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The influence of the method of supersaturation on the course of precipitation hardening of chill castings made of aluminium silicon alloys

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A comparative study of the two methods of precipitation hardening of Al–Si cast alloys is presented, i.e. the ordinary and the simplified method. The latter consists in application of the quenching of chill castings directly after solidification. The microscopic structure and the hardness of laboratory-cast specimens as well as mechanical properties of production castings were investigated. It is concluded that the simplifed method of supersaturation has an essential impact on the kinetics of the ageing process and the structure o of the alloy. The mechanical properties obtained by this method can be satisfactory and the savings of energy, labour and equipment can be significant.

1. Introduction

New core sands produced in the Metal Casting section of Warsaw Technical University enable cores made of those sands to be removed from castings by immersing them in water [1–3]. This creates the possibility of simplification of the supersaturation process of the Al–Si alloy castings. Chill castings, with cores made from the new core sands, directly after taking them out of the mould, i.e. at a temperature of 600 to 800 K, are placed in water in order to remove the cores from them. Under the influence of water the cores disintegrate. This makes it possible to combine the operation of removal of the cores with the operation of quenching of the alloy in order to obtain a supersaturated solid solution. Elimination of the heating up and soaking operations, applied to castings super-saturated in the ordinary heat-treatment enables a considerable simplification of this process and gives substantial savings of energy and labour.

The core sand consists of a quartz sand and a binder not used up to now in foundry practice: sodium carbonate together with sodium hydroxide or a hydroxide of other elements. The core sand is hardened by blowing of the densified core with CO_2 in a core box.

In this paper the examination of the influence of the simplified supersaturation conditions on the course and mechanism of the process and the results of the experiments on the process in shop-floor conditions are described.

2. The course of the ordinary and simplified super-saturation processes

Precipitation hardening of Al–Si alloys castings consists of two stages: supersaturation and precipitation heat-treatment. The supersaturated structure is obtained as a result of rapid cooling of castings previously soaked at a temperature of 803 ± 5 K for 2 to 5 h [4].

The time period from the removal of a casting from the furnace to the immersion of it in the cooling medium should be as short as possible (30 to 60 sec) because of the decrease in mechanical properties of castings after completion of the heat-treatment process [5].

Ambient temperature water is most often used for quenching of castings; however, in order to ensure a proper cooling rate and a decrease in residual stresses in castings, boiling water, oils or salt solutions may be used [6]. The rapid decrease of the alloy temperature causes a considerable part of the alloy-forming elements (Mg and Si), dissolved as a consequence of the long-lasting soaking operation, to be arrested in the solid solution at ambient temperature.

The super-saturated solution contains an excessive quantity of vacancies and dislocations besides excessive concentrations of the alloy forming elements.

Because the system tends to an equilibrium state, vacancy groups appear which may transform into dislocation loops [7]. At the second stage of the precipitation hardening operation, i.e. the precipitation heat-treatment consisting of heating of the supersaturated castings to a temperature of 433 to 473 K, soaking them for 3 to 10 h and slow cooling, the effect of grouping of the atoms of the supersaturating element in certain places of the crystal lattice occurs. In this way zones of increased concentration of Mg and Si atoms are formed (so-called Guinier–Preston zones), which generate a state of stress in the structure causing an increase in strength and hardness. According to the literature [8], excessive vacancies and dislocation loops are of great importance in these effects.

The process of supersaturation of castings as described here is very energy- and labour-consuming and requires costly furnaces for heat-treatment and a large production area, which considerably increases the manufacturing costs.

On the grounds of analysis of Al–Mg_2Si pseudo-double equilibrium system, it is possible to simplify this process for castings made in permanent moulds using the heat of solidification and cooling down of the casting [9]. During cooling every casting passes the range of variable solubility, but because of a too-small rate of cooling, precipitation of the alloy element occurs, and the equilibrium structure is obtained at ambient temperature.

Because of the possibility of removal of the casting at a temperature above 653 K from a metal mould followed by rapid cooling by immersion into water, it should be assumed that it is possible to obtain a supersaturated alloy directly in the casting manufacturing cycle. An additional advantage of the simplified method of supersaturation is the possibility of simultaneous removal of the core (in the case of cores made of sands disintegrating in water) in the casting properties forming cycle, and almost entire elimination of supersaturation costs.

3. Preparation of material for experiments

Experiments were carried out on cylindrical specimens of 20 and 40 mm diameter cast in metal moulds coated with a 0.1 mm thick chromium oxide-based layer. The mould was heated to a temperature of 623 K prior to pouring. The alloy AK-9 having the composition Si 8.6%, Mg 0.3%, Mn 0.4%, Fe 0.4%, Cu 0.5%, Zn 0.04%, Ti 0.03%, was refined with "Rafal 2".

Temperature changes of the casting from the moment of pouring to the immersion in water were measured continuously using a chromel–alumel thermo-couple plunged in the riser. Two kinds of specimens were prepared:

(1) conventionally supersaturated by soaking at a temperature of 803 K for 3 h followed by rapid cooling in water;

(2) supersaturated by the simplified method by removing them from the mould followed by immersion in water; the supersaturation temperature changed within the range 803 to 553 K.

After quenching, 10 mm thick discs were cut from both types of specimen and isothermally aged at a temperature of 473 K. The ageing time varied within the range 0 to 6 h for specimens of 20 mm diameter and within the range 0 to 8.5 h for specimens of 40 mm diameter. Hardness measurements were carried out on the section surface of the disc specimens after heat-treatment operation, and then cylindrical specimens 3 mm thick and 15 mm long were taken for structural tests.

4. Hardness test results

The hardness tests were carried out using a Brinell hardness tester with a 5 mm ball loaded with a force of 250 Kg for 30 sec. The results were statistically worked out using a computer program, in which statistical as well as function smoothing and result printing procedures were used.

In Fig. 1 variations of hardness for 20 mm diameter specimens are presented and in Fig. 2 for 40 mm diameter specimens, plotted against the method and temperature of supersaturation. The plots are rather complicated, but of a similar nature. It can be seen from Figs. 1 and 2 that hardness after supersaturation decreases with the decrease of the supersaturation temperature. Hardness for a 20 mm diameter specimen varies from

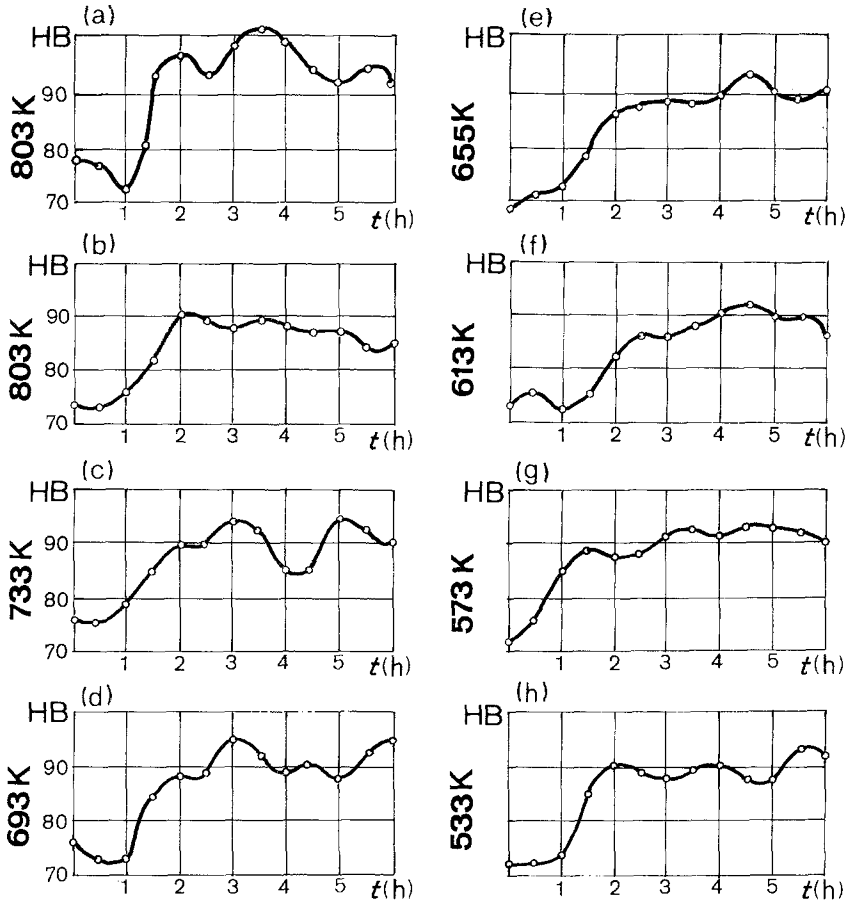

Figure 1 Variations of hardness of a cylindrical specimen, 20 mm diameter during isothermic ageing at a temperature of 473 K against method and temperature of supersaturation. (a) Conventional supersaturation method (heating and soaking of castings in a furnace at a temperature of 803 K for 3 h. (b) to (h) Simplified supersaturation method within the temperature range 803 to 533 K.

78 HB after conventional supersaturation and 75 HB after simplified supersaturation, starting from a temperature of 805 K, to 71 HB after supersaturation from the temperature of 553 K. Hardness for a 40 mm diameter specimen after traditional supersaturation from a temperature of 803 K was 72 HB, and after simplified supersaturation, 80 HB.

Hardness decreases monotonically with decrease in temperature up to 68 HB at the supersaturation temperature of 533 K. During ageing, an initial hardness drop followed by a rapid increase can be seen for both series of curves. For 40 mm diameter specimens the initial hardness drop is greater and lasts longer for the alloy supersaturated by the simplified method from a temperature of 803 K (see Fig. 2).

Decreasing the supersaturation temperature results in a decrease of the hardness drop. Hardness increases with the time of ageing reaching its first maximum value ranging from 96 to 90 HB fro 20 mm diameter specimens, and from 98 to 88 HB for 40 mm diameter specimens. The time necessary to attain the maximum remains nearly the same in the first case and amounts to about 2 h; however, in the simplified supersaturation it varies from 2 h for supersaturation from a temperature of 803 K to 4 h for a temperature of 533 K. Further ageing initially causes some drop in hardness followed by attaining of the maximum hardness in both kinds of specimens. The time to attain this maximum increases with the decrease of the supersaturation temperature. It should be emphasized that a 40 mm diameter specimen supersaturated from a temperature of 803 to 693 K has its maximum hardness greater than that after conventional heat-treatment. The difference is 8 HB. During further ageing the shape of the curves is fairly complicated; however, it exhibits a slow decrease in hardness showing local variations.

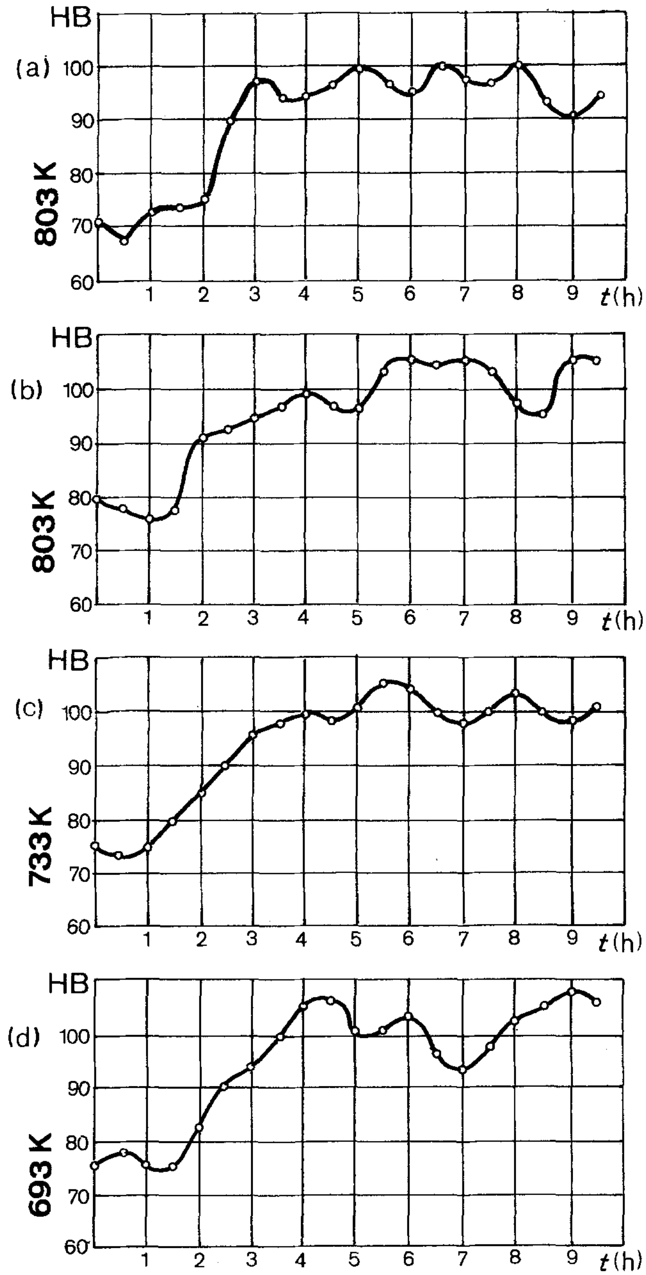

Figure 2 Variation of hardness of a cylindrical specimen, 40 mm diameter, during isothermic ageing at a temperature of 473 K against the method and temperature of the supersaturation. (a) Conventional supersaturation method (heating and soaking of castings in a furnace at the temperature of 803 K for 3 h). (b) to (h) Simplified supersaturation method within the temperature range 803 to 533 K.

5. Microscopic tests

Microscopic tests were carried out using a Philips EM 300 transmission electron microscope. Specimens 0.15 mm thick were cut out from cylinders 3 mm diameter by the abrasive cutting method and electrolytically thinned by the single-jet method.

The alloy structure supersaturated by the conventional method is presented in Fig. 3a to c, directly after supersaturation (a), and aged for 1.5 h (b) and for 3 h (c). The alloy structure after supersaturation has small quantity of dislocations. Dislocation loops occur sporadically. After ageing for 1.5 h (Fig. 3b) the alloy structure changes a little; on some dislocations only, the contrast occurs showing heterogeneous nucleation of precipitations.

After 3 h ageing a great number of uniformly distributed GP (Guinier–Preston) zones appear.

The structure of the alloy supersaturated by the simplified method from a temperature of 803 K is presented in Fig. 4a to d. The alloy directly after supersaturation is shown in Fig. 4a. It differs

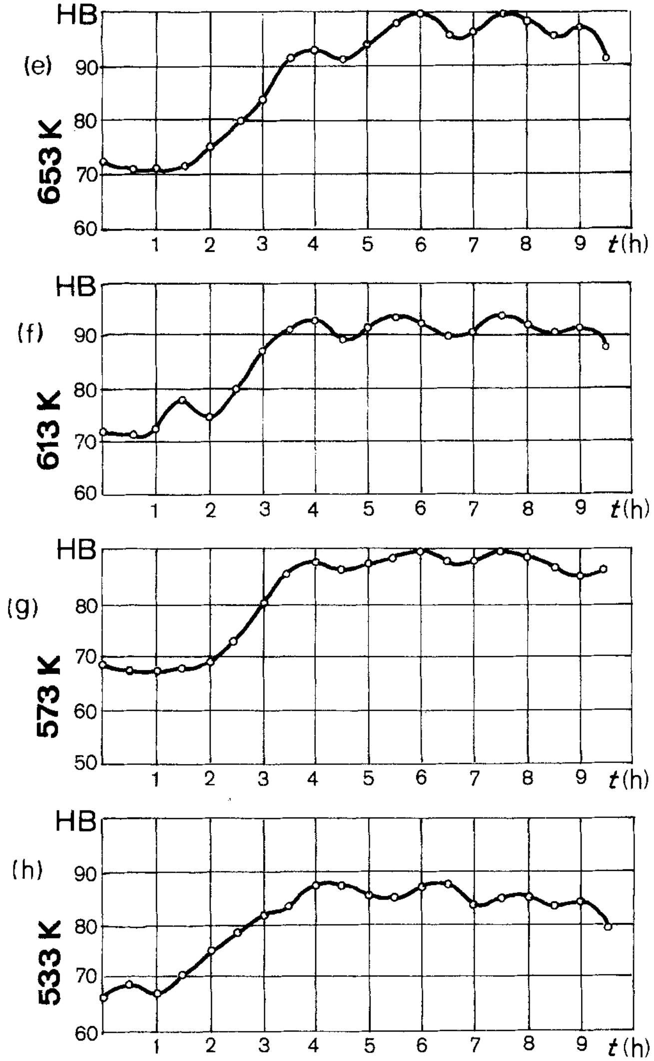

Figure 2 continued.

radically from the alloy presented in Fig. 3a. The structure is strongly defected. Numerous dislocation loops of various sizes and a strongly tangled dislocation lattice can be seen. After ageing for 1.5 h (Fig. 4b) an order of structure follows which is indicated by a decrease in the number of dislocations. Small GP zones appear. After ageing for 3 h (Fig. 4c) a great number of GP zones, of various lengths, appear. Moiré fringes also appear on rod-like precipitations (Fig. 4d), which indicates that after this ageing time metastable precipitations of β'-phase had already appeared.

6. Summary of test results

The tests proved that the supersaturaion process carried out directly within the process of cooling of castings in a metal mould generates variations in the alloy structure. These variations have an essential impact on the kinetics of the ageing process. The alloy structure, after the simplified supersaturation, is more defected than that in conventionally supersaturated alloy. It may also be supposed that the concentration of excessive vacancies is much greater. The numerous dislocations and dislocation loops occurring in the alloy structure supersaturated by the simplified method cause a quicker nucleation of GP zones in the ageing process and a greater hardening of the alloy. Evidence for this is given by the correlation shown between the number of precipitations and the density of dislocation loops, and confirmed by the published data [8, 10].

The temperature of castings removed from metal moulds before immersion in water should be above 653 K. However, the negative effect of lower supersaturation temperature on hardness can

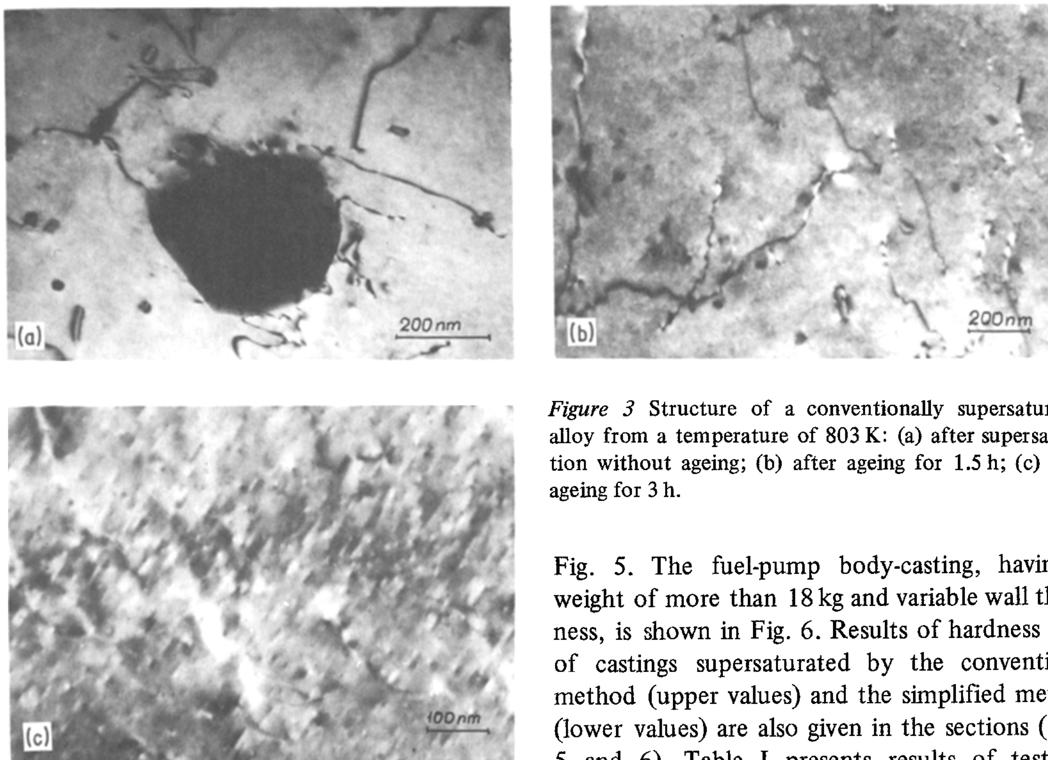

Figure 3 Structure of a conventionally supersaturated alloy from a temperature of 803 K: (a) after supersaturation without ageing; (b) after ageing for 1.5 h; (c) after ageing for 3 h.

be partly compensated by an increase in ageing time.

The results presented of tests carried out on cylindrical specimens fully confirmed the efficiency of the simplified method of supersaturation. It provided a reason for repetition of tests on the simplified method of supersaturation for castings made in industry.

7. Industrial tests

Industrial tests of the simplified method of supersaturation were carried out on four selected types of actually manufactured castings made of AK-7 and AK-9 alloys. These castings differed greatly from each other in weight, wall thickness and dimensions. For each type two series of castings were made, five castings for each series. The castings were supersaturated by the conventional and simplified method from a temperature ranging from 673 to 693 K, and then aged at a temperature of 473 K for 3 to 5 h depending on the weight of the casting.

This paper presents the results of tests carried out on two types of castings with extrmely different wall thicknesses (Fig. 5) and size. The regulator body casting, having a weight of 1.5 kg and an average wall thickness of about 12 mm, is shown in Fig. 5. The fuel-pump body-casting, having a weight of more than 18 kg and variable wall thickness, is shown in Fig. 6. Results of hardness tests of castings supersaturated by the conventional method (upper values) and the simplified method (lower values) are also given in the sections (Figs. 5 and 6). Table I presents results of tests of mechanical properties (R_m, A_5, HB) carried out on specimens cut from casting walls.

Mechanical properties of castings supersaturated by the simplified method were lower than those for castings heat-treated by the conventional method; however, all castings met the technical acceptance requirements, i.e. $R_m > 210$ MPa, $A_5 > 2.1\%$, HB > 80.

Hardness tests carried out on sections of the simplified method supersaturated castings showed some decrease in hardness in hot spots and near the sand cores. Hardness in these spots was 15% lower; however, in no case was it lower than 80 Hb.

8. Conclusions

The results of tests presented above, both laboratory and industrial, allow conclusions to be drawn of both a cognitive and production nature

Cognitive conclusions

(1) The simplified method of supersaturation has an essential impact on the kinetics of the ageing process. It consists of a more rapid rate of strain hardening of an alloy.

(2) The structure of a casting after supersaturation by the simplified method is much more defective and includes a greater number of dislocations and loops of dislocation as compared to a

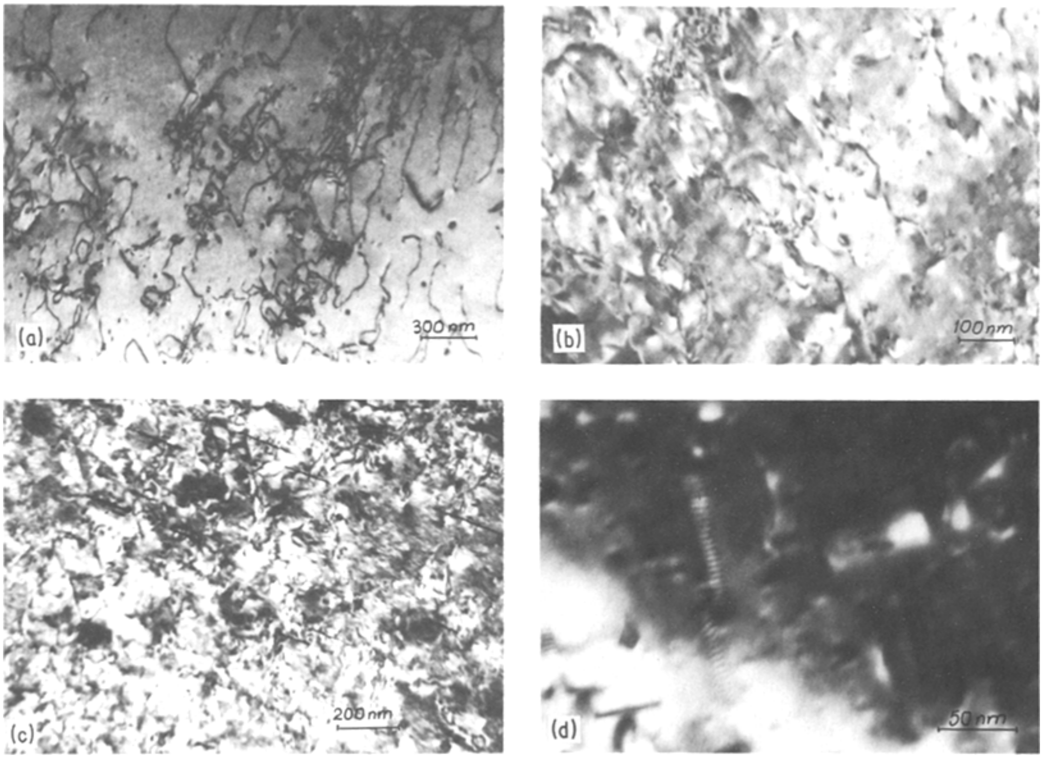

Figure 4 Structure of a simplified method supersaturated alloy from a temperature of 803 K: (a) after supersaturation without ageing; (b) after ageing for 1.5 h; (c) after ageing for 3 h; (d) after ageing for 3 h (another area).

casting supersaturated by the conventional method.

A great number of dislocations may indicate much greater supersaturation of the structure with excessive vacancies.

Production conclusions

(1) The simplified method of supersaturation ensures that relatively high mechanical properties of a casting are obtained.

(2) The temperature of a casting before immersing it in water should be taken within the range 803 to 653 K.

(3) In case the supersaturation temperature is too low there is a possibility of compensating for

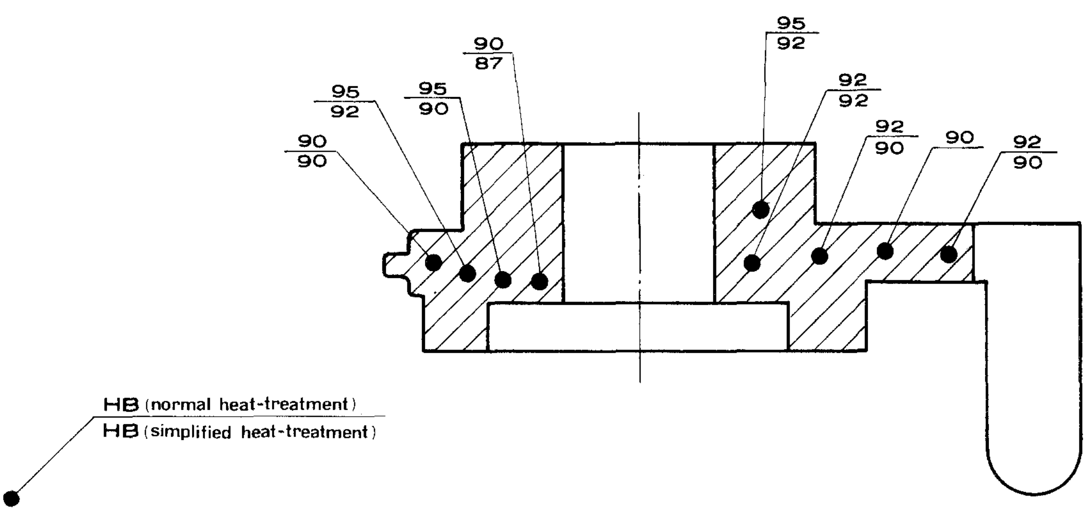

Figure 5 Draft of the regulator body casting with hardness measurements at wall sections.

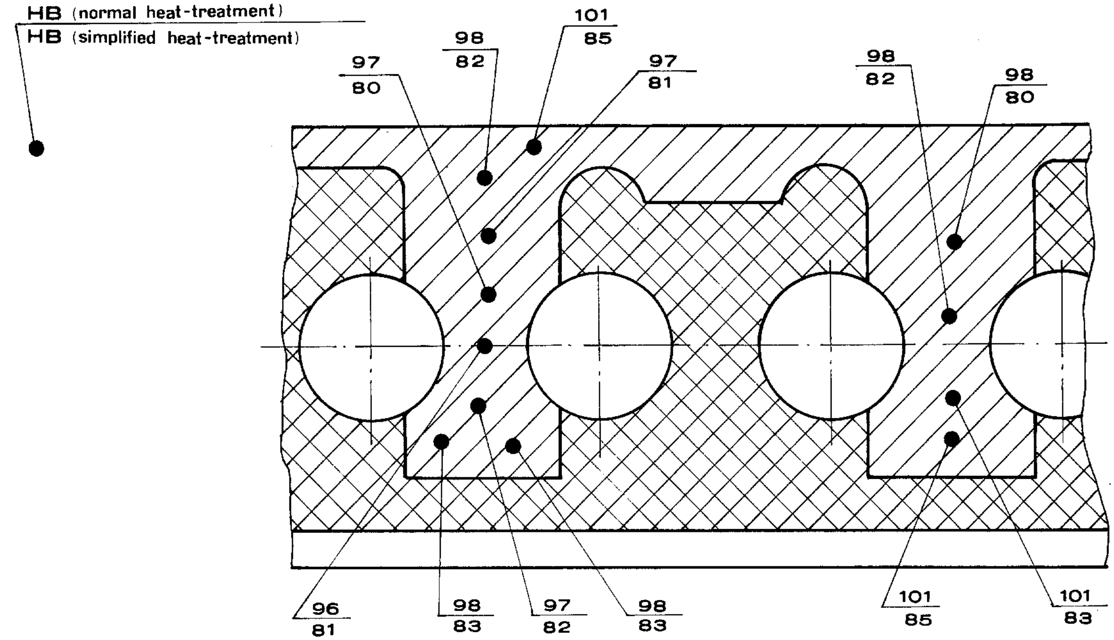

Figure 6 Draft of the pump-body casting with hardness measurements at wall sections.

its negative effect by the extension of the ageing time.

It may be assumed that the simplified method of super-saturation may be applied without any limitations for thin-walled chill castings. In the case of thick-walled castings, particularly castings with sand cores, the minimum supersaturation temperature and ageing time appropriate for obtaining the required properties must be determined experimentally.

The savings achieved by the application of this process are considerable and amout to about 1000 zł/ton of castings. They result from savings of energy (up to 1 MWh/ton of castings), labour and equipment (supersaturation furnaces, baskets etc.).

The simplified method of supersaturation also makes it possible to introduce the heat-treatment processes of silumins into those foundries, which have not yet applied the process because of lack of the necessary equipment. The castings supersaturated by the simplified method may be aged in core-drying stoves, because the required temperature is 450 to 470 K. It enables a considerable increase in

TABLE I Comparison of mechanical properties of castings supersaturated by the conventional and simplified methods (ageing temperature 473 K, time 3 h)

Type of casting	Supersaturation method	Results	Mechanical properties		HB
			R_m (MPa)	A_5 (%)	
Regulator body (Fig. 5)	Conventional	average	259	2.5	97
		highest	270	2.8	98
		lowest	245	2.3	96
	Simplified	average	234	2.6	89
		highest	246	2.8	90
		lowest	220	2.3	88
Fuel-pump body (Fig. 6)	Conventional	average	252	2.4	90
		highest	260	2.7	95
		lowest	235	2.3	88
	Simplified	average	237	2.4	84
		highest	245	2.7	86
		lowest	230	2.3	82

casting quality to be made at minimum cost. It may be expected that it would be economically reasonable to recover the heat from the water used for cooling of the castings (for example by means of heat exchangers). The method of supersaturation presented above will bring about an improvement in working conditions in a metal mould foundry owing to the elimination of storage of hot castings. The advantages of the simplified method of supersaturation described above, as well as a possibility of immediate, practically no-investment introduction into production, should interest industry and should cause the introduction of this method into the manufacturing practice.

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