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Principles of Ultrasonic Treatment: Application for Light Alloys Melts

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Abstract. Scientific and practical aspects of ultrasonic treatment of light alloy melts followed with development of acoustic cavitation in liquid metals are discussed. It is shown, that the ultrasonic melt treatment raises the rate of degassing and fine filtration of light alloy melts and very strongly effects ingot structure. Furthermore, an inherited effect of ultrasonic melt treatment on the structure and properties of wrought light alloy semis is shown.

Keywords: acoustic cavitation, non-dendritic grain, dendritic parameter, cavitation nuclei, solidification nuclei, fine filtration

Abbreviations

UST	ultrasonic melt treatment
Usfirals-process	fine filtration with ultrasound

The current consideration of the melt, on the one hand, as a complex microheterogeneic system and, on the other hand, the severity of requirements for the quality of wrought light alloy semiproducts leads to the need for the search for new physical means to act on liquid and solidify metal. At present, some techniques have found their commercial application—vacuum treatment of the melt, electromagnetic stirring, continuous casting in an electromagnetic mould and oscillation.

Among physical means of action on the melt, the treatment of the melt with powerful ultrasonic waves plays as important role.

Although the effectiveness of such treatment was found long ago [1–4], this technique of an active treatment of the melt during melting and casting of light alloys has been brought into a commercial level only recently.

Acoustic cavitation in light alloys melt

One of the remarkable features of the action of a powerful ultrasound on liquid metal is the creation of cavitation phenomenon in the melt. Application of an alternating pressure above a specific threshold (about 0.8–1.0 MPa), as it takes place at propagation of a powerful ultrasound, leads to breaks of the liquid in places, where discontinuities present and to formation of fields of cavitation spaces.

Spaces (bubbles) generating in places of breaks behave differently under action of ultrasound. Some of them can pulse without the change in gas content over their whole volume.

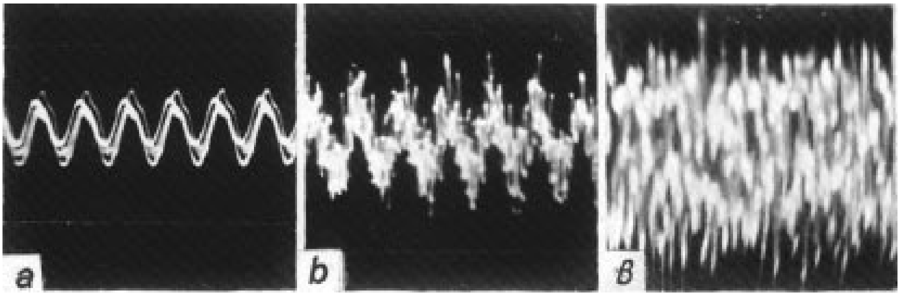

Figure 1. Typical oscillograms for the ultrasonic treatment of light alloy melts: a) without cavitation; b) cavitation threshold; c) developed cavitation.

On the contrary, the others grow actively due to the action of tensile stresses of the sound wave and one-direction diffusion of hydrogen from the melt into a bubble.

A part of the formed cavitation bubbles does not have time to fill with gas solved in the melt and collapses under the action of compression of the sound wave. In this case, local pressure pulses (up to 1000 MPa) and cumulative liquid jets, with their speed being up to 100 m/s are formed.

Figure 1 shows typical oscillograms of three regimes of ultrasonic treatment of light alloy melts: a) no cavitation; b) beginning or the threshold of cavitation and; c) developed cavitation.

The most important feature of formation and development of cavitation effects in melts is the connection of cavitation with the liquid metal purity in terms of non-metallic dispersive impurities. As a liquid, the real melt is a long way from ideal and contains many non-solutable impurities (so called “plankton” of particles). Cavitation strength of the melt and its structure, after solidification, is strongly related to metal purity in terms of these hard nonmetallic inclusions. As a rule, hard dispersive inclusions present in a real melt adsorb gas phase through their surface. That is why the cavitation develops in a real melt just on “melt-hard non-wettable particle of inclusion” interface.

As for melts of aluminium and magnesium alloys actively interacting with hydrogen and oxygen, these inclusions consist of, mainly, their own oxides, i.e., stable chemical compounds with a low degree of thermal dissociation. It is well known, that these dispersive particles are not wetted by melts and do not take part in the solidification process. On the other hand, these dispersive non-metallic impurities are perfect nuclei of cavitation and degassing of the melt.

Refining of melts in an acoustic cavitation field

Ultrasonic melt treatment (UST), before the beginning of solidification, has a noticeable effect on melt refining processes and thereby eliminates gas and solid non-metallic inclusions.

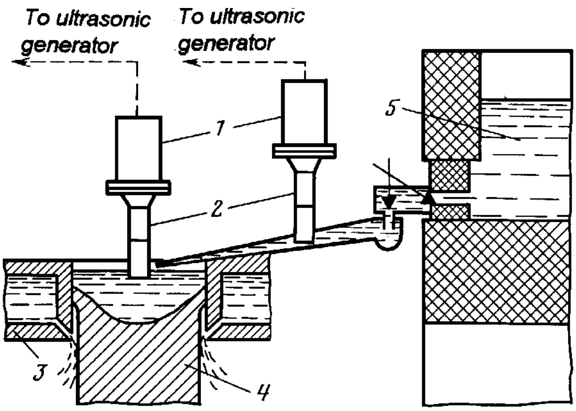

Figure 2. Schematics of the ultrasonic treatment of light alloy melts during continuous casting of ingots: 1) ultrasound source; 2) waveguide-emission system; 3) mould; 4) ingot; 5) holding furnace with melt.

Ultrasonic melt degassing

This process can be referred to as the first commercial introductions of UST into the light metallurgy. Melt degassing in an ultrasonic field is based on diffusional filling of small cavitation bubbles with hydrogen dissolved in the melt due to so called “straight” diffusion [5].

Figure 2 shows two schematics of UST applied during continuous casting of light alloys: in the running channel and immediately in the liquid bath of an ingot. The identification of these two processes lies in an obligatory movement of the melt through an active cavitation zone near an ultrasound source.

Analytical treatment of the efficiency of metal degassing in the running channel has shown, that a sharp reduction in hydrogen content results mainly from the transition to the conditions of developed cavitation practically independent from the alloy composition (figure 3). Studies showed, that the effectiveness of reduction in hydrogen content present in the melt of Al-Mg alloys (5xxx-alloys and others) can be rather high. When casting large-size flat ingots (300 $\times$ 1700 mm in cross section) from AMg6 alloy (Al-6Mg) at one of the metallurgical works, it was found that the efficiency of ultrasonic degassing of the metal flow is near to that of vacuum melt degassing in a holding furnace and results in a reduction

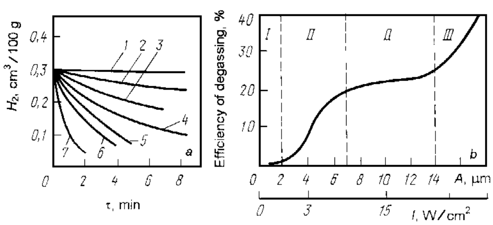

Figure 3. Kinetics of ultrasonic degassing of c.p. aluminium melt (a) and the effect of UST-conditions on the efficiency of the ultrasonic degassing (b): I—without cavitation; II—cavitation threshold; III—developed cavitation: 1) the amplitude of a source displacement of 2 μm; 2) 3 μm; 3) 5 μm; 4) 10 μm; 5) 15 μm; 6) 18 μm; 7) 22 μm.

of hydrogen content in ingots down to 0.25–0.30 cm^3/100 g. Unlike vacuum degassing, the cavitation treatment of the melt is accompanied with flotation of hard oxide inclusions. A reduced content of hydrogen and oxides in the ingot promotes an improvement in quality of rolled semis and welded products.

Fine melt filtration in an acoustic cavitation field

If 3–5 layer filter from 0.4×0.4 mm cell fiberglass is placed in the running channel, it provides not only melt degassing, but also a high degree of the melt refining from hard inclusions due to the sound-capillary effect [6]. USFIRALS-process based on this principle allows a very effective refining of dispersive particles of inclusions down to 1–3 μm by a multilayer filter. It allows production of high-quality blanks for magnetic disks from 5xxx alloys, fine foils, sheets and other semis from 6061-type alloys sensitive to impurities.

Fine filtration according to "USFIRALS-process" technique results in an improvement to service-life performances in short-transverse direction. According to our data, fracture toughness in short-transverse direction and durability at LCF (160 MPa) of D16ch (2324) alloy extruded strip of 65×200 mm in cross-section were increased from 29 to 39 MPa.$m^{1/2}$ and from 162 to 259 kilocycles respectively.

Solidification in cavitation fields

According to the current theoretical opinion about dendritic solidification, each dendrite grows from one center. That is why the refining degree of grain structure of an ingot or a casting is effected only by the number of real solidification centers. The number of solidification centers forming in a melt depends, in its turn, on active solidification nuclei wetted with matrix liquid and able to form solidification centers.

Development of the cavitation in the melt promotes activation (wetting) of hard dispersive impurities and their introduction into the solidification process as an active material used for formation of solidification centers. Studies undertaken by VILS showed that the solidification in a cavitation field provides new potentialities in the control of ingot structure and wrought semis made from these ingots.

Sequential solidification and formation of non-dendritic grain structure

Depending on conditions of solidifying metal, purity of the melt in terms of active impurities and intensity of external actions on the melt, ingot (or castings) structure can consist on both dendritic and non-dendritic grains. An important feature of non-dendritic structure (sometimes is called as predendritic, subdendritic or microcrystalline one) is the formation of finest globular grains related to a certain cooling rate. Such grains have high-angle grain boundaries and their size is approximately equal to that of dendritic arms formed in an analogous casting (ingot) with dendritic structure [7–9].

Differences in the structure of dendritic and non-dendritic grains are clearly seen from figures 4(a) and (b), where views of microstructural zones with crystallographic orientations are

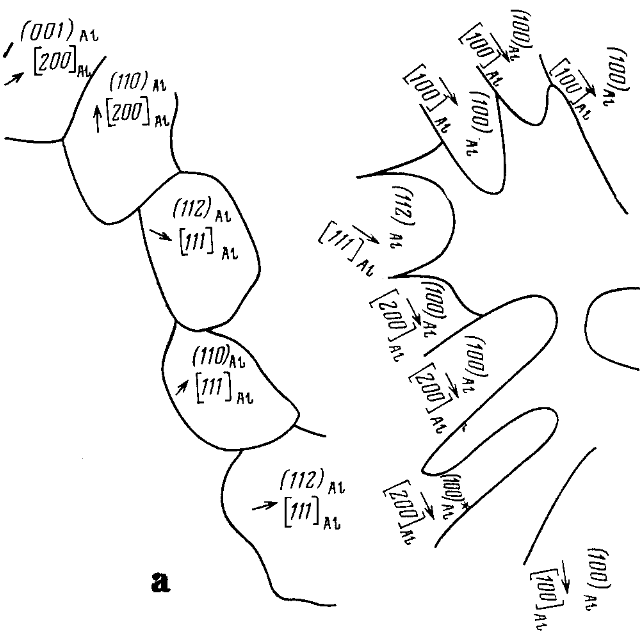

Figure 4. Views of microstructure of 1960 (7055) alloy ingot of 70 mm in diameter with non-dendritic (a) and dendritic (b) zones. Crystallographic orientations are shown too.

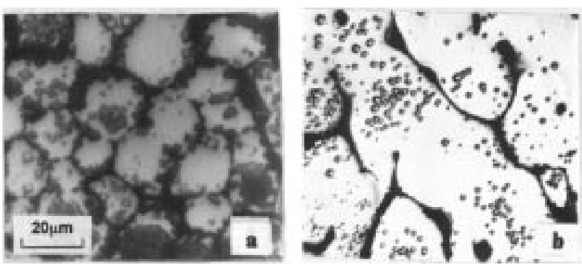

Figure 5. Typical microstructure of 1960 (7055) alloy ingot of 70 mm in diameter with non-dendritic (a) and dendritic (b) zones after etching with Villon's reagent (×800).

shown. Figure 5 shows a typical microstructure of non-dendritic (a) and dendritic (b) grains of 1960 (7055) alloy ingots of 70 mm in diameter. Differences in orientation angles of non-dendritic grains and dendritic arms existing in dendritic grains are perfectly seen due to etching cells formation resulted from the sliding surface treatment with Villon's reagent ($HNO_3 + HCl + C_3H_8OH + HF$). On the base of analysis of non-dendritic and dendritic structure one can conclude that non-dendritic solidification provides high-angle boundaries in 90% of grains while only 10% of grains have such boundaries in a dendritic structure.

For many years, investigations undertaken using ingots of various cross-sections made from aluminium alloys with small (up to 0.15%) additions of transitive metals (Ti, Zr,

Table 1. The effect of structure of 7050-type alloy ingot of 960 mm in diameter on mechanical properties of large size extruded and forged semis.

	Non-dendritic structure						Dendritic structure					
	Shape			Forging			Shape			Forging		
Direction of sampling	UTS, MPa	0.2% YS, MPa	El, %	UTS, MPa	0.2%, YS, MPa	El, %	UTS, MPa	0.2%, YS, MPa	El, %	UTS, MPa	0.2%, YS, MPa	El, %
T	554	517	13.0	478	410	17.0	556	492	12.0	494	417	12.0
L	528	484	11.2	476	405	15.2	539	482	10.0	501	416	12.5
ST	528	488	8.5	463	400	8.8	513	461	4.5	433	384	3.5

T—transverse direction;
L—longitudinal direction;
ST—short transverse direction.

Sc) and magnesium alloys with Zr, Ce, Nd and other additions showed the possibility of transition to a non-dendritic solidification mode due to cavitation treatment of solidifying melt. According to our previous works [7–9], the transition to a non-dendritic solidification of light alloy ingots can be considered as an obligatory condition to provide for a high property level of ingots and semis.

The main advantages of non-dendritic solidification of light alloys are as follows:

— an improvement in ductility of cast metal and, as a result, an increase in crack resistance of large-size ingots;
— an increase in ductility of ingots by hot deformation;
— heredity in an improvement in service life performances of wrought metal;
— a hereditary ductility of welded joints resulted both from base materials and from welding wires manufactured from non-dendritic structure ingots.

The effect of structure of 7075 alloy-type ingot of 960 mm in diameter on mechanical properties of large-size extruded and forged semis is shown in Table 1. From this table it is clearly seen, that the non-dendritic ingot structure has a positive effect on metal properties in the critical short-transverse direction and on fracture toughness through the whole volume of a large-size semiproduct.

As earlier studies [10, 11] showed, formation of non-dendritic ingot structure can have a decisive effect on deformation process in semisolid state. Non-dendritic grains can easily slide relative to one another in a liquid matrix, since the advantages of non-dendritic structure (in comparison with a dendritic one) result both in a reduction in deformation forces and in an improvement in formability of complex-shaped products.

Bulk solidification of light alloys and formation of excessive phases

Activation of nucleation in acoustic cavitation field is an important condition for formation of a grain structure of solid solution and serves as a regulator of dispersity and distribution of primary solidifying excessive phases.

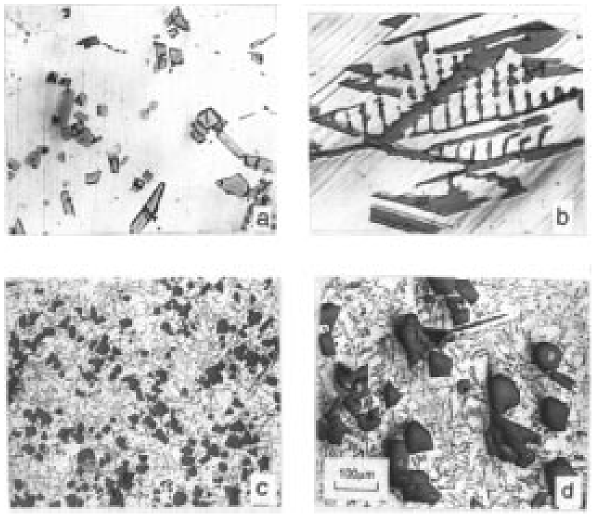

Figure 6. Microstructure of ingot of 98 mm in diameter made from binary alloys: Al-3% Mn (a,b) and Al-18 % Si (c,d) a,c—casting with UST; b,d—casting without UST (×125).

In our earlier studies on solidification of primary Mn-crystals in binary Al-Mn alloys [7] it was shown already that UST under cavitation conditions above liquids temperature resulted in a considerable refining of Al_6Mn intermetallic compounds. Subsequent investigations [8, 12] showed, that UST can be helpful for formation of other excessive phases such as primary Si-crystals in hypereutectic silumins.

Microstructure modes of ingots of 98 mm in diameter made from binary aluminium alloys (with 3% Mn or 18% Si) with/without UST are shown in figure 6. Modification of the ingot structure of such composite materials by their nature in an ultrasound field allows an increase in their ductility and provides for new potentialities for application of the common process of continuous casting in production of wrought semies with special properties. Furthermore, the introduction of UST into a production run leads to an improvement in properties of Al- and Mg-based structural alloys due to an increase in concentration of transitive metals but does not result in formation of large size intermetallic compounds [8].

Rapid solidification of aluminium alloys

Production of dispersive powder particles via various techniques leads, in some cases, to formation of non-dendritic structure in light alloys [13–14] due to melt overcooling and homogeneous nucleation during rapid solidification. However, application of ultrasonic atomization (granules, flaks), spinning (fibers) and other rapid solidification techniques connected with ultrasonic melt dispersion (figure 7(a) and 7(b)) demonstrates a predominant formation of a non-dendritic structure [14, 15].

Furthermore, our studies [15] verified, that the reliability of formation of non-dendritic structure in a rapid solidified casting can be increased due to cavitation treatment (figure 7(c))

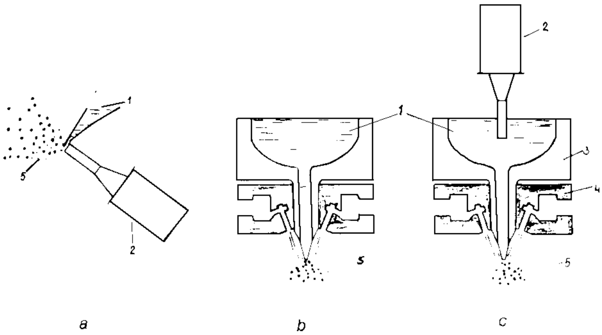

Figure 7. Schematics of ultrasonic atomization of aluminium alloys: (a) thin-layer ultrasonic atomization; (b) acoustic atomization with a pulsing jet of noble gas; (c) acoustic atomization with noble gas (preliminary cavitation treatment of the melt). 1) Melt; 2) ultrasound source; 3) pouring cup; 4) acoustic noble gas-jet atomizer.

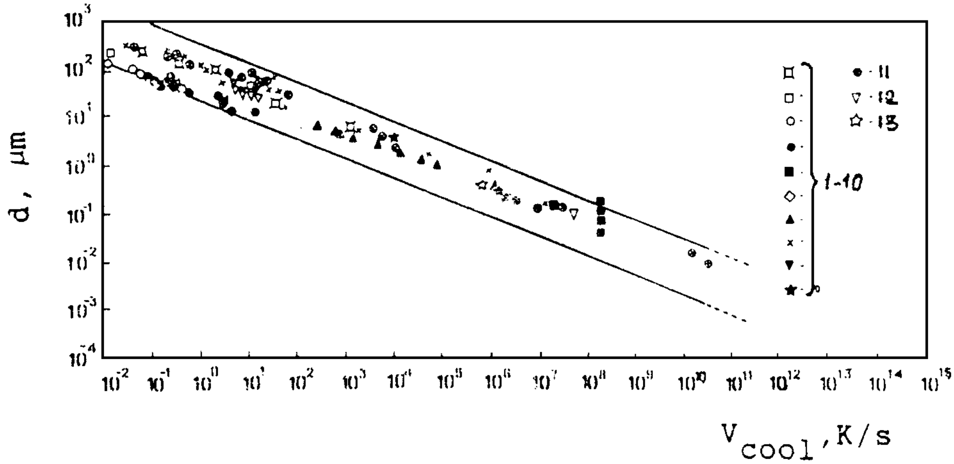

Figure 8. The change in sizes of non-dendritic grain (11–13) and dendritic parameter (1–10) as a function of the melt cooling rate during solidification of aluminium (1–8, 11), magnesium (9–12) and nickel (10–13) alloys according to our data and those obtained in Works 18–19.

of the melt before its rapid solidification. Development of the cavitation processes in the melt has a positive effect on the formation of solidification nuclei involving heterogeneous and homogeneous nucleation mechanisms. In co-operation with Dobatkin [16, 17] and based on data obtained at VILS for non-dendritic solidification with melt cooling rate of 10^3–10^8 grad/s we have complemented an earlier deducted dependence between the size of a non-dendritic grain, dendritic parameter and cooling rate with new data (figure 8, Table 2). This general mechanism of metal solidification effected by the melt cooling rate is based on an assumption, that in the case of an excess of solidification nuclei, the size of a non-dendritic grain and the dendritic parameter are effected only by thermal conditions of the solidification process. The diagram shown in figure 7 is plotted in accordance with own data and those given in special literature [18, 19].

Table 2. The effect of cooling rate on the non-dendritic grain sizes in the ingots and castings in an a Al-Zn-Mg-Cu-Zr alloys [18].

Sizes of ingots, granules, mm	Grain sizes, μm		Cooling rate, $K.s^{-1**}$
	UST	Without UST*	
	Continuous casting of ingots		
960	150	≥1500	0, 25
830	130	≥1000	0, 35
650	110	≡1000	0, 6
370	90	≡1000	1, 2
200	50	500	6, 0
70	30	300	60
	Ultrasonic-aided atomization		
0, 1	5	50	4.10^3
0, 05	3	30	1.10^3

*Non-dendritic grain.

**Temperature range of solidification 100°C.

Conclusion

The above data concerning the effect of ultrasonic (cavitation) treatment of light alloy melts on refining and solidification processes show potentialites of this ecologically-compatible technique for the melt treatment. Acoustic cavitation is a powerful physical means of a radical change of the melt microheterogeneity promoting the main processes of refining and solidification in light alloys. Ultrasonic melt treatments under cavitation conditions can serve as a "source" for an improvement in quality of ingots and semis made from common and newly developed light alloys.

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