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RESEARCH ON THE STRUCTURE OF METAL PARTS MANUFACTURED BY THE INNOVATIVE PROCEDURE OF COMBINED PROCESSING OPERATIONS

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Abstract: *The analysis of the structure of metal parts made by the innovative technological procedure of combined processing operations requires the investigation of parts by electronic and optical microscopy and micro-hardness determinations. In most investigations, the structural analysis reveals a homogeneous, finished, predominantly martensitic structure with micro-alloying elements finely dispersed in the form of complex carbides. The agglomerations of chemical elements such as Si, Mn and C in the form of strips and strings are rare and they are completely missing in the form of mesh. The optimization measures aim to reduce and eliminate the agglomerations because these ones create inhomogeneities that lead to variations of the properties during utilization conditions. Optimization deals especially with the values of the main technological parameters for the technological phase of liquid form micro-alloying and for the technological phase of induction heat treatment. The optimization measures that are required and the conclusions that are drawn support the viability of the innovative technological procedure of combined heat treatment.*

Key words: *structure, combined heat treatment, agglomerations.*

1. INTRODUCTION

The innovative technological procedure of combined processing includes 12 technological phases. The metal parts made by combined processing have the following characteristics [4, 5]:

- medium to high level of durability;
- low wear supporting the idea of proper durability during operation;
- high mechanical strength.

Most investigations on the structural analysis highlight the following aspects [1, 3]:

- finished homogenous structure, predominantly with micro-alloying elements in form of dispersed carbides;
- the agglomerations of Si and Mn as well as the ones of carbon in form of strips, strings or mesh are rare;
- the accidental non-homogeneities and the isolated agglomerations are eliminated through an optimization of the technological parameters, especially for the technological phase of liquid form micro-alloying and for the technological phase of induction heat treatment.

The analysis of the micro-structure of the parts obtained by the technological process of combined processing (micro-alloying directly from liquid phase and induction heat treatment in solid state) is in accordance with the results of the distribution of micro-alloying elements in the superficial layer of the parts.

2. ASPECTS REGARDING THE INNOVATIVE TECHNOLOGICAL PROCEDURE

The innovative technological procedure of combined processing of metal parts is based on a sequence of 12 technological phases. Obtaining metal parts in the form of a finished product involves the following binding technological path:

Phase 1: preparation of the PM micro-alloying paste

Phase 2: preparation of casting mould;

Phase 3: elaboration of the basic material;

Phase 4: casting and micro-alloying from liquid phase;

Phase 5: preliminary mechanical machining;

Phase 6: control of the superficial layer;

Technological phase 7: preparation of hardening mixture;

AD Phase 8: applying the hardening mixture to the surface of the part;

Phase 9: induction heat treatment;

Phase 10: final heat treatment;

Phase 11: layer control;

Phase 12: delivery of finished part [2].

The technological phases with a great influence on the quality of the product are: technological phase no.4 (casting and micro-alloying from liquid phase) and technological phase. 9 (induction heat treatment) [4, 8].

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Combined processing procedure has the following technological flow:

Technological phase 1 – preparation of microalloying paste PM:

- preparation of microalloying paste PM: metallic dust 40% + carburizing powder 60%;
- chemical composition of microalloying paste PM: Ni 14%, Cr 14%, V 12%, charcoal 35%, BNaCO3 5%, coke 15%, CaCO3 2% Na2Co32%, binder 1%.
- particle average size: 40 µm;
- particle shape: granular;

Technological phase 2 – preparation of casting mold:

- chemical and mechanical cleaning: chemical solvent-based cleaning solution + mechanical brushing;
- ventilated air drying: air flow from 0.5 to 1 m^3/min;
- applying of microalloying paste PM: Applying type: manual paint brushing, Number of layers: 3.

Technological phase 3 – elaboration of basic material:

- furnace type: induction furnace; capacity: max. 100 kg;Chemical composition of the basic material: C<0.3%;S<0.02%; Si = max.1%; Mn = max.0.45; alloying elements under 0.5%;
- $T_{elaboration}$ = 1600ºC; $t_{elaboration}$ = 2 – 3 hours; $t_{evacuation}$ = max. 1 min.

Technological phase 4 – casting and microalloying from liquid phase:

- $T_{casting}$= 1550 – 1600°C; $V_{casting}$ = 0.2 – 2 kg/s;
- $t_{casting}$ = 2 – 60 s.
- microalloying is performed by interaction of liquid steel with layers applied on the walls of the casting mold;
- successive layers are applied as microalloying paste PM;
- casting total period < 20 min for avoiding metal bath oxidation.

Technological phase 5 – preliminary machining operations: finishing turning of superficial layer:

- depth of cut: a_p = 0.05 – 0.40 mm;
- feed: f = 0.05 – 0.10 mm/rev;
- average chemical composition at surface of superficial layer after preliminary machining: C 0.50%; Ni 0.40%; Cr 0.40%; V 0.05%.

Technological phase 6 – superficial layer control:

- macroscopic control;
- metallographic structure control;
- control of superficial layer chemical composition: highlighting of energy dispersive X-ray spectrum (EDAX);
- scanning electron microscopy SEM;
- optical microscopy.

Technological phase 7 – preparation of hardening mixture AD:

- preparation of hardening mixture AD: metallic dusts 35% + carburizing elements 65%.
- chemical composition of hardening mixture AD: Ni 10%, Cr 10%, V 10%, Mo 5%, charcoal 30%, BNaCO3 5%, coke 20%, CaCO3 4% Na2Co3 4%, Binder 2%; Particle shape: granular.

Technological phase 8 – application of hardening mixture on the surface of the part:

- cleaning of surface: chemical solventbased cleaning solution + mechanical brushing;
- applying of AD mixture, number of layers – 3;
- ventilated air drying: air flow 0.5 – 1 m^3/min;
- average thickness of coating mixture: 0.1 mm.

Technological phase 9 – induction thermal processing:

- T = 1000 – 1050°C; $T_{heating}$ = 2 – 5 s; hold time = 2 – 5 min; part diameter – max. 35 mm;
- optimal frequency, $f_{optimal}$ = 10 kHz;
- specific power at surface of the part: Psp = 1 kW/cm^2; current intensity – 700 A; voltage – 20 – 30 V; depth of heated layer: 2 – 4 mm;

Technological phase 10 – final heat treatment:

- variant A – direct hardening CD +low tempering RJ (applicable to parts of minor importance which must have particularly high values of hardness);
- variant B – increased cooling + simple hardening layer CS + low tempering RJ (to be applied for parts with deformations, dropping the direct hardening);
- variant C – increased cooling + sub-critical intermediate annealing RcI + simple hardening layer CS+ low tempering RJ (applicable to parts and components that require machining after treatment).

Technological phase 11 – control of layer:

- control of hardness – average hardness of superficial layer: 55 HRC;
- control of structure – transition zone structure: from a predominantly martensitic structure to a predominantly ferrite+ carbides-free pearlite structure;
- layer structure – finished, predominantly martensitic, presence of alloying elements as disperse carbides(variant C of final heat treatment).

Technological phase 12 – delivery of finished part:

- checking the competitiveness elements: the estimated production costs fall within quality-cost matrix required by the market;
- verification of compliance for – green product → green supplier.

3. EXPERIMENTS REGARDING THE CHECKING OF TECHNOLOGICAL PARAMETERS OF MANDREL TYPE PART

The checking of the technological parameters during experiments required the manufacturing of mandrel type parts, Fig.1.

During experiments, the main technological parameters had the values below:

- Micro-alloying powder PM : metal powders 40% + carburizing powders 60%;
- $d_{a\,k}$= 1 m^3/min;
- S = 3; $T_{pre\text{-}heating}$ = 100ºC;
- Basic material: C = 0.26%; S = 0.01%; Si = 0.9%; Mn = 0.40%; alloying elements = 0.5%;
- $T_{elaboration}$ = 1600ºC; $t_{elaboration}$ = 2.5 hours; $t_{exhaust}$ = 1 min; $T_{casting}$= 1580°C; $V_{casting}$ = 1 kg/s; $t_{casting}$ = 50 s; $D_{casting}$= 20 min;

Fig. 1. Type of part made by the innovative technological procedure – mandrel.

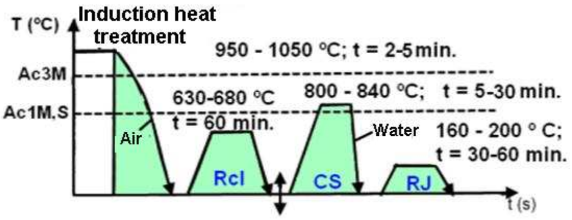


Fig. 2. Final heat treatment, C variant.

- Hardening mixture AD: metal powders 35% + carburizing elements 65%;
- $T_{\text{processing}}$=1020°C; t_{heating}=5 s; t_{holding}= 4.5 min; f_{optimal} = 10 kHz; Psp = 1 kW/cm^2; P_u = 20 kW; I =700 A; U = 30V;

Final heat treatment, C variant –heavy cooling + sub-critical intermediate re-annealing RcI + layer simple hardening CS+ low tempering RJ, Fig. 2.

4. STRUCTURAL ANALYSIS. RESULTS

The structural analysis involved investigations by scanning electron microscopy, optical microscopy and micro-hardness determinations. Figure 3 shows the scanning electron microscopy analysis (SEM) and the interpretation of the microscopy image.

Figures 4 and 5 present the investigations of optical microscopy with structural interpretation of the microscopic images

The micro-composition and micro-hardness determined per micro-zones of interest are shown in Figs. 6 and 7.

The values of the determinations in the superficial layer 844 HV (65 HRC) are consistent with the results of micro-alloying elements distribution in the superficial layer (medium diffusion of Ni, Cr and V).

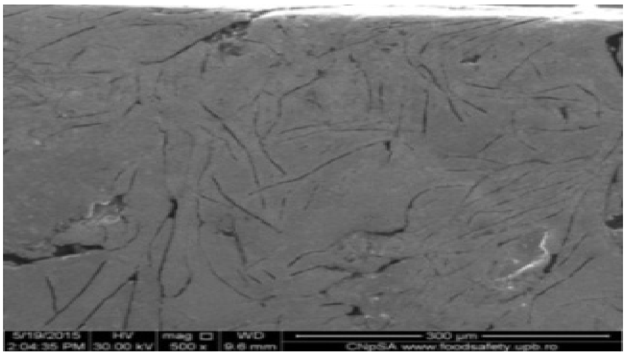


Fig. 3. Image of scanning electron microscopy (SEM), magnification x 500 (Condition: not attacked; Micro-zone of interest: layer; Structure: finished, predominantly martensitic, presence of alloying elements in form of dispersed carbides (after final heat treatment, variant C).

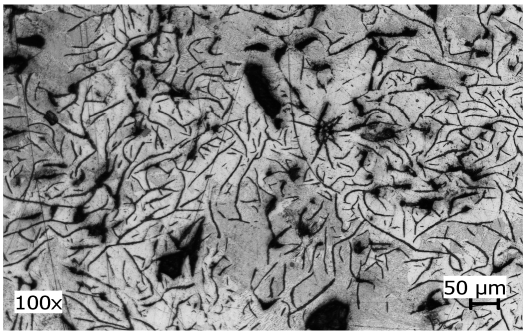
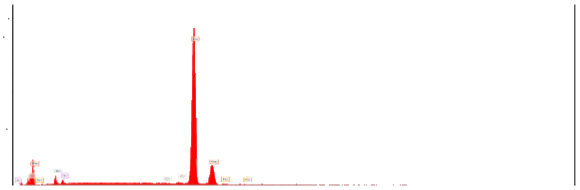


Fig. 4. Image of optical microscopy (Leika –Germany), magnification × 100 (Condition: nital attack 2%; Micro-zone of interest: layer; Structure: finished, predominantly martensite + ferrite, presence of alloying elements in form of dispersed carbides, after final heat treatment – variant C).

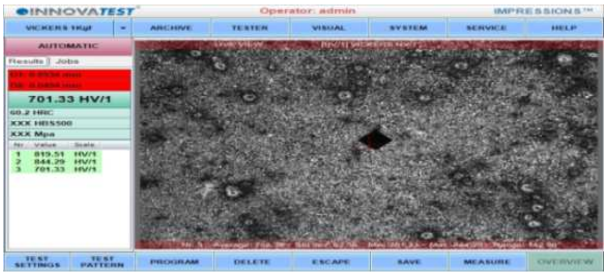
Fig. 5. Image of optical microscopy magnification × 200 (Condition: nital attack 2%; Micro-zone of interest: layer; Structure: finished, predominantly martensite + ferrite, presence of alloying elements in form of dispersed carbides, rare agglomerations of Si in form of strips).

The values of the determinations of micro-composition and micro-hardness are in accordance with the micro-structure obtained and support the results and interpretations performed by microscopy.



Element	Weight %	Atomic %	Error %	Net Int.	K Ratio	Z	R	A	F
C K	1.57	6.82	43.74	1.06	0.0042	1.2625	0.8361	0.2128	1
Si K	1.04	1.94	27.79	7.39	0.0034	1.1406	0.9179	0.287	1.01
V K	0.19	0.19	68.54	2.98	0.0025	0.9759	0.9847	0.9606	1.4245
Cr K	0.24	0.24	42.5	4.06	0.0037	0.9932	0.9911	0.9782	1.5901
Fe K	96.72	90.58	1.62	880.94	0.9831	0.9932	1.0033	0.9988	1.0247
Ni K	0.25	0.22	66.8	1.49	0.002	1.0097	1.0145	0.7759	1.0373

Fig. 6. Micro-composition: energy-dispersive X-ray spectroscopy (EDAX) (Condition: not attacked; Micro-zone of interest: layer; Analysis: Presence of Ni, Cr and V in the superficial layer in form of complex carbides (medium diffusion of micro-alloying elements in the superficial layer).



701.33 HV/1
60.2 HRC
XXX HB5500
XXX Mpa

Nr	Value	Scale
1	819.51	HV/1
2	844.29	HV/1
3	701.33	HV/1

Fig. 7. Micro-hardness determination.

5. DEGREE OF ACHIEVEMENT OF THE ESTIMATED RESULTS

5.1. Machining – estimated results

The machining of the parts by the proposed technology ensures a regular, homogeneous, martensitic, smooth and defectless structure with carbides.

The degree of achievement of the estimated result is highlighted by investigations resulting in optical microscopy images (Fig. 8).

The degree of achievement of the estimated result is high.

5.2. Technological procedure – estimated results

The technological procedure has ensured a tenacious core which has not been hardened after carburizing; this suggests that the procedure is easy to conduct and monitor.

The degree of achievement of the estimated result is highlighted by investigations resulting in images of optical microscopy (Fig. 9)

The degree of achievement of the estimated result is equal to the expected result.

5.3. The V content – estimated results

The V content in the superficial layer is of 0.15% V obtained under conditions in which $T_{\text{processing}}$=1050°C.

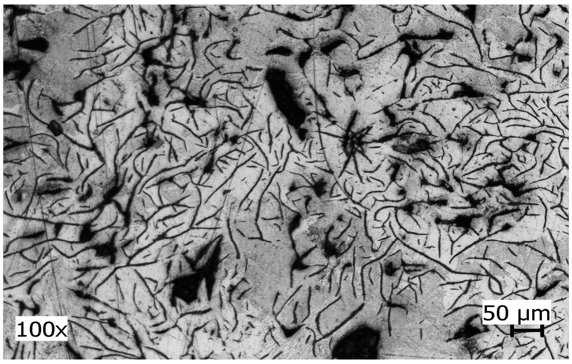


Fig. 8. Images of optical microscopy, magnification x 100 Type of part: mandrel; Condition: 2% nital atack; Micro-zone of interest: layer; Structure: finished, predominantly martensite + ferrite, presence of micro-alloying elements in form of dispersed carbides

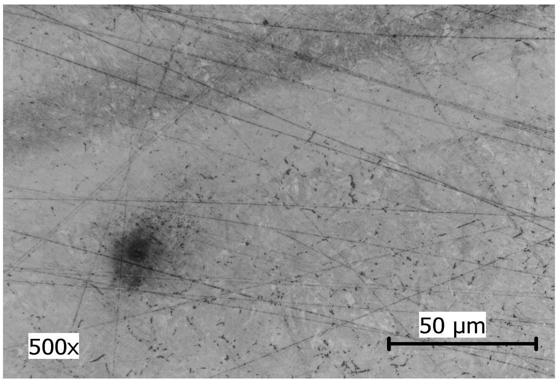


Fig. 9. Images of optical microscopy , magnification x 500 Type of part: mandrel; Condition: 2% nital attack; Micro-zone of interest: core; Structure: medium finished, mainly ferrite-perlite. Concentrations of perlite and accidental agglomerations of Si and Mn.

The content of V obtained in the superficial layer is within the optimal limits of 0.10 – 0.20% V, providing fine grains with effect upon tenacity.

The higher concentrations have an unfavourable effect on the depth of hardening penetration and on the polishability (Fig. 10).

The samples are characterized by:

- sample 1: medium diffusion of V in the superficial layer (constant uniform distribution in micro-zone 1 – layer, uniformly decreasing distribution in micro-zone; 2 – layer and micro-zone 3 - layer);
- sample 2: medium to high diffusion of V in the superficial layer (constant distribution in micro-zone 1 – layer, uniformly decreasing distribution in micro-zone; 2 layer and micro-zone 3 - layer).

The degree of achievement of the estimated result is highlighted by investigations based on micro-composition analysis – energy-dispersive X-ray spectroscopy EDAX.

Analyzing the micro-composition of the samples, the distribution of V in the superficial layer has been plotted for the studied samples.

The maximum content of vanadium in the superficial layer was 0.30% V.

The degree of achievement of the estimated result is high.

5.4. Content of Ni – estimated results

The highest content of Ni at the surface of a part is 0.40–1.00 % Ni. This value contributes to increased hardness, mechanical strength, limit of elasticity, resistance to corrosion and oxidation and favors the obtaining of fine structures (Fig. 11).

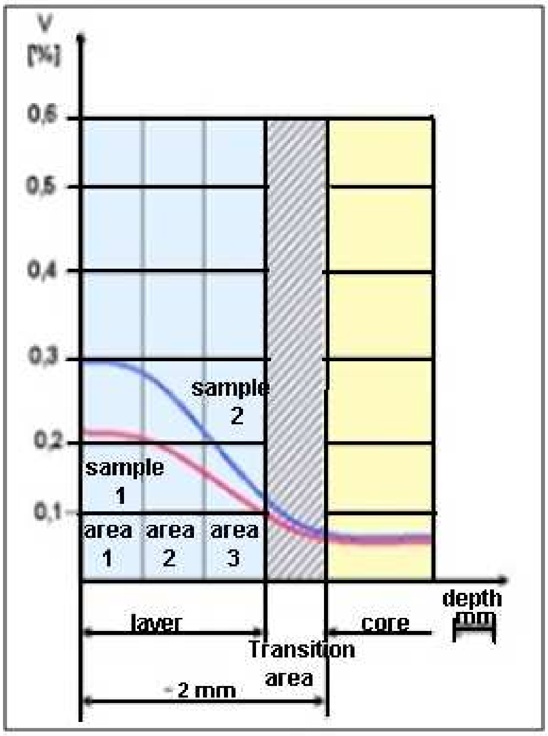


Fig. 10. Distribution of V in superficial layer (sample 1, 2).

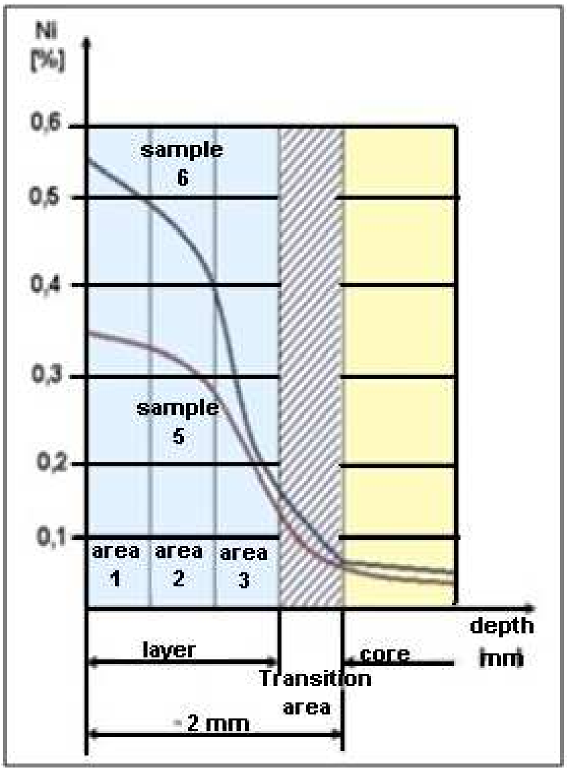


Fig. 11. Distribution of Ni in the superficial layer (sample 5, 6)
-sample 5: medium diffusion of Ni in the superficial layer (accelerated decreasing distribution in micro-zone 3 – layer);
-sample 6: appropriate diffusion of Ni in the superficial layer (relatively uniform presence in micro-zone 1 –layer and accelerated decreasing distribution in micro-zone 3 - layer).

The degree of achievement of the estimated result is highlighted by investigations based on micro-composition analysis – energy-dispersive X-ray spectroscopy EDAX.

Analyzing the micro-composition of the samples, the distribution of Ni in the superficial layer has been plotted for the studied samples. The maximum content of Ni in the superficial layer was 0.55% Ni.

The degree of achievement of the estimated result is equal to the expected result.

5.5. The content of Cr – estimated results

The highest content of Cr in the superficial layer of the parts is 0.40-1.00 % Cr, obtained in the conditions of $T_{processing}$=1050°C. The content of Cr kept within the optimal range of 0.40–1.20% Cr favoring the formation of carbides with direct effect on the resistance to wear and on the possibility of hardening.

The degree of achievement of the estimated result is highlighted by investigations based on micro-composition analysis – energy-dispersive X-ray spectroscopy EDAX (Fig. 12).

Analyzing the micro-composition of the samples, the distribution of Cr in the superficial layer has been plotted for the studied samples. The maximum content of Cr in the superficial layer was 0.60% Cr.

The degree of achievement of the estimated result is equal to the expected result.

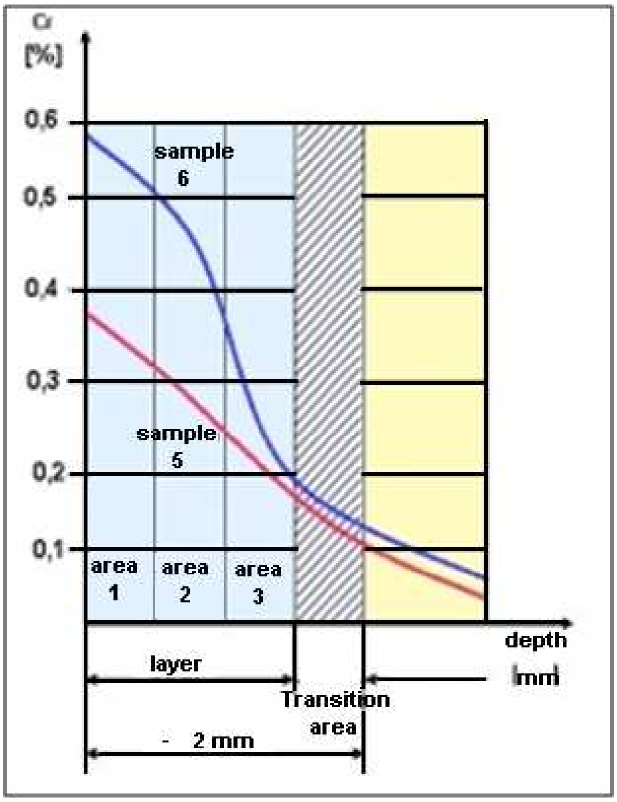


Fig. 12. Distribution of Cr in the superficial layer (sample 5, 6)
-sample 5: medium diffusion of Cr in the superficial layer (uniformly decreasing distribution in micro-zone 1 – layer, micro-zone 2 — layer and micro-zone 3 - layer);
-sample 6: appropriate diffusion of Cr in the superficial layer (accelerated decreasing distribution in micro-zone 3).

6. OPTIMIZATION MEASURES

In order to improve the quality of the part, namely the hardness and compactness of the superficial layer while maintaining a tenacious core, it is necessary to improve the following aspects:

- the values of the micro-hardness determinations in the superficial layer are high, confirming the micro-alloying in the superficial layer;
- in order to maintain a tenacious core one must diminish the duration of holding during the operation of induction field treatment $t_{holding}$ = 3 minutes;
- for the mandrel type part, with the following basic material composition C = 0.26%; S = 0.01%; Si = 0.9%; Mn = 0.40%; alloying elements = 0.5%, the optimal values of the main technological parameters will raise up to the values: $T_{elaboration}$ = 1600ºC; $t_{elaboration}$ = 2.5 hours; $t_{exhaust}$ = 1 min; $T_{casting}$= 1580°C; $V_{casting}$ = 1 Kg/s; $t_{casting}$ = 50 s; $D_{casting}$= 20 min; $T_{processing}$=1020°C; $t_{heating}$=5 s; $t_{holding}$= 3 min; $f_{optimal}$ = 10 kHz; Psp = 1 kW/cm^2; P_u = 20 kW; I = 700 A; U = 30V; final heat treatment – variant C.

7. CONCLUSIONS

The verification of the values of the main technological parameters confirms the diffusion of the hardening mixture elements into the superficial layer during the technological phase of induction heat treatment. Diffusion takes place with intensity depending on the technological parameters: processing temperature, time of heating and duration of holding.

The analysis performed with the energy-dispersive X-ray spectrometer reveals the presence of the alloying elements in form of dispersed carbides in the layer zone and transition zone concomitantly with the presence of carbon agglomerations.

The values of the main technological parameters (especially the technological phase of casting and micro-alloying in liquid form and the technological phase of induction heat treatment) directly influence the in-service behavior through the durability level. An uneven dispersion of the alloying elements cumulated with the existence of carbon agglomerations, Si and Mn in form of strips, strings or mesh decrease the durability quickly.

A disadvantage for the superficial layer quality is the unevenness of the applied layers of micro-alloying paste PM and hardening mixture AD corroborated with the inappropriate dimensions of metal powders and their compositions.

The inadequate values of the main technological parameters (temperature of casting, temperature of processing, composition of the micro-alloying paste PM, composition of the hardening mixture AD, layer uniformity) lead to chemical non-uniformities in the layer with implications on the generation of unfinished and non-homogeneous structure with faults converging towards low levels of durability and hardness of the layers.

The accentuated cooling after the technological phase of micro-alloying directly from liquid phase and after the technological phase of induction heat treatment result in the fragility of the layer, decrease of the adherence and obtaining of a rough structure with the reduction of the durability.

Variant C of final heat treatment is suitable for a large number of parts and components because it is an optimal variant especially in terms of economic efficiency and final quality level. An inappropriate final heat treatment diminishes the level of the results obtained in the previous technological phases and leads to a decrease in the characteristics and quality of the parts.

The optimization of the values of the main technological parameters will take into account the results of the alloying elements distribution in the superficial layer obtained after the micro-alloying directly from the liquid phase and induction heat treatment in solid state, according to the analysis of the micro-structure, micro-composition and micro-hardness of the layer.

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