K. NOWACKI

ISSN 0543-5846
METABK 50(3) 213-216 (2011)
UDC – UDK 669.18:669.17:621-498:534-8=111

INFLUENCE OF ULTRASONIC TREATMENT ON THE STRUCTURE OF HIGH-CARBON STEEL

Received – Prispjelo: 2010-06-21
Accepted – Prihvaćeno: 2010-11-10
Professional Paper – Strukovni rad

Discussion on the results of industrial tests of sound amplification of high-carbon steel in a 130 kg ingot mould. The sound amplification was conducted using a waveguide immersed in liquid steel and connected with a piezoelectric head excited acoustically with a power oscillator. The ultrasonic treatment had several purposes, one of which was inducing motion in the liquid steel during solidification.
As result of the tests conducted, it was determined that, in ingots submitted to ultrasonic treatment compared with the ingots solidifying without, the axial segregation of elements was reduced and the share of the equiaxed zone in the area of acoustic wave impact increased by several percent.

Key words: liquid steel, ingot, ultrasounds, acoustic treatment, quality

Utjecaj ultrazvučnog tretmana na strukturu visokougljičnog čelika. Rasprava rezultata industrijskog ispitivanja ultrazvuka kod visokougljičnog čelika u 130 kg ingotu. Pojačavanje zvuka je provedeno korištenjem ultrazvučnog provodnika uronjenog u tekući čelik, spojenog s piezoelektričnom glavom pobuđenom akustički s oscilatorom. Ultrazvučni tretman ima nekoliko svrha, od kojih je jedna induciranje gibanja u tekućem čeliku tijekom skrućivanja. Rezultati provedenog testa pokazali su da ingoti izloženi ultrazvučnom tretmanu u usporedbi s onim koji skrućavaju bez ultrazvučnog tretmana, imaju smanjenje aksijalnih segregacija od nekoliko posto.

Ključne riječi: tekući čelik, ingot, ultrazvuk, akustički tretman, kvaliteta

INTRODUCTION

Specific qualitative requirements force steel manufacturers to strive to obtain ingots of the highest quality available the measure of which are on one hand, the cleanliness and homogeneity of chemical composition of steel, and the largest equiaxed zone on the other hand.

Nowadays, a decided majority of steels is manufactured with continuous casting with structure homogenisation through electromagnetic mixing of steel, both in the crystalliser and in the cooling zone. However, no such treatment is performed by traditional steel casting technology.

There are numerous information available in the specialist sources concerning the changes taking place as result of ultrasonic treatment applied in crystallising metals and cast iron. The most apparent effect of such treatment observed is the size reduction of grains. One of the direct effects of the impact of ultrasonic field is the change of structure of metals during solidification.

Ultrasounds eliminate columnar structures and exert positive influence on formation of equiaxed grains and homogeneity of metals. Structural changes in solidifying metals occur due to the processes taking place in the liquid-solid two-phase zone such as formation of crystal nucleuses and mixing. All these changes are caused by the impact of ultrasonic waves with a specific power and frequency. The propagation of waves also leads to such phenomena as cavitation, acoustic wind and radiation pressure [1-6].

K. Nowicki, Department of Metallurgy, Silesian Technical University, Katowice, Poland

EXPERIMENTAL PART

The melting was conducted in electric induction furnaces and melting pots of inactive lining. Industrial tests were performed using experimental apparatus (Figure 1) consisting if a power generator (1,000 W) and a piezoceramic power head as cooling system [7,8]. The sound amplification of steel was conducted in round, conventional big-end-down ingots of weight of 130 kg. Each time an ingot was cast, a tip of the wave-guide was introduced into the crop end of the ingot to a specific depth and the sound amplification was performed in accordance with the scheduled time. The maximum time of sound amplification was established consider temperature interval ΔT ($\Delta T = T_{liquid} - T_{sol}$), the superheating temperature of the steel being cast as well as the computer-based simulation enabling to determine the growth speed of solid phase in the ingot. The industrial tests were performed with 3 test melts of high-carbon steel of the chemical composition in Table 1.

Table 2 contains the characteristic parameters of the tests. In the course of melting 01 and 02, reference in-

Figure 1 Experimental apparatus for acoustic treatment of ingots.

Table 1 **Chemical composition of experimental steel / wt %**

	Melt no.		
	01	02	03
C	0,60	0,60	0,58
Mn	0,77	0,83	0,79
Si	0,35	0,36	0,41
P	0,018	0,015	0,020
S	0,014	0,025	0,027
Cr	0,50	0,11	0,30
W	<0,01	<0,01	<0,01
Ni	0,11	0,11	0,12
V	<0,01	<0,01	<0,01
Mo	0,01	0,02	0,20
Cu	0,10	0,13	0,13

gots (B and D) were cast and then solidified traditionally without interference, while no reference ingot was cast of the melt 03. For comparison, both ingots obtained in the course of melting 03 (E and F) were submitted to acoustic treatment with different treatment times.

With the aim to determine the impact of the acoustic treatment on the primary structure of steel, the macrostructure was examined. A crop end and a foot were cut out from each ingot, and then the ingots were cut into sections from which longitudinal disks were sampled in according to the diagram in Figure 2. The scope of tests comprised the following:

Table 2 **Casting temperature and acoustic treatment parameters for experimental melting**

Parameter		Melt no.		
		01	02	03
Ingot designation	Acoustically treated	A	C	E / F
	Without acoustic treatment	B	D	-
Ingot casting temperature with/ without acoustic treatment / K		1 783 / 1 763	1 783 / 1 763	1 773 / 1 773
Acoustic treatment time / *s*		100	210	90 / 300
Resonant frequency / *Hz*		17 200	18 330	18 160 / 18 160

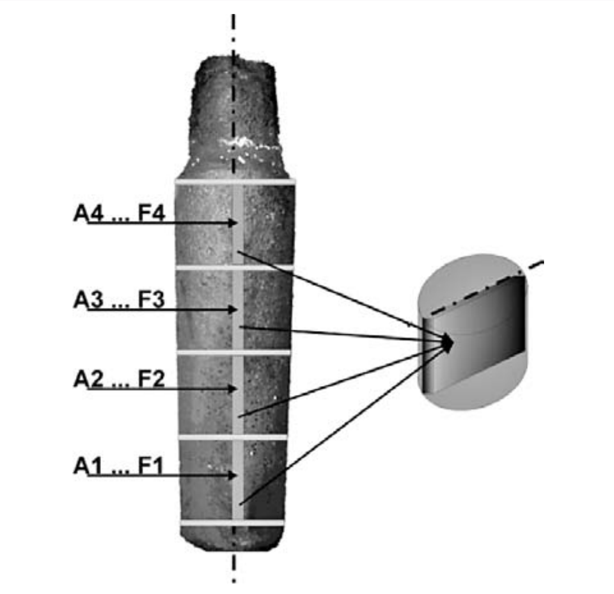

Figure 2 Diagram of longitudinal disk sampling from cast ingots.

– preparation of Baumann prints on longitudinal sections (disks) indicating the distribution of sulphur in the ingots tested,
– macroetching test to show the macrostructure on longitudinal sections of the ingots.

The metallographic tests were conducted at the Institute or Ferrous Metallurgy in Gliwice [9].

TEST RESULTS

The intensity of the sulphur distribution on the Baumann prints depends mainly on the overall content of this element in steel, the degree of modification of non-metallic inclusions in liquid steel and the casting and solidification conditions for the given grade of steel that effect the distribution of sulphide or oxide-sulphide inclusions in ingots.

In all ingots of high-carbon steel, in their bottom parts, the distribution of sulphur is homogenous, whereas in the middle and upper parts it is inhomogeneous. In the ingot B that was not submitted to acoustic treatment, on longitudinal sections of the ingot's middle and

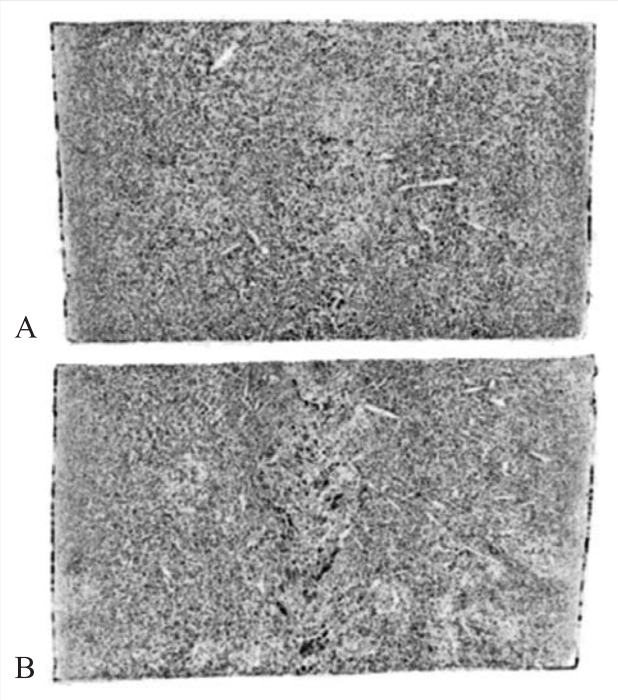

Figure 3 Distribution of sulphur on longitudinal section of high-carbon steel ingots (samples A3 and B3); ingot A – with acoustic treatment; ingot B – without acoustic treatment.

upper part, type V segregation was observed, while, in ingot A submitted to acoustic treatment, the distribution of sulphur was far more homogeneous (see Figure 3). In ingots C and D, in their bottom parts, the distribution of sulphur visible on the longitudinal sections was homogeneous, whereas, in the middle part of both ingots and in the upper part of ingot D (no acoustic treatment), type V segregation occurred. Clusters of sulphides in the V segregation zones, especially in the upper part of ingot D, were considerably larger. In ingot C, submitted to acoustic treatment, the sulphide clusters related to type V segregation faded in its upper part as the V segregation disappeared. In the upper part of acoustically treated ingot C, the distribution of sulphur was homogeneous, in the bottom part on foot side.

In further ingots of high-carbon steel (E and F) submitted to acoustic treatment with different ultrasonic impact times (90 and 300 seconds respectively), type V segregation was observed also, however, the distribution of sulphur in individual parts of these ingots was more homogeneous than in the corresponding parts of ingots A, B, C and D (Figures 4 and 5).

The macrostructure of ingots of high-carbon steel is dendritic. The segregation zones visible on the macrostructure images correspond to the sulphur segregation on the Baumann prints. Comparing the macrostructure images of the steels examined, one could claim that the most apparent effects of ultrasonic treatment was observed in ingot C. In reference ingot D, middle part V segregation occurred, and in ingot C, the middle part segregation was disrupted. The most evident effects of

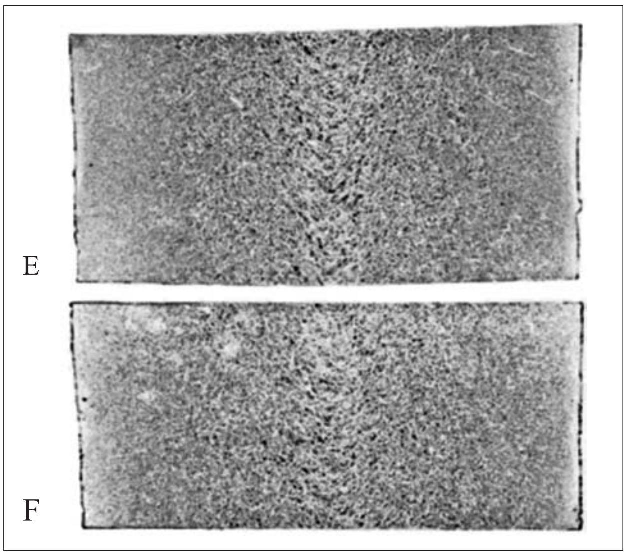

Figure 4 Distribution of sulphur on the longitudinal section of high-carbon steel ingots (samples E3 and F3); ingot E – time of acoustic treatment 90 seconds; ingot F – time of acoustic treatment 300 seconds.

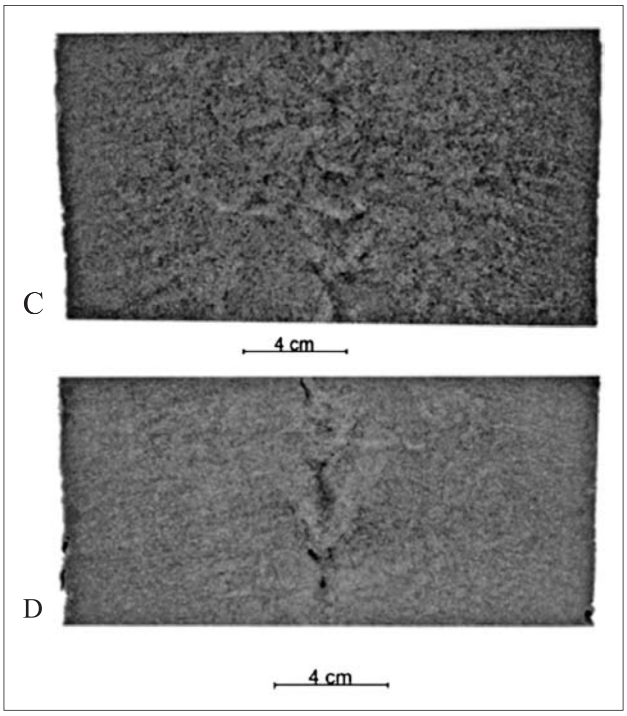

Figure 5 Macrostructure image on longitudinal section of an ingot cast of high-carbon steel (samples C3 and D3); ingot C – with acoustic treatment; ingot D – without acoustic treatment.

the said phenomenon were noticed in the upper ingot part (Figures 5 and 6).

The measurements of dimensions of the chill, columnar and equiaxed zones were performed on macrostructure images of the disks on several points by means of a rule, and the percentage share (U) of the equiaxed zone was calculated based on the proportion between the width of this zone (l_i) and the sample width (l) the diameter of the ingot's cross-section at the measurement point:

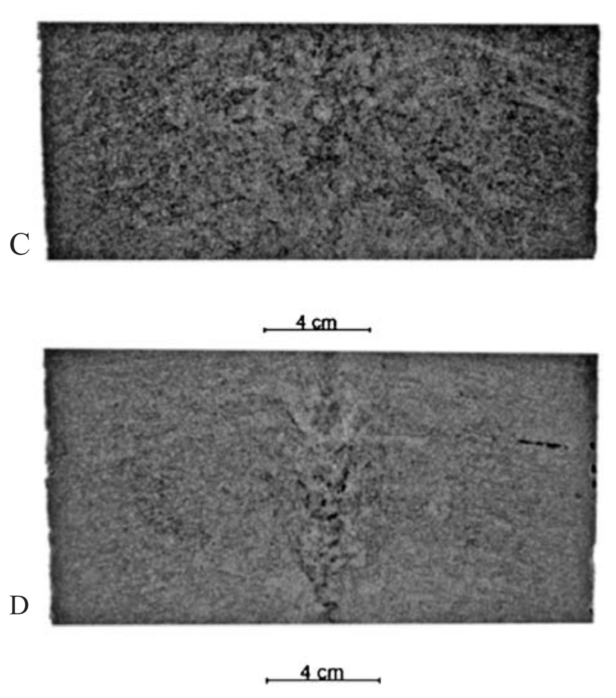

Figure 6 Macrostructure image on longitudinal section of an ingot cast of high-carbon steel (samples C4 and D4); ingot C – with acoustic treatment; ingot D – without acoustic treatment.

$$U = \frac{l_i}{l} \cdot 100\% \tag{1}$$

The average parameters of the ingot macrostructure established as result of measurements on four disks with reference to the average ingot diameter are shown in Table 3. The results obtained implied that acoustic treatment had contributed to the increase of the equiaxed zone share in the acoustically treated ingots if compared with the reference ingots. In the middle and upper part of the ingot, a far larger growth of this zone was observed due to the crystallisation front proceeding from the bottom and a longer time of acoustic treatment in the upper part of the ingot. In ingots E and F, no significant differences were observed as due to the influence of treatment time on ingot macrostructure, although the average share of equiaxed zone in ingots E and F was larger than in reference ingots B and D. This implies that, with the lapse of time, the processes occurring in the solidifying ingot (transfer of heat and weight, growing solid phase on the wave-guide) disturb the acoustic wave's influence on liquid steel. Therefore, it is substantial to claim that the largest impact exerted by an acoustic wave on the liquid steel takes place during the initial period of its acoustic treatment.

CONCLUSION

The results of the tests have enabled to draw a conclusion that acoustic treatment of liquid steel in an ingot mould reduced the middle part of V type segregation in high-carbon steel ingots.

The macrostructure tests and calculations have implied that the influence of acoustic treatment on size and share of the equiaxed zone, as one of the most crucial parameters for the quality of ingots, is advantageous.

The experiments have led to the conclusion that acoustic treatment of liquid steel in an ingot mould is possible on a semi-industrial scale (130 kg). Therefore, further investigations aimed to determine the potential for application of this technological operations in forging ingots of the weight of several Mg as well as in quality (e.g. austenitic) steel ingots seem well-grounded and reasonable.

Table 3 **Average macrostructure parameters of ingots**

Ingot designation					
A	B	C	D	E	F
Chill zone size / *mm*					
14	15	5	5	5	5
Columnar zone size / *mm*					
35	39	35	40	37	38
Equiaxed zone size / *mm*					
75	70	100	91	95	94
Equiaxed zone share / %					
46	44	55	50	52	52
Average ingot diameter / *mm*					
174	177	180	181	180	180

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Note: P. Nowak is responsible for English language, Katowice, Poland.