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A selection of the protective atmosphere eliminating the inter-operational copper plating step in the processing of gear wheels

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ABSTRACT

Purpose: of this paper is modification of the processing procedures of selected components, which would allow one to eliminate the operations of copper plating and copper strip steps.

Design/methodology/approach: Along with its technical advantages, helping to satisfy the customers' needs, the technology of copper plating has one major disadvantage, comprised of the necessity to use highly toxic solutions, and a subsequent need to dispose the toxic wastes. The process of galvanic copper plating is, therefore, an operation unjustified both on ecological as well as on economical grounds.

Findings: Application of a fully controlled and reproducible protective atmosphere in the hardening procedure as a replacement approach for a disadvantageous measure of inter-operational copper plating in the production of gear wheels and pinions.

Research limitations/implications: The energetic development in automotive and aviation industries have played a significant role in development of modern multitooling technologies in the production of gear wheels [11-14]. As discussed in the works of Dowes and Cooksey [1], Drug and Ghelec [2], Edenhofer [3-5], Hoffmann [8], working components of the bevel and hypoid gear systems in aerospace and automotive industries are usually made of low carbon steels with the gas carburizing operation used for their hardening.

Practical implications: The requirements of the aerospace industry do not permit any structural alterations of the surface layer of the processed parts (oxidizing, carburizing or decarburization).

Originality/value: Thanks to the specific modifications presented in this work the following achievements were made: lowering the production costs of gear wheels, improvement of environment protection and work conditions by a partial elimination of toxic chemicals.

Keywords: Copper plating; Heat treatment; Protective atmosphere; Gas carburizing; Gear wheels

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Aerospace transmission constructions are based on gear wheels and pinions. The character of these devices' operation, comprised of varying loads, alternated bending, large surface pressures during mating as well as extensive abrasive wear, makes the design become a real challenge for their constructors. As an enhancement of that design, demands put on materials used to manufacture aerospace transmission gear wheels and pinions are also very high. These demands comprise: high strength both transient and fatigue, plasticity of the core, hardness of the gear surface and high impact strength.

A mass character of the aerospace production together with the very high safety standards put on this industry make it fairly conservative – for many years traditional procedures of carburizing and hardening low carbon steels have been continuously used as a processing technology for gear wheels and pinions. Thanks to this technology, an extremely hard (resistant to abrasive wear and to surface pressures) martensite structure of the surface layer with the simultaneous ductility of the core, facilitating transfer of impact loads, is achieved. In addition, as the studies of Fernades et al. [6], Gawroński [7] and Hoffmann et al. [8] have clearly demonstrated, compressive stresses introduced into the carburized film in the hardening process ensure high contact, bending and twisting strength.

Both the design and the manufacture of gear wheels and pinions require that only certain surfaces of a component undergo hardening. The remaining surfaces have to be protected against, disadvantageous in their cases, diffusion of carbon.

There exist a number of protective measures aimed at the hindrance of unwanted carburizing, such as:

- technological material allowance
- local or overall coating with special protective pastes
- heating in salt baths
- heating in furnaces with protective atmospheres
- covering with galvanic copper layer.

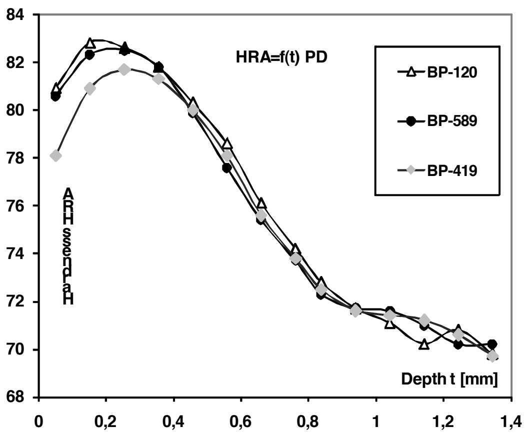


Fig. 1. Results of decarburization

High quality requirements as well as other economic standards used in the aerospace industry (PRATT & WHITNEY CANADA (PWC), PRATT & WHITNEY AMERYKA (PWA), HAMILTON SUNSTRAND, SIKORSKY, PZL WSK - RZESZÓW) make PRATT & WHITNEY KALISZ use anti-diffusion protection measures based on galvanic copper plating, assisted by an additional application of a protective paste.

In spite of the maturity of the production processes and high working culture in the company, a quality drop of the heat treatment, comprised of surface decarburizing (Figs. 1, 2) and carburizing (Fig. 3) of unwanted areas, was recently observed.

The following may be the reasons for quality non-conformances due to unwanted decarburizing or carburizing effects:

- copper punctures, aggregation, porosity, blistering
- concavity of the layer
- too coarse grain structure of copper
- continuity failure of the layer
- weak adherence of copper to the base
- discoloration of the layer
- too thin layer of copper
- mechanical damage of copper layer.

In PRATT-WHITNEY, the majority of quality non-conformances, directly resulting from the heat treatment and chemical heat treatment, are due to mechanical scratches of the copper layer, with the rest being made up of stray carburizing due to inappropriate application of copper plating.

Fig. 2. Example of part with decarburized surfaces

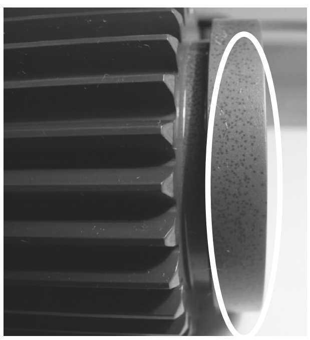


Fig. 3. Example of part with stray carb on non carburized area

2. An improvement of the heat treatment process subsequent to carburizing gear wheels

In order to minimize the number of quality non-conformances, resulting from surface faults in the heat treatment of a batch, a use of protective atmosphere has been proposed as a replacement for the inter-operational copper plating step. With the assumption of a good reproducibility of the heat treatment processes one should expect a substantial reduction of manufacture costs accompanied by simultaneous decrease of toxic wastes emission. An increase of the process competitiveness is, therefore, anticipated.

For the sake of elimination of both inter-operational copper plating and copper strip steps (preceding the hardening step), certain modifications of the system construction as well as its operation procedures had to be made. These modifications are a consequence of our studies of the effect of working atmosphere on the hardening process of gear wheels and pinions.

In order to protect the hardened steel against oxidation, oxygen partial pressure in the processing atmosphere must remain below the equilibrium pressure of the oxide dissotiation reaction. In the everyday practice of PRATT & WHITNEY KALISZ this condition is realized by an introduction of oxygen binding gas (propane, endothermic atmosphere) resulting in the formation of H_2O and CO_2.

Because of the oxidizing character of H_2O and CO_2 species, the appropriate ratio of H_2 to H_2O had to be determined. Since the sensitivity of all steel types to water vapour is inversely proportional to temperature, particular attention should be drawn to the question whether oxidation of the batch occurs in the heating chamber itself or it takes place during the transfer between the heating chamber and the entrance chamber, where temperature is lower.

The results of laboratory tests have demonstrated a disadvantageous influence of entrance chamber atmosphere. The value of internal oxidation for specimens subjected to the effect of the entrance chamber was on average about 4 µm higher than that determined for cylindrical samples which were not subjected to such an effect.

As a consequence of the above finding and in accordance with the guidelines proposed by Gawroński et al. [9,10,15], the following modifications have been introduced:

- an additional propane feed-in system, ensuring entrance chamber overpressure thus eliminating external air leaks, has been installed in the entrance chamber,
- an analysis of the components cooling method after their carburizing in terms of cooling rates and duration of its phases has been performed and followed by its modification involving the shortest possible cooling cycle with the maintenance of the allowed deformation,
- the constructions of explosion doors and that of the upper ring burner have been modified,
- a leak map of the furnace has been drawn with the help of Industrial Scientific M40 leak detector and, subsequently, the existing leaks have been either removed or minimized and periodic furnace leak inspection has been introduced,
- a system of a continuous monitoring of pressure inside the furnace heating chamber has been set up,
- a system of blowing the transportation chamber (integrated with the of heating chamber of the furnace) with the process working atmosphere, preventing an accumulation of humidity in that chamber has been introduced.

Due to the presence CO and CO_2, and to their potential disadvantageous effect on the surface of the batch in particular, it is important to maintain the appropriate (for given processing conditions) CO to CO_2 ratio. In all cases the steel sensitivity to the carbon dioxide content is inversely proportional to temperature.

Because the controlled endothermic atmosphere contains both types of components, namely carburizing (CO, CH_4) and decarburizing (H_2, H_2O, CO_2) species, the ratios between H_2O and H_2 and between CO_2 and CO have to be adjusted in such a way that the furnace atmosphere has an overall reductive effect on metal oxides (during both batch heating and cooling phases).

From the consideration of the functional relationship of the equilibrium constant:

$$Kp = \frac{P^2_{CO}}{P_{CO_2}} \tag{1}$$

to temperature, with the assumed concentration of both species CO_2 and CO in the furnace atmosphere equal 20%, it follows that within the temperature range of 820° - 840°C, the Boduard reaction will proceed in the direction of carbon binding in CO – thus resulting in the decrease of carbon content in the surface layer of the components.

When considering, on the other hand, the equilibrium constant:

$$Kp = \frac{P^2_{H_2}}{P_{CH_4}} \tag{2}$$

as a function of temperature and the concentration of the respective components, one comes to the conclusion that the reaction of methane dissotiation should contribute to the enrichment of the components surface layer with carbon.

Taking the above considerations into account we have established that, for hardening temperatures within the range 820° - 840°C, the protective atmosphere for iron should be characterized by:

- the value of CH_4 to H_2 ratio lower than 0.05
- the value of CO_2 to CO ratio lower than 0.49
- the value of H_2O to H_2 ratio lower than 0.52

When relating the above data to the steel grade 4NiCrMo13-4, one should stress that the values of CO_2 to CO ratio and CH_4 to H_2 ratio should be even lower (CO_2 to CO ratio because of the risk of carburizing and CH_4 to H_2 ratio because of the risk of decarburizing). An analysis of equilibrium curves of the CO-CO_2 gas mixture over carbon in steel containing 0.8% C as a temperature function in the range 820° – 840°C reveals that, at the CO content in the protective atmosphere equal 30%, the allowed concentration of carbon dioxide should amount to, respectively:

at T=820°C

$$P_{CO_2} = \frac{0.3^2}{7} = 0.012 \quad (1.2\% CO_2 vol.) \tag{3}$$

at T=840°C

$$P_{CO_2} = \frac{0.3^2}{10} = 0,009 \quad (0.9\% CO_2 vol.) \tag{4}$$

Since the endothermic atmosphere contains all the following species: CO, CO_2, CH_4, H_2, H_2O, one has to remember that in reality the equilibrium of the protective atmosphere with carbon contained in steel is determined by the reactions of all those components with carbon and by the equilibrium constants of these reactions in particular.

Since theoretical computation of equilibrium conditions is both complex and erroneous, further works were conducted on the basis of empirically determined relationships of equilibrium between endothermic atmosphere and carbon present in 14NiCrMo13-4 steel hardened in the Casemaster universal furnace and their temperature dependencies.

Selected samples (of geometry corresponding to typical gear wheels and pinions) were subjected to the processing conditions presented in Table 1.

Table 1.
Parameters of thermochemical treatment of the samples

Carburizing (group I, II, III, IV)				
	Time [min]	Temp. [°C]	Carbon potential [%C]	Remarks
Heating	~ 50	-	0.3	
Carburizing st. I	~ 105	920	1.2	
Carburizing st. II	~ 25	920	1.1	
Cooling	30	-	-	With fan
Hardening				
Group I	$90^{\pm5}$	$830^{\pm10}$	0.2	Oil Hartenol 120 (40-60°C)
Group II	$90^{\pm5}$	$830^{\pm10}$	0.25	Oil Hartenol 120 (40-60°C)
Group III	$90^{\pm5}$	$830^{\pm10}$	0.4	Oil Hartenol 120 (40-60°C)
Group IV	$90^{\pm5}$	$830^{\pm10}$	0.8	Oil Hartenol 120 (40-60°C)

As a consequence of the presented modifications, the following was achieved:

- oxidation after carburizing of approximately 0.005 mm (Fig. 4.), with the acceptable value equal 0.008 mm
- a selection of the protective atmosphere for 14NiCrMo13-4 material in the process of its direct hardening subsequent to carburizing (Figs. 5-8)
- acceptable hardness distribution in the surface layer of samples processed according to Group IV parameters (Fig. 9)
- correct core structure (Fig. 10)
- correct structure of the carburized layer (Fig. 11)

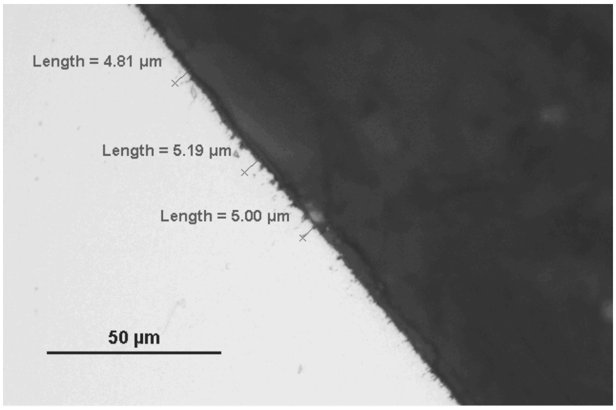


Fig. 4. Results of value of intergranular oxidation (after carburizing of the order of 0.005 mm)

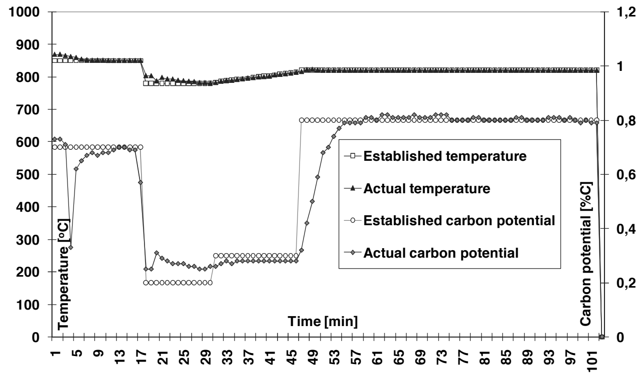


Fig. 5. Sample run of hardening process of hardening according to group No 4

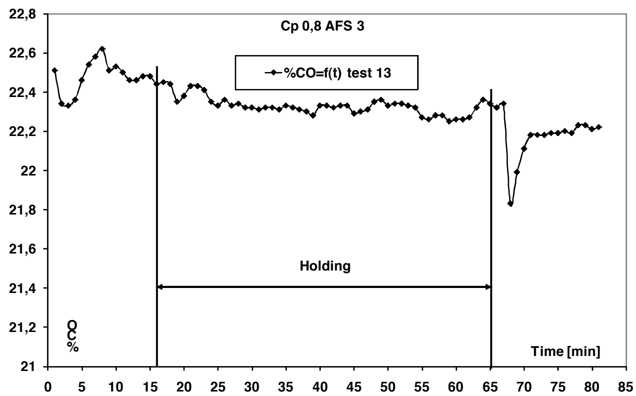


Fig. 6. Example of relation percentage content of CO in furnace atmosphere in function of time of hardening as per group No 4

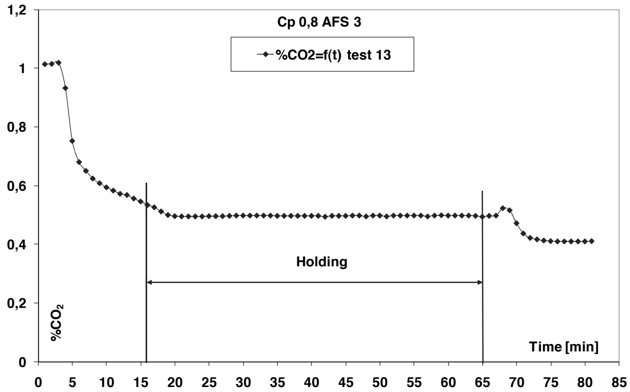


Fig. 7. Example of percentage content of CO_2 in furnace atmosphere in function of hardening time as per group No 4

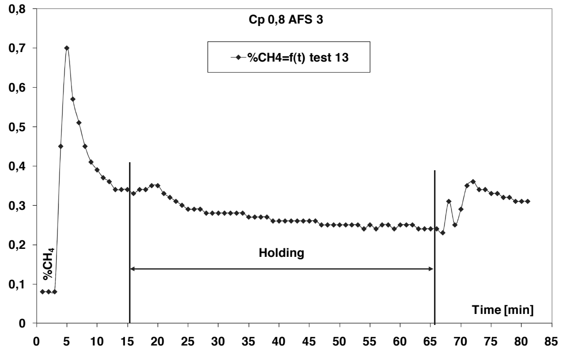


Fig. 8. Example of relation of percentage content of CH_4 in furnace atmosphere in function of hardening time as per group No 4

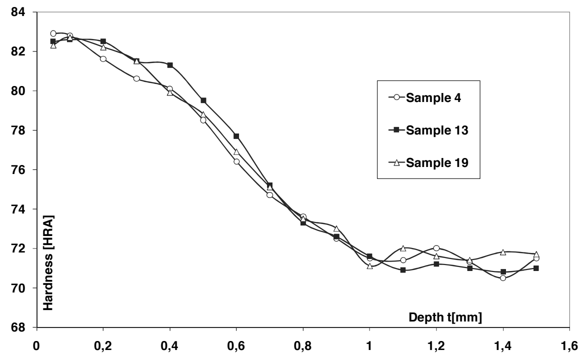


Fig. 9. Hardness chart for gear top layer after protection implementation

A very good reproducibility of these advantageous results was an argument and an inspiration for such a modification of the processing procedures of selected components, which would allow one to eliminate the operations of copper plating and copper strip steps.

The differences between the currently used processes of the heat treatment and those being introduced as a result of the presented work are shown in Tables 2 and 3, for a gear wheel of a planetary gear (Fig. 12) and a gear wheel of an oil pump (Fig. 13), respectively.

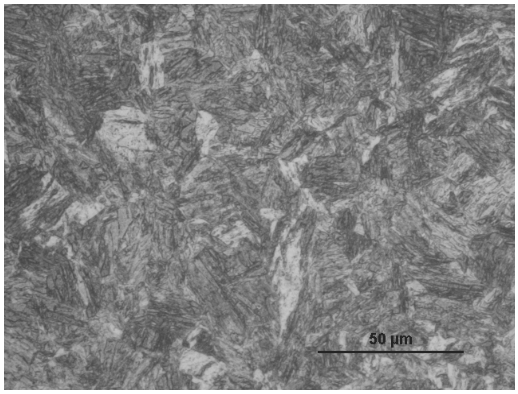


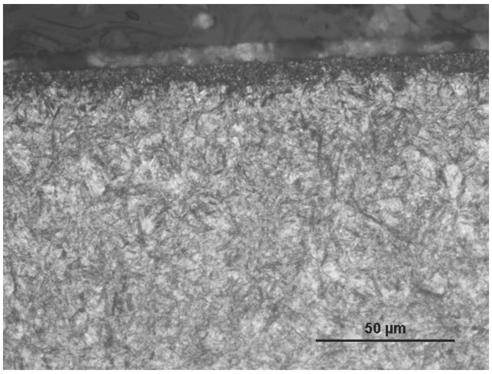
Fig. 10. Example of the core microstructure with visible tempered martensite

Table 2.
Comparison of seqence of operations for heat treatment current vs revised – planet gear

Current heat treatment process		**Modified heat treatment process**	
No.	**Operation**	**No.**	**Operation**
35	Hardening	35	Hardening
45	Tempering	45	Tempering
90	Copper plating*	90	Copper plating*
120	Copper plating**	120	Copper plating**
123	Chemical leaning	123	Chemical leaning
125	Carburizing	125	Carburizing
145	***Copper plating of samples***		
150	Heat treatment of samples	150	Heat treatment of samples
160	***Copper strip***		
165	***Cleaning***		
170	***Copper lating****		
175	Hardening	175	Hardening
185	Cold treatment	185	Cold treatment
190	Low tempering	190	Low tempering
195	Copper strip	195	Copper strip
210	Inspection	210	Inspection

Protection of surfaces:
* surfaces of faces - other protected with masking stoppers.
** surface of hole - toothing protected with mastic gum
*** all surfaces protected

a)



b)

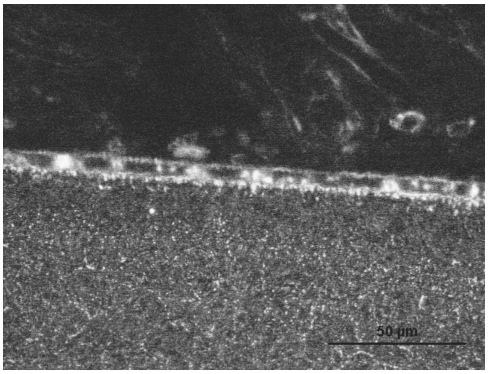


Fig. 11. (a) Example of the microstructure of carbureted layer in the area of the tip diameter of the gear with visible visible tempered martensite, (b) example of the microstructure of the carbureted layer - without the precipitate of carbides

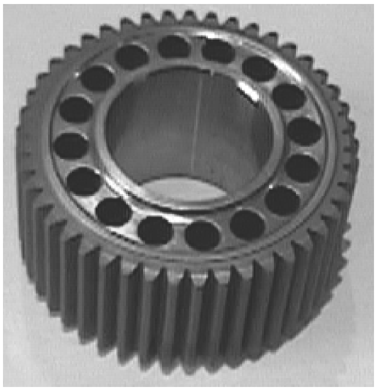


Fig. 12. Planet gear

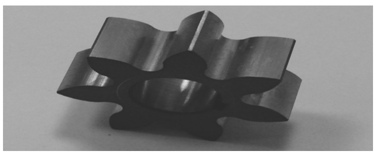


Fig. 13. Oil pump gear

Table 3.
Comparison of seqence of operations for heat treatment current vs revised- oil pump gear

Current heat treatment process		**Modified heat treatment process**	
No.	**Operation**	**No.**	**Operation**
122	Copper plating*	225	Copper plating*
135	Carburizing	290	Carburizing
137	***Copper plating of samples***		
138	Heat treatment of samples	320	Heat treatment of samples
145	***Cleaning***		
150	***Copper plating*****		
155	Hardening	410	Hardening
165	Cold treatment	430	Cold treatment
170	Low tempering	440	Low tempering
175	Copper strip	450	Copper strip
190	Inspection		Inspection

Protection of surfaces:
* surfaces of faces and hole
** all surfaces protected

3. Conclusions

Thanks to the specific modifications presented in this work the following achievements were made:

- lowering the number of quality non-conformances resulting from the heat treatment process and the low-quality production costs connected,
- shortening the production cycle duration from maximum 13.5 days to maximum 6 days,
- lowering the production costs of gear wheels, which currently amount to 430 000 $/year. With the assumption that the average cost of thin copper plating and inter-operational copper strip is 7.5 $, a target cost reduction (due to the subsequent technological modifications of the selected components) of 208 000 $/year is aimed at,
- improvement of delivery time
- improvement of environment protection and work conditions by a partial elimination of toxic chemicals. An analysis of the number of components processed using the protective atmosphere presented in this work shows that they constitute approximately 12% of the entire component production (with their target fraction amounting to 15%). In this way, a detrimental effect of chemicals used in copper plating and copper strip operations is also reduced by 12%. With the assumed production of 6500 pieces/year it is estimated that the yearly number of copper strip batches will be reduced by 20. This signifies a reduction of toxic wastes volume by approximately 20 m^3 per year.

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