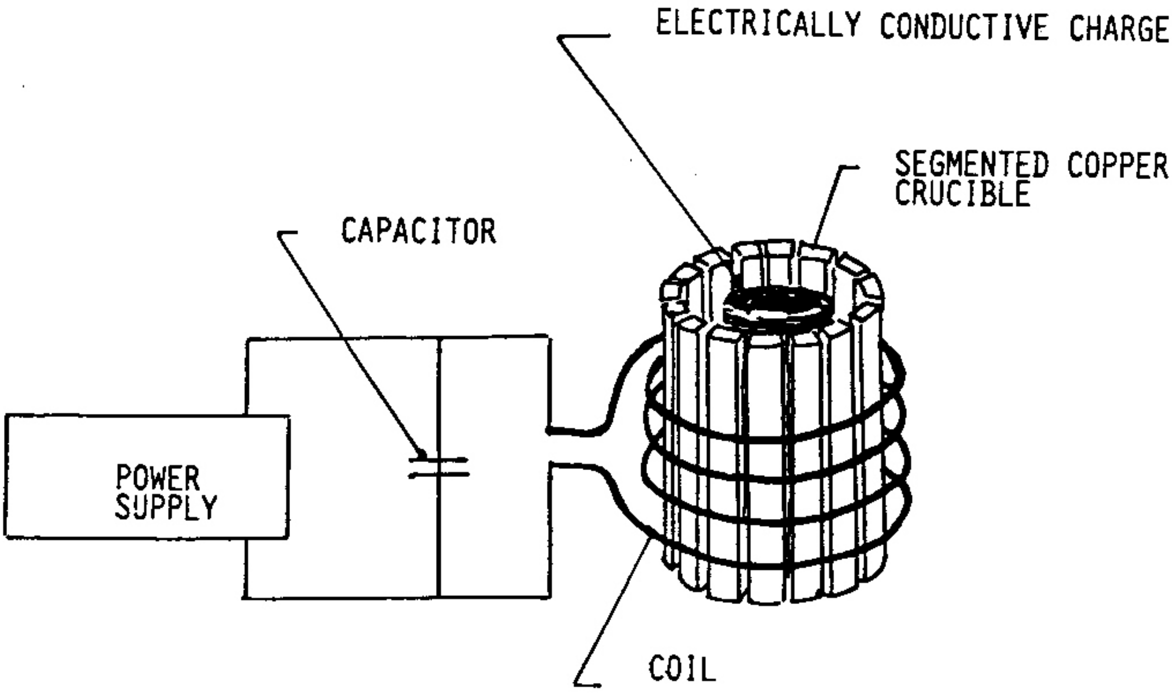
. THE OPERATING FREQUENCY IS SET BY SELECTING THE VALUE OF THE ADJUSTEMENT CAPACITOR

. THE POWER IS GRADUALLY TRANSMITTED UNTIL THE CHARGE MELTS AND FORMS A DOME

. THE SUPPLY OF TURNINGS AND THE SIMULTANEOUS CONTINUOUS EXTRACTION OF THE BILLET CAN BE STARTED.

DESCRIPTION OF THE PROCESS

PRINCIPLE



USE OF A SEGMENTED, WATER COOLED COPPER CRUCIBLE

- TO PROMOTE ELECTROMAGNETIC COUPLING WITH THE METALLIC CHARGE

- TO AVOID POLLUTION OF THE METAL

OPTIMISATION
FOR CONTINUOUS CASTING

THE CONTACT AREA BETWEEN LIQUID METAL AND CRUCIBLE IS AN IMPORTANT PARAMETER.

TOO LARGE ===> NO POSSIBLE BILLET EXTRACTION

TOO SMALL ===> METAL RUN-OUT

OPTIMISATION OF THE

- CRUCIBLE GEOMETRY
- COIL GEOMETRY
- ELECTRIC PARAMETERS

====>

. CONTINUOUS CASTING
  WITHOUT SLAG
. HIGH TEMPERATURES

MUST TAKE IN ACCOUNT OTHER CHARACTERISTICS OF THE PROCESS.

- THE HEIGHT AND STABILITY OF THE DOME
- THE STIRRING
- THE MELTING RATE
- THE ENERGY EFFICIENCY

THREE EFFECTS

- THERMAL EFFECT (WHICH ALLOWS THE CHARGE TO BE MELTED)
- FIRST MECHANICAL EFFECT : PRESSURE WHICH DETERMINS THE FORM OF THE DOME
- SECOND MECHANICAL EFFECT : STIRRING OF THE METAL.

CHOICE OF THE FREQUENCY ===> FAVORISES ONE EFFECT.

DIMENSIONLESS PARAMETER "SCREEN PARAMETER" R

$$R_\omega = \mu_0 \sigma \omega R^2$$

WITH
μ_0 MAGNETIC PERMEABILITY
σ ELECTRICAL CONDUCTIVITY
ω CURRENT PULSATION ($W = 2\pi F$)
F FREQUENCY
R CRUCIBLE RADIUS

CHARACTERISTICS VALUES OF R_ω

2 : VALUE FOR A PLANE FREE SURFACE

ELECTRICAL POWER

ADAPTED TO THE METAL AND TO THE MELTING RATE

NOT TOO STRONG ===> HIGH AND UNSTABLE DOME

$$H = \frac{B^2}{2 \mu_0 \rho g}$$

WITH

H	DOME HEIGHT
B	MAGNETIC FIELD IN THE CRUCIBLE
ρ	METAL DENSITY
g	GRAVITY CONSTANT
μ_0	MAGNETIC PERMEABILITY

METALLURGICAL

RESULTS

BILLETS OF EXCELLENT SURFACE QUALITY

(WHEN FREQUENCY AND POWER ARE CORRECTLY SELECTED)

NO CHEMICAL POLLUTION

WITH OXYGEN OR NITROGEN

WITH COPPER ===> THE CRUCIBLE IS NOT ATTACKED

6.4 ALLOY

	Al (%)	V (%)	Fe (ppm)	Cu (ppm)	O (ppm)	N (ppm)	C (ppm)
Turnings	6.2	4.1	1500	<50	2200	130	250
Billet	6.2	4.0	1550	<50	2250	120	260

NO LOSS BY VOLATILISATION

IN AL FOR 6.4. ALLOY

FINE EQUIAXED MACROSTRUCTURE

(EFFECT OF THE STRONG STIRRING)

CONCLUSIONS

. THE COLD CRUCIBLE CONTINUOUS CASTING IS A NEW PROCESS FOR THE INDUCTION MELTING OF REACTIVE AND REFRACTORY METALS AS TITANIUM.

. THE OPTIMISATION OF THE DESIGN AND OF THE ELECTRICAL PARAMETERS ALLOWS THE BILLETS CONTINUOUS DRAWING WITHOUT SLAG.

. BY MELTING TURNINGS, GOOD QUALITY BILLETS HAVE BEEN OBTAINED IN TITANIUM AND TITANIUM ALLOYS. (Ø < 150 MM   L = 2000 MM)

THEY HAVE THE QUALITY REQUIRED FOR A DIRECT TRANSFORMATION BY ROLLING OR EXTRUSION.