THE DEVELOPMENT OF AUTOMATED CONTROL SYSTEM FOR THE GROWTH OF SHAPED SAPPHIRE CRYSTALS: COMBINED CONTROL

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Abstract

New method of control based upon a physical model of the Stepanov growth technique has been developed. The controller keeps the system stable and completely denies operator's interference into the process. The system demonstrates very reliable results under commercial production of shaped sapphire crystals.

Introduction

Weighting sensors are extensively used in automated control systems for growing crystals from a melt by the Czochralski technique. In order to accomplish an automated crystal growth process by the Stepanov (EFG) technique we studied the influence of the growth process parameters on the force sensor readings [1]. The obtained data suggest that along with the forces such as the crystal and meniscus weights, the surface tension force and the force stipulated by hydrostatic pressure, the growing crystal is subject to extra forces caused by hydrodynamic flow of the melt in meniscus and capillary regions. Later pressure distribution caused by a hydrodynamic stream was calculated and all the forces acting on crystal during the Stepanov (EFG) growth were analyzed. Considering our experimental data and numerical analysis results we proposed the following model [2]:

$$W(t) = \int_0^t \rho_S g S(t)\ V dt_1 + S(t)\rho_L g h + \Gamma(t)\sigma_{LG}\cos\varepsilon +$$

$$+ H_{eff}\rho_L S(t) + K_R V + \int_{S_S} p(h,V) ds$$

where ρ_S, ρ_L is the density of crystal and melt, respectively, σ_{LG} is the factor of surface tension, ε is the growth angle, $S(t)$, $\Gamma(t)$ is the crystal cross section area and perimeter, V is the pulling rate, h is the meniscus height, K_R is the die resistance factor against melt flow, $p(h,V)$ is the hydrodynamic pressure under crystallization front.

It is shown that there is a range of meniscus heights where the change of the force stipulated by hydrodynamic pressure redistribution is considerably more than the deviation which the static model describes. In this range the force stipulated by hydrodynamics has the domonant effect on crystal, and, accordingly on the force sensor readings. This force increases linearly with the pulling rate and essentially nonlinearly with the meniscus height decrease, Fig. 1. From the presented data it is concluded that the system force response to the meniscus height oscillation increases essentially with decreasing meniscus. Such diminution usually takes place as in neighboring media temperature changes abruptly, when, for example, a crystal leaves radiation shields of the heat zone. Thus, it is impossible to perform an optimal feed-back control using implemented in power channel PID-regulator with constant tuning coefficients, which is commonly applied to automate the Czochralski growth process.

In this work a “combined” method of regulation is used to improve the control system performance. This control technique is successfully applied to grow shaped sapphire crystals.

Combined control

Growth processes were performed on an apparatus ‘NIKA-S’ for growing crystals by the Czochralski and Stepanov methods, produced serially by the Experimental Factory of Scientific Engineering (EFSE RAS).

The machine is supplied with a force sensor of 20 mg sensitivity installed in the upper part of the water–cooled rod, pulling up a crystal. A thin filament inside the rod connects the sensor and the holder of a seed crystal. An analog signal of the sensor is transformed into a serial binary code and is transmitted through an open optical channel (a light-emitting diode - photodiode), transformed into a parallel code and read-out by an IBM PC. Table 1 shows the characteristics of the force measuring system. The force acting on crystal, its deviation from the reference value (Δm), the first- and second-order deviation derivatives ($\Delta\dot{m}$, $\Delta\ddot{m}$) and current power can be presented numerically or in the form of dynamic graphs. The software operates under Windows’95.

In all growth processes involving the PID control show that a crystal overcooling, followed by meniscus height diminution, causes an increase in the amplitude of the $\Delta\dot{m}$ registered value. In the case of rather deep overcooling a thermal overcorrection immediately took place, the system looses its stability and the automated control failed. Usually, when crystal is overcooled, an operator, in order to carry on the growth process has to correct the situation manually by increasing greatly the power of heating.

One of the ways to perform continuous feed-back control is to maintain the height of the meniscus in certain range and, therefore, the dynamic response of the system constant, automatically. As mentioned above the magnitude of crystal overcooling correlated well with the amplitude of the $\Delta\dot{m}$ registered value. So, through evaluating this parameter the controller is able to get indirect information about the meniscus height and, in the case of small meniscus, change the way of control to avoid overcorrection and to keep the control stable.

The block-diagram of the applied system is shown in Fig.2. The mean value $\overline{A}$ is compared with A_{cr}, which is chosen so that if $\overline{A} \le A_{cr}$ the PID control is stable and the operator can fully rely on its performance. When the condition $\overline{A} > A_{cr}$ is satisfied, PID control is canceled automatically and power of heating increases by a certain value ΔP. On the second "by-pass" loop regulator delays for period T, waiting for the effect of power increase. Further, a new value of $\overline{A}$ is calculated and compared with A_{cr}. This procedure will be completed as soon as $\overline{A} \le A_{cr}$, when the regulator switches again to PID-control. Adjusting the values of ΔP, n, A_{cr}, T one can maintain the PID-control stability and improve the feed-back performance.

This method of control was applied in the growth processes of fifteen sapphire rods of rectangular cross-section. The values of current power and first-order derivative $\Delta\dot{m}$ depending on grown length were registered. The section when illustrating switches from PID-control to by-pass contour and back represented in Fig. 3 (a, b). These figures clearly demonstrate that after such switches the amplitude of $\Delta\dot{m}$ decreased considerably and PID-control retained its stability. The grown rods are shown in Fig. 4.

Thirty packages of fifteen sapphire rods were grown in order to compare the performances of PID and combined controllers. A combined controller was applied for ten of them and, when the values of ΔP, n, A_{cr}, T had been adjusted, no operator interference in the process of growth was allowed. The following data (Fig.5) represent the total amount of sapphire items, the mean yield and the mean percent yield of the process depending on the controller type.

These quantitative assessments demonstrate that when the combined controller is applied the capacity of the process and the quality of the grown crystals are sufficiently improved.

Conclusions

Combined method of controlling based upon the physical model of the Stepanov growth technique has been developed. This controller keeps the system stable and completely denies the operator's interference in the process.

Controller is adjusted by tuning by-pass loop parameters ΔP, n, A_{cr}, T along with the PID-controller coefficients. When the appropriate parameters are chosen, the by-pass loop action does not lead to overheating the crystal and to decreasing its cross-section but to minimizing the crystallization front oscillation. As the result, the capacity of growth process and the quality of crystals are improved.

References

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[2] A.V. Borodin, V.A. Borodin, A.V. Zhdanov, J. Crystal Growth, (1999) 220-226

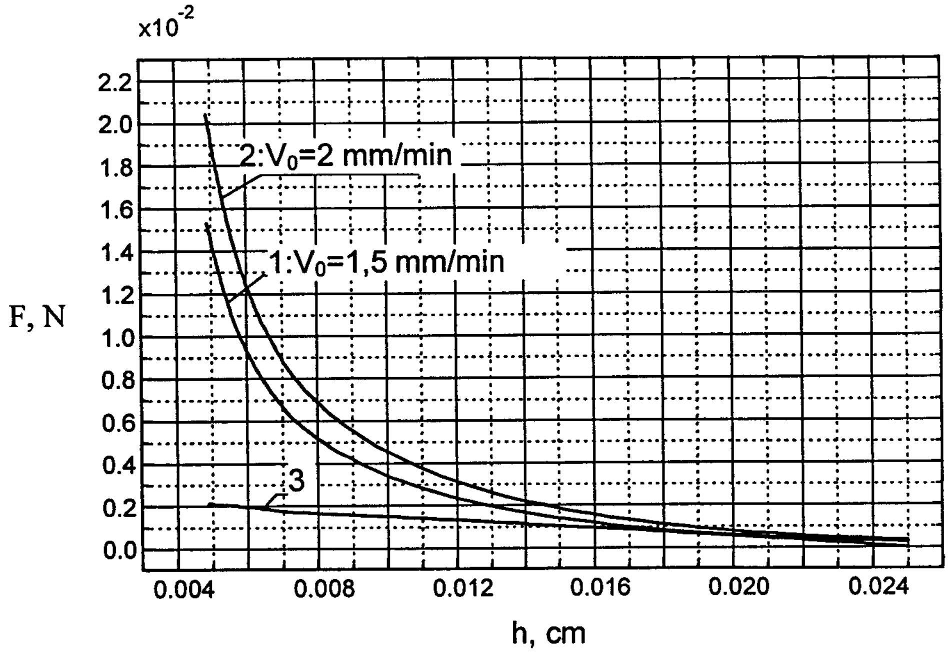


Fig.1. The curves 1 and 2 correspond to pulling rates of *1,5 mm/min* and *2 mm/min* respectively. The curve 3 shows the changes of hydrostatic force acting on crystal.

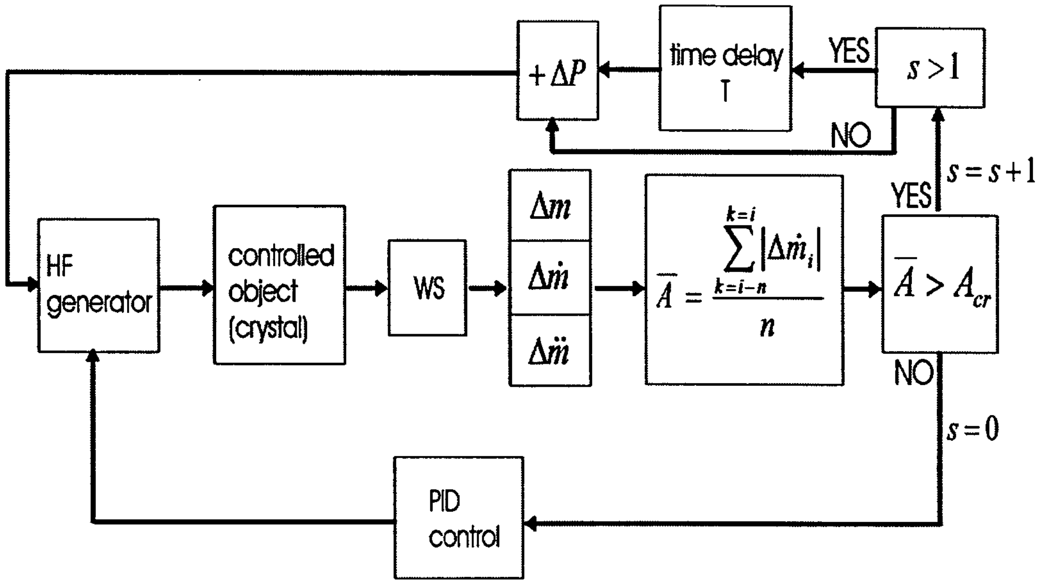
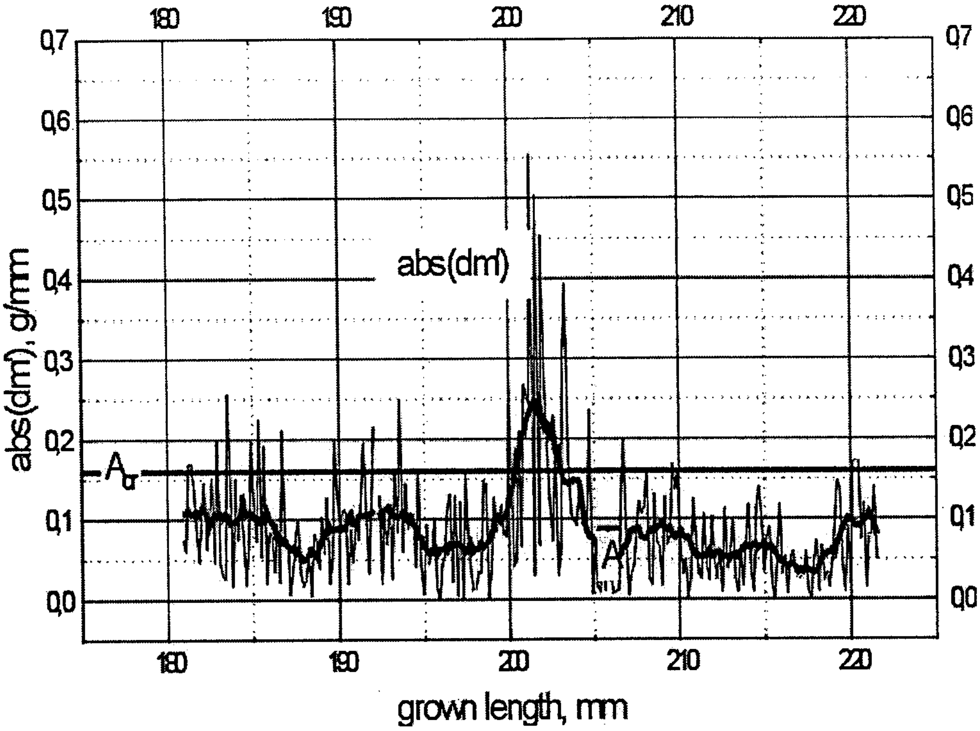
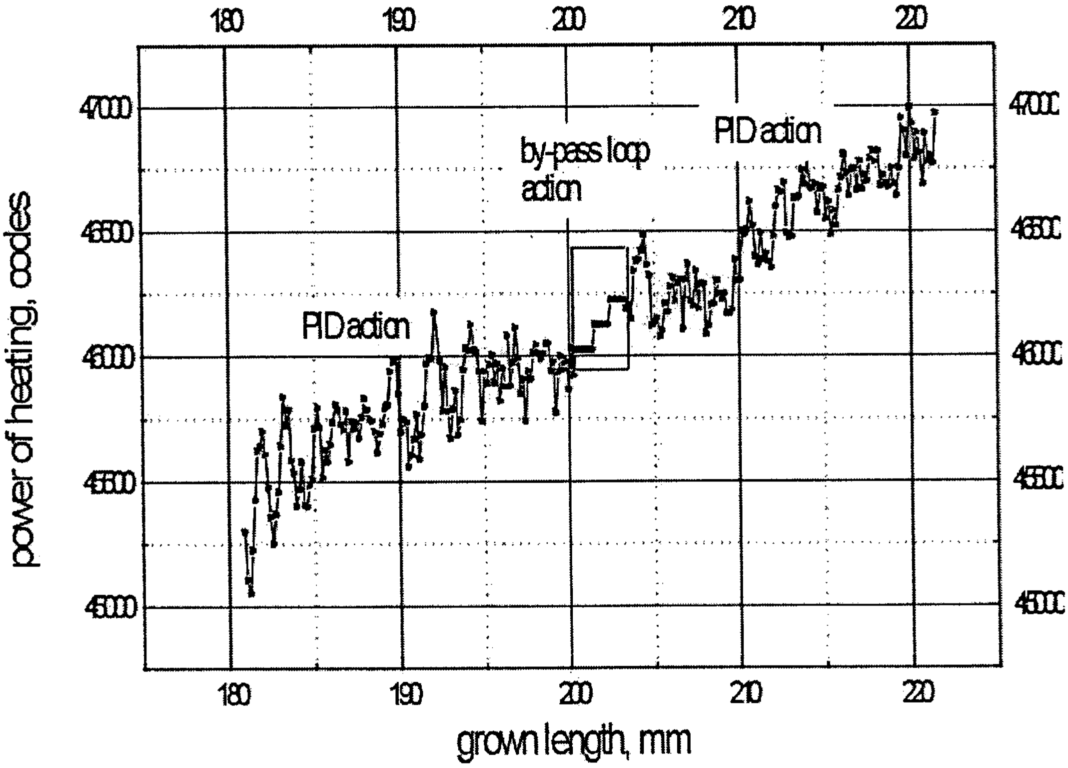


Fig.2. The block-diagram of the combined controller



(a)



(b)

Fig.3 (a, b). Controller switches to by-pass loop and back

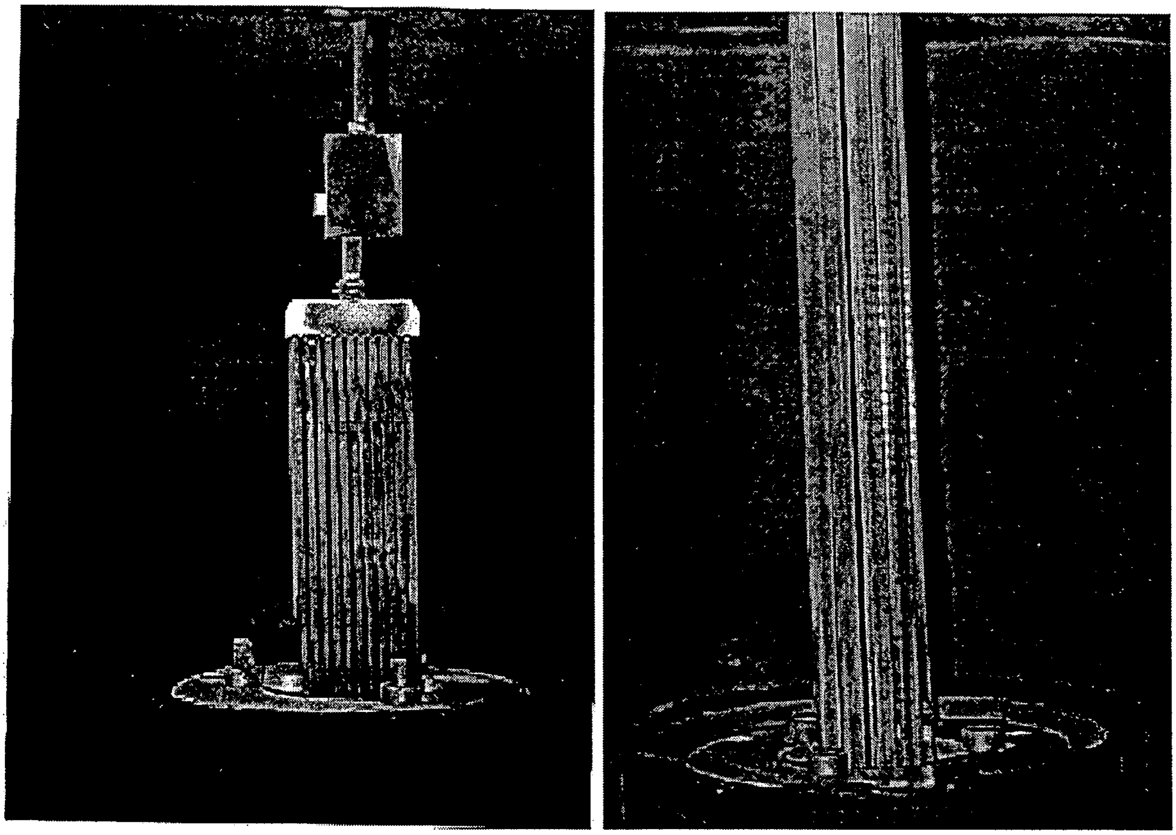
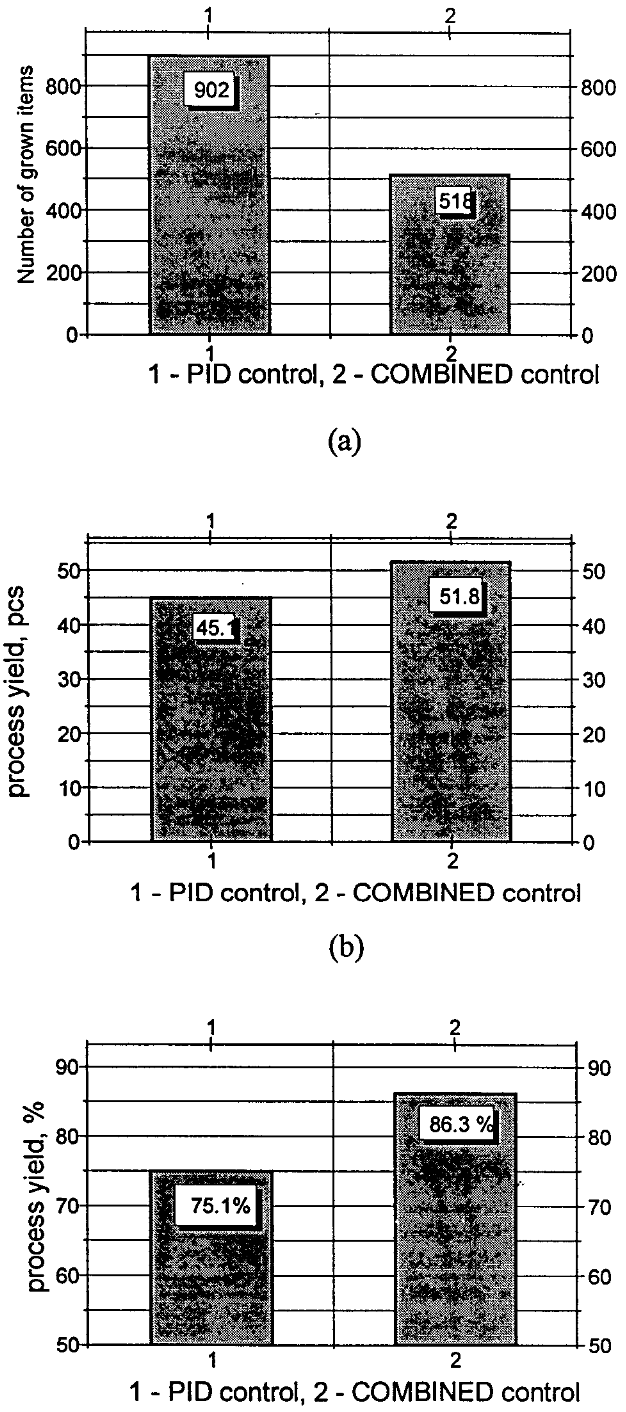


Fig.4. Sapphire crystals grown using combined controller



(a)

(b)

(c)

Fig.5 Total amount of sapphire items (a), mean yield (b) and mean percent yield (c) of the process depending on the type of controller