New Concepts and Characterization of Gradient Castings Composed by low Alloyed White Cast Iron and Spheroidal Graphite Cast Iron

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This work deals with the problem of casting production regarding composed castings for rolls, also called gradient castings. The technology of production is a combination of the horizontal centrifugal casting of alloyed white cast iron (two sequences) and gravity casting of cores which occurs in third sequence. From the industrial casting, the systematic sampling for different investigation methods was done. The following examination methods were used: chemical analyses, thermodynamic calculation of equilibrium phases by TCW and Computerm programs, dilatometry in the solid state, calculation of density for extracted microstructural components by program TAPP 2.2, linear hardness measurements, determination of mechanical properties at room temperature and higher temperatures, optical and electron microscopy, FEM calculation of casting processes for all three sequences of casting.

The working layer of the roll is made from chromium alloyed white cast iron. The core is made of spheroidal graphite cast iron (SGI). The main focus was on the intermediate layer, which is made from flake graphite cast iron. Microstructural constituents were determined quantitatively and qualitatively.

Centrifugal casting is a highly complex process. With the help of the mentioned programs, the calculation of density was done for each microstructural constituent. It was discovered that austenite and M_7C_3 types of carbides have a difference in densities of approximately 0.3kg/dm^3 which influences the distribution of microstructural constituents in the roll cross-section due to centrifugal forces. The internal stresses in the casting were also calculated and measured. The explanations of the influences of inhomogeneous carbide distribution in the first and second layers, and the influence of core made by SGI on the mechanical properties of the casting were also made, together with internal stress.

Keywords: composed castings, centrifugal and gravity casting, white cast iron, spheroidal graphite cast iron, FEM casting and stress calculations, “in situ” experiments, characterization of microstructure

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Introduction

Centrifugal pouring technology is a casting process, where metal can be poured and solidified in a rotating permanent mold under the influence of centrifugal force. [1] The direction of solidification during the centrifugal process differs from the sand casting. Due to the rapid transfer of heat to the permanent mold, crystallization starts on the outer surface of the casting and progresses towards the inside. The result is a fine-grained surface crust, further solidification towards the interior takes place with the growth of dendrite crystals. [2]

A combination of centrifugal and gravity casting is used during roll production, where the working layer and intermediate layer are cast centrifugally and the core is gravity cast from spheroidal graphite cast iron. The working layer is made of chromium white cast iron to achieve hardness and wear resistance, the intermediate layer is sort of grey cast iron for producing good bonding of the working layer and core, whilst the core is made of spheroidal graphite cast iron to obtain toughness of the roll. [3]

In regard to the chromium white cast iron layer, it is desirable to have as little retained austenite as possible in the matrix and that it does not contain the pearlite phase within the microstructure.

In the as cast state, the matrix contains a substantial proportion of residual austenite (30–60 %), which is necessary to decompose with single or multistage heat treatment, in order to achieve the required microstructure, which contains small and evenly distributed $M_{23}C_6$ type carbides in α-metallic matrix. [4] Due to their high hardness and uniform distribution in the matrix, secondary carbides are of great importance for wear resistance.

The target mechanical properties are obtained by heat treatment, where casting is heated to austenitising temperature and control cooled to room temperature. Such treatment allows a good control over the segregation of secondary carbides within the temperature range from 800 to 1050 °C.

Experimental work

Analyses were carried out on samples taken from a working layer, intermediate layer, and the core. Optical microscopy was carried out using an Olympus BX61 microscope, scanning electron microscopy with a JEOL JSM–5600 electron microscope equipped with EDS-analysis, tensile tests at various temperatures by an Instron 1255 machine, hardness measurements by an Instron Tukon 2100 B machine, and dilatometric analysis by a BÄHR DIL 801 instrument. Densities of solidified phases were calculated using the TAPP 2.2 program and thermodynamic phase equilibrium calculations performed by Thermo-Calc software.
The chemical compositions of all three layers are presented in Table 1.

Table 1: Chemical analysis of gradient casting (mass. %).

	C	Si	Mn	P	S	Cr	Ni	Mo	Mg	Cu	Sn	Al	V	Ti	W	Co	Fe
Working layer	2,799	0,703	0,965	0,030	0,037	16,681	1,433	1,154	0,003	0,081	0,000	0,0000	0,296	0,000	0,000	0,000	75,818
Intermediate layer	3,118	1,034	0,342	0,026	0,010	0,129	0,247	0,029	0,000	0,039	0,005	0,0013	0,012	0,006	0,009	0,018	94,965
Core	3,002	2,734	0,366	0,031	0,007	0,131	0,247	0,029	0,099	0,039	0,007	0,0229	0,013	0,007	0,009	0,017	93,198

Results and discussion

Figure 1 presents the boundary layer of the working layer, intermediate layer and core of a roll. The microstructure of the working layer consisted of austenite and carbides as these alloys are rich chromium. The intermediate layer, which merges with the core, is highly rich with M_7C_3 carbides. At solidification of the intermediate layer melt in the first stage the formation of primary austenite crystals occurs which, by means of centrifugal force due to higher density than the rest of the melt, starts to impose towards the direction of the working layer. The melt of the intermediate layer re-melts a thin layer of a working layer and some carbide promoting elements, especially chromium, dissolves within the intermediate melt causing the formation of carbides, and due to the lower density compared with the γ begin to deposit on the interface of the intermediate layer and core. The large amount of carbides can be clearly seen in Figure 1. Sufficient solidification interval and a lower cooling rate are necessary to produce such a stratified intermediate layer that is an undesirable microstructure. Carbides, which are unevenly dispersed on the metal matrix, represent a brittle layer in the casting.

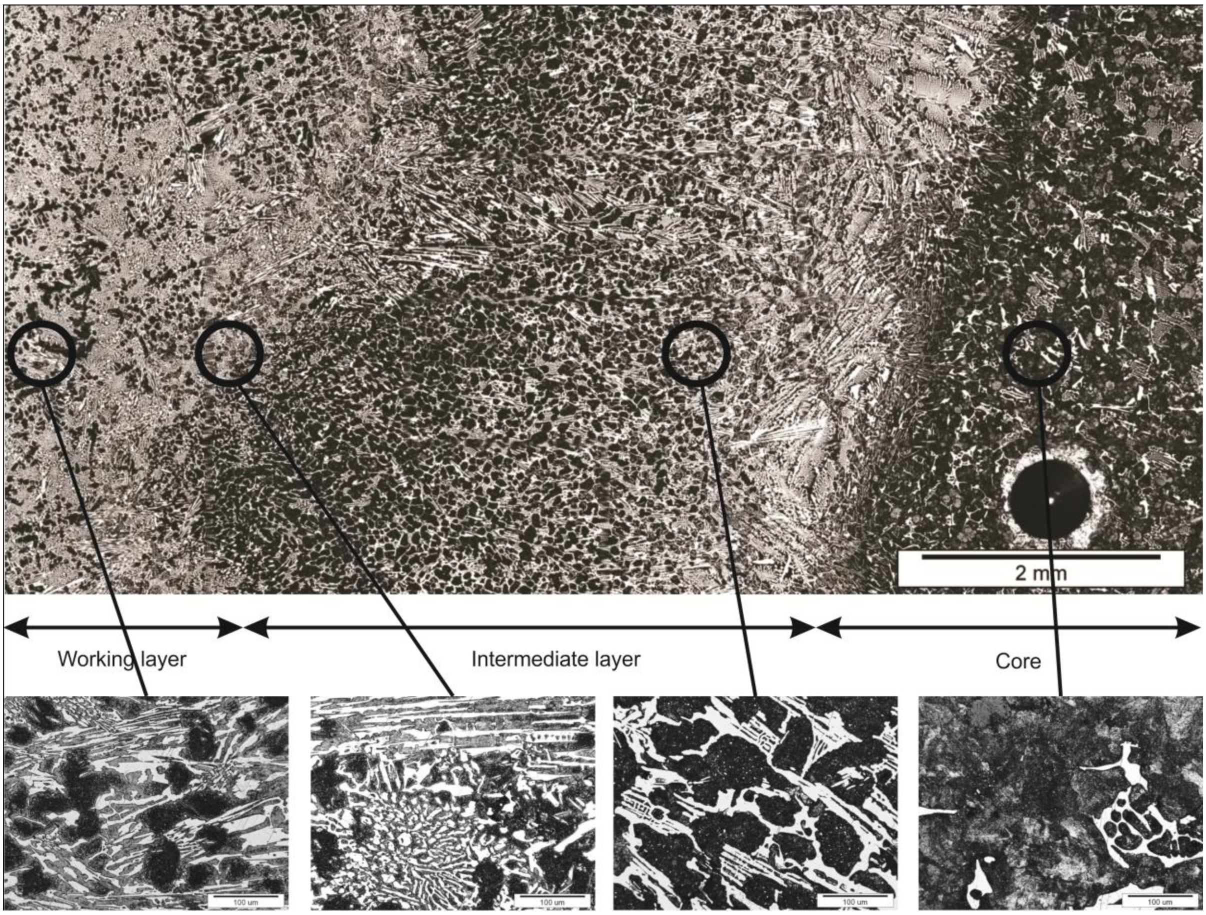


Figure 1: Macrostructure of a working layer, intermediate layer, and a core.

Figure 2 shows an isopleth phase diagram of the working layer material. Solidification starts with the solidification of austenite followed by eutectic reaction with the solidification of M_7C_3 type carbides between 1260 and 1230 °C. Precipitation of $M_{23}C_6$ type carbides takes place at 820 °C.

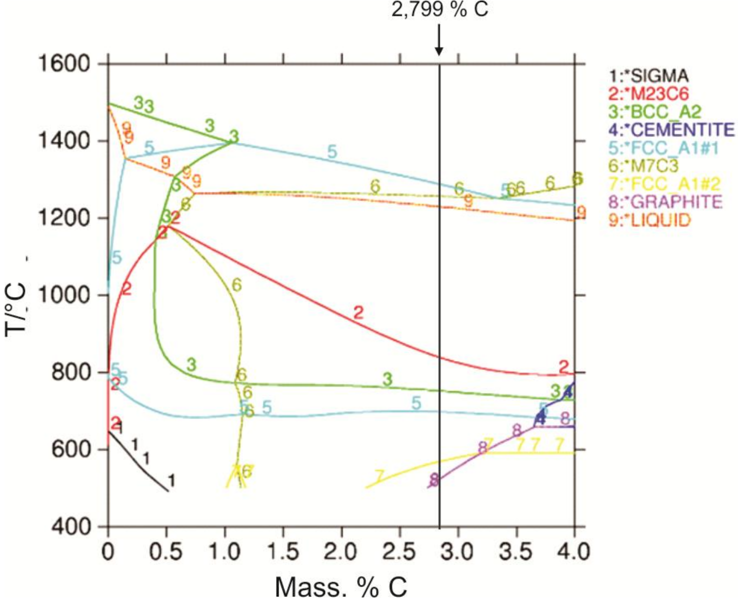


Figure 2: The isopleth phase diagram of the working layer.

With the help of the TAPP 2.2 program, the density of eutectic M_7C_3 carbides and austenite at the reference solidification temperature were calculated. The density of carbide M_7C_3 is 6.738kg/dm^{3}at temperature of precipitation; austenite has a density of a 6.99kg/dm^3 at a temperature of precipitation. Given the relative differences in density between the austenite, carbides, and the melt during the solidification stage of the intermediate layer, it seems that stratification of both microstructural ingredients occurs. In the first stage austenite dendrites appear and are pushed by centrifugal forces and higher density in the direction near the working layer. When the temperature of the remaining melt falls within the scope of eutectic solidification, leading to the development of nucleation and growth of the carbides, they are pushed in the direction of the interface between the intermediate layer and core, as carbides have lower densities than austenite. The difference in density between the austenite and carbide is only 0,3kg/dm^3 but the difference is more significant at centrifugal forces of 120G leading to inhomogeneous microstructure development.

Figure3a shows the SEM-microphotograph of the working layer where the large particles are carbides solidified during eutectic reactions. EDS-analysis showed that these should be carbides of M_7C_3 type. The smaller particles in the matrix are carbides of $M_{23}C_6$ type precipitated in solid state from the solid solution of austenite. It is clear that practically all the austenite was transformed into martensite during heat treatment. The intermediate layer also contains carbides, determined by EDS-analysis to be M_7C_3 type, as seen in Figure 3b. There was a small amount of smaller particles of secondary carbides distributed in the martensite matrix but the amount was much lower as the concentration of carbide-promoting elements is much lower than for the working layer. Figure 3c shows an optic microphotograph of a core in a polished state where graphite is seen in the iron matrix. The graphite should be in nodule- like form but this is not because insufficient Mg-treatment and burn-off of Mg during the long solidification time of a core.

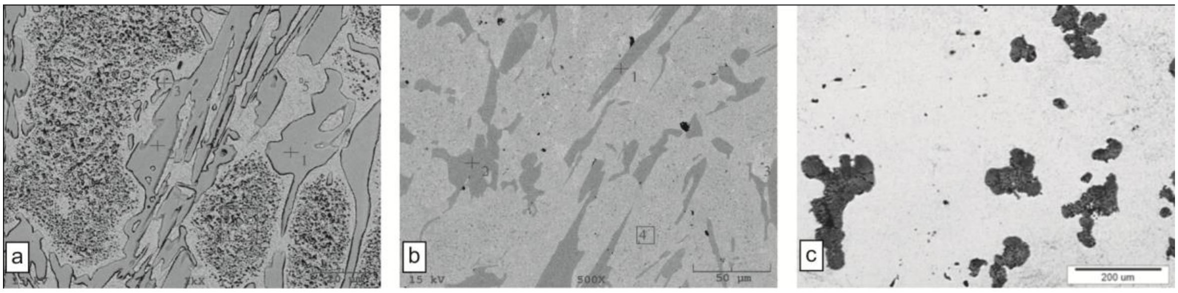
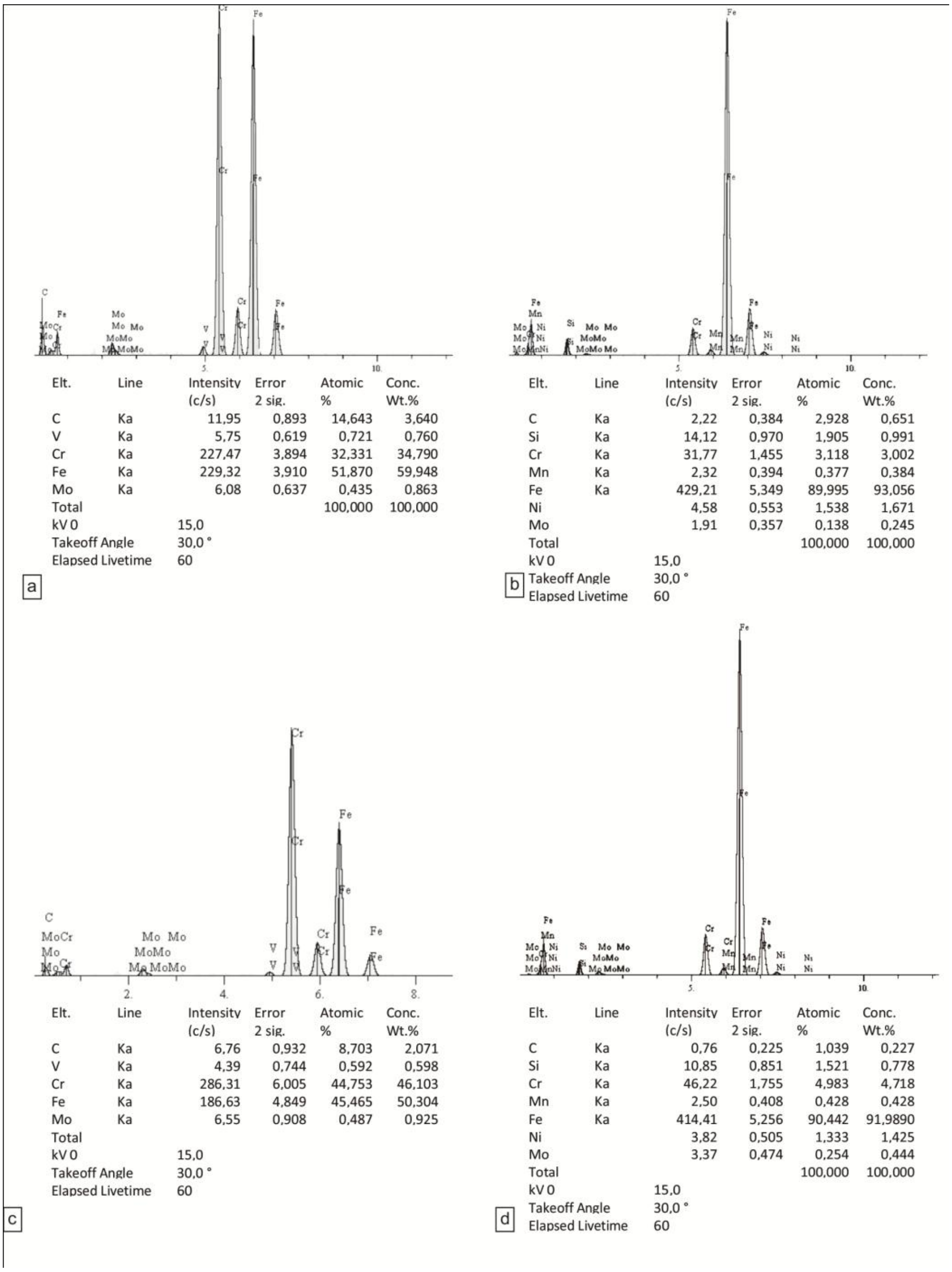


Figure 3: microstructures of all three layers: SEM microphotograph of the working layer (a), SEM microphotograph of the intermediate layer (b), and optic microphotograph of the core(c).

Figure 4 presents the EDS spectra of the analyzed microstructural constituents marked in Figures 3a and b.



Elt.	Line	Intensity (c/s)	Error 2 sig.	Atomic %	Conc. Wt.%
C	Ka	11,95	0,893	14,643	3,640
V	Ka	5,75	0,619	0,721	0,760
Cr	Ka	227,47	3,894	32,331	34,790
Fe	Ka	229,32	3,910	51,870	59,948
Mo	Ka	6,08	0,637	0,435	0,863
Total				100,000	100,000
kV 0		15,0			
Takeoff Angle		30,0 °			
Elapsed Livetime		60			

a

Elt.	Line	Intensity (c/s)	Error 2 sig.	Atomic %	Conc. Wt.%
C	Ka	2,22	0,384	2,928	0,651
Si	Ka	14,12	0,970	1,905	0,991
Cr	Ka	31,77	1,455	3,118	3,002
Mn	Ka	2,32	0,394	0,377	0,384
Fe	Ka	429,21	5,349	89,995	93,056
Ni		4,58	0,553	1,538	1,671
Mo		1,91	0,357	0,138	0,245
Total				100,000	100,000
kV 0		15,0			
Takeoff Angle		30,0 °			
Elapsed Livetime		60			

b

Elt.	Line	Intensity (c/s)	Error 2 sig.	Atomic %	Conc. Wt.%
C	Ka	6,76	0,932	8,703	2,071
V	Ka	4,39	0,744	0,592	0,598
Cr	Ka	286,31	6,005	44,753	46,103
Fe	Ka	186,63	4,849	45,465	50,304
Mo	Ka	6,55	0,908	0,487	0,925
Total					
kV 0		15,0			
Takeoff Angle		30,0 °			
Elapsed Livetime		60			

c

Elt.	Line	Intensity (c/s)	Error 2 sig.	Atomic %	Conc. Wt.%
C	Ka	0,76	0,225	1,039	0,227
Si	Ka	10,85	0,851	1,521	0,778
Cr	Ka	46,22	1,755	4,983	4,718
Mn	Ka	2,50	0,408	0,428	0,428
Fe	Ka	414,41	5,256	90,442	91,9890
Ni		3,82	0,505	1,333	1,425
Mo		3,37	0,474	0,254	0,444
Total				100,000	100,000
kV 0		15,0			
Takeoff Angle		30,0 °			
Elapsed Livetime		60			

d

Figure 4: EDS-spectrums of phases: M_7C_3 carbide, spot 1 in Figure 3b (a), martensite spot 3 in Figure 3b (b), carbides $M_{23}C_6$, spot 6 in Figure 3a (c) and martensite with carbide $M_{23}C_6$, spot 4 in Figure 3b (d).

Rockwell Hardness measurements were carried out from the surface of the roll to an 80mm depth. Figure 5 presents the hardness of a working layer which is around 61HRC until 60mm in depth when the intermediate layer starts. In this layer hardness starts to descend and proceeds to descend into the core too where the hardness is only 32 HRC.

Tensile tests of the working layer at different temperatures showed that tensile strength is lowered by about 10% at 400 °C and at higher temperatures is lowered even faster and reaches only 200MPa at 700 °C. This means that the working layer has a tendency to form a crack formation during cooling after casting as the core has much higher temperature and causes tensile stresses in the working layer.

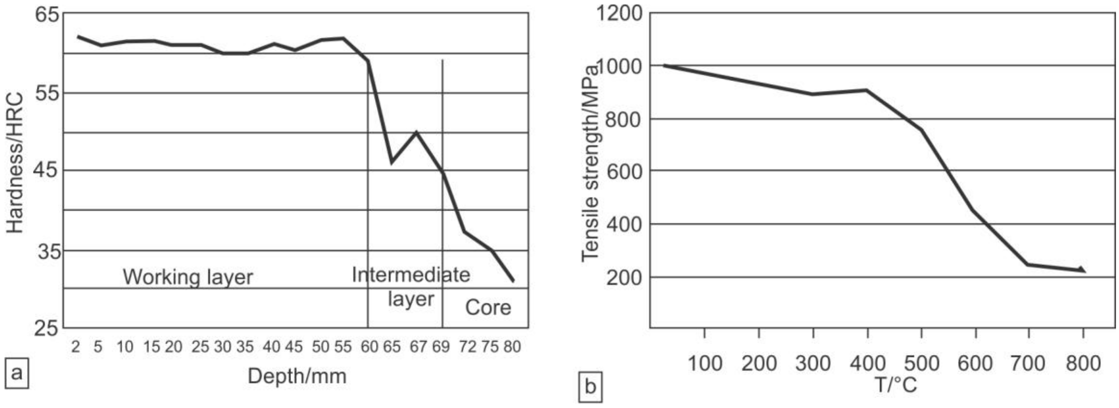


Figure 5: Mechanical properties: Hardness (a) and Tensile strength at different temperatures (b).

Figure 6 presents the dilatometric analysis of the samples, two from the working layer, one from the intermediate layer, and one from the core. It can be seen that the working layer had the lowest dilatation within the temperature range from room temperature up to 1100 °C. The Intermediate layer had slightly higher dilatation at the highest temperature but the core had the highest dilatation. These differences in dilatation cause high internal stresses during cooling of the gradient casting. It is clear that when the casting is cooling the surface – the working layer in this case shrinks faster than the core which causes tensile stresses in the working layer that might lead to a crack formation. A similar situation is met during heat treatment of the role, where the whole casting is heated to austenitising temperature and the core expands more than the working layer thus causing tensile stresses again. From Figure 6 it can be seen that the quantitative difference in dilatation of the samples is 0.055mm at 1000 °C which is not an insignificant value.

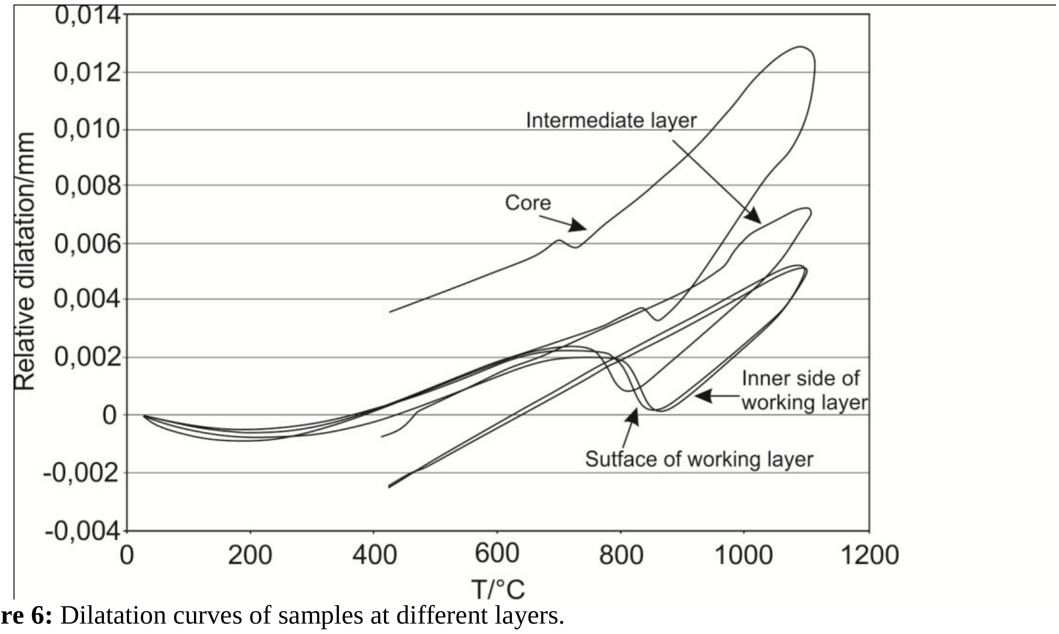


Figure 6: Dilatation curves of samples at different layers.

Stresses caused by different dilatations of layers during solidification and cooling of the casting were also calculated by Procast software and are presented in Figure 7. It is seen that the highest tensile stresses are reached just at the interface between intermediate layer and the core, which can lead to a crack formation and a failure of a role such as spall. [5]

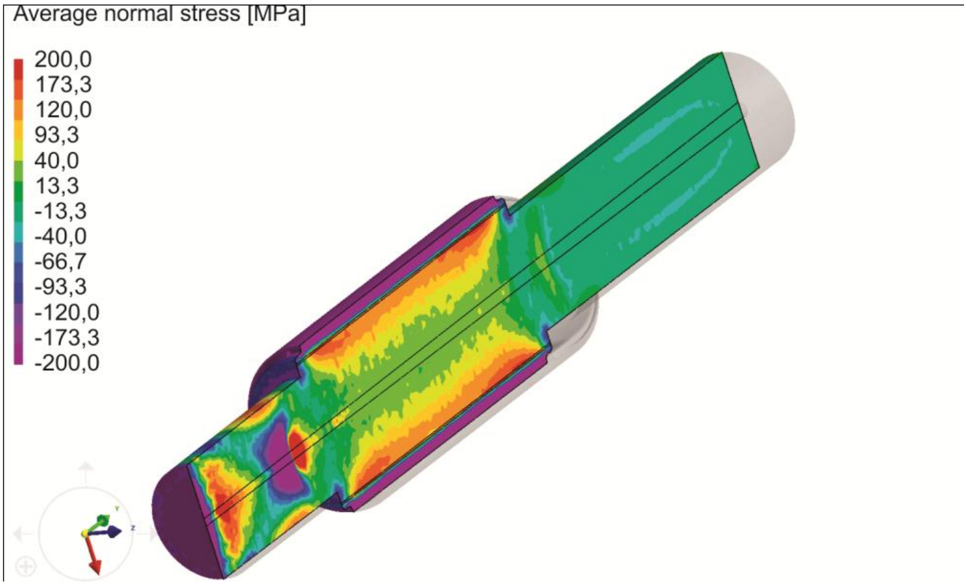


Figure 7: Simulation of normal stresses at the end of solidification.

Conclusions

1. Solidification of different layers was determined. It is clear that the intermediate layer re-melts the working layer and some carbide-promoting elements dissolve in an intermediate layer melt, which cause the formation of M_7C_3 type carbides. The working layer consists of secondary carbides too of a $M_{23}C_6$ type.
2. M_7C_3 type carbides have lower densities than austenite which are the reason that at slow solidification of the intermediate layer the formed carbides are pushed by high centrifugal forces into the inner side of the layer. Inhomogeneous microstructure is obtained in this way.
3. The tensile strength of a working layer is not changed until 500 °C, then it rapidly lowers which can lead to role failure if such working temperatures are reached.
4. The hardness of the roll's cross-section is lower in the intermediate layer and in the roll as a result of lower concentrations of primary and secondary carbides.
5. Dilatometric analysis showed big differences in the linear expansion coefficients of different layers. The difference in the dilatation of a working layer and a core is 0,055 mm at 1000 °C. Such differences may have already caused problems during cooling of the casting after solidification or during the following heat treatment.

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