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EFFECTS OF VARIATIONS IN ALLOY CONTENT AND MACHINING PARAMETERS ON THE STRENGTH OF THE INTERMETALLIC BONDING BETWEEN A DIESEL PISTON AND A RING CARRIER

VPLIV SPREMEMB V SESTAVI ZLITINE IN PARAMETROV OBDELAVE NA TRDNOST INTERMETALNE VEZAVE MED DIESELSKIM BATOM IN NOSILCEM OBROČKA

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The intermetallic bonding between an aluminium alloy piston and a cast-iron ring carrier must be able to withstand prolonged exposure to the high-pressure and high-temperature environment of a diesel engine. Weak cohesion may result in the debonding of the ring carrier. Such debonding causes devastating damage to the piston while the engine is in service. Thus, the quality and strength of the intermetallic bonding is very important in piston manufacturing.

In the present study, the effects of variations in the alloy content and the machining parameters on the overall strength of the intermetallic bonding are investigated. The defects are determined by ultrasonic inspection.

The results indicate that the variation in the alloy content and graphite flakes affects the bond quality adversely. It was determined that the graphite size is a very important parameter. If the graphite size gets smaller, then stronger intermetallic bonding is observed. The graphite accumulation can be resolved by choosing the right amount of alloying elements. The machining process parameters were found to be ineffective for the formation of defects on the intermetallic bonding.

Keywords: diesel piston; ring carrier; Alfin bond, intermetallic bonding

Intermetalma zveza med batom iz aluminijeve zlitine in litoželeznim nosilcem obročka mora dolgo prenašati obremenitev pri visoki temperaturi dieselskega motorja. Šibka kohezija lahko povzroči odstopanje nosilca obročka in povzroči veliko poškodbo pri obratovanju motorja. Zato sta kakovost in trdnost intermetalne zveze zelo pomembni pri izdelavi batov. V tem delu smo raziskali vpliv sprememb v sestavi in parametrov obdelave na trdnost intermetalne zveze. Napake smo odkrili z ultrazvočno kontrolo. Rezultati kažejo, da spremembe v sestavi zlitine in grafitni lističi vplivajo različno na kakovost zveze. Velikost grafitnih lističev je zelo pomemben parameter in pri manjših lističih grafita je trdnost povezave večja. Kopičenje grafita se lahko prepreči s pravo vsebnostjo legirnih elementov. Parametri obdelave ne vplivajo na nastanek napak intermetalne zveze.

Ključne besede: dieselski bat, nosilec obročka, zveza Alfin, intermetalna zveza

1 INTRODUCTION

Pistons are commonly made of a cast aluminium alloy for reasons of its excellent and lightweight thermal conductivity. An aluminium-silicon alloy is commonly used for the piston material and provides the best overall balance of properties [1,2]. The piston features include the piston head, the piston pin bore, the piston pin, the skirt, the ring grooves, the ring lands, and the piston rings. A ring groove is a recessed area located around the perimeter of the piston that is used to retain the piston ring. Piston rings are used to prevent the leakage of combustible gas and to control the oil film of the liner when the piston is working in the cylinder. The rings are inserted into the ring grooves on the piston. These grooves are called the ring carrier. The ring carrier is made of Ni-resist (Niresist) cast iron consisting of graphite in a matrix of austenite. The cast iron retains the integrity of its original shape under heat, load, and other dynamic forces. These materials usually contain alloying elements such as nickel, chromium, copper or molybdenum to increase the strength or in order to facilitate the formation of austenitic cast iron. The corrosion and wear resistances of these materials are quite high. These materials are suitable for corrosive environments, such as sour well oils, salts, salt water acids, and alkalis. Niresist is denser than gray or ductile irons and has a higher coefficient of thermal expansion. Ring carrier materials are melted in induction furnaces in the temperature range 1400–1450 °C. Then, the final shape of the ring carrier is produced by a spin casting machine. These ring carriers are placed in the piston mould and the molten piston material is poured in. The most important thing is that the Niresit die cast material (ferrous) must be bonded by a non-ferrous piston material during the casting of the piston. Because of the fact that diesel engines are worked at high temperatures and under high pressure, the durability of the bond between the aluminium piston and the Niresist piston ring is very crucial. The serious problems that can be caused by bond defects are available in the literature [3]. The intermetallic bonding between the ring carrier and piston must be able to withstand prolonged exposure to the high-pressure and temperature environment of the diesel engine. Weak cohesion may result in the debonding of the ring carrier. This debonding causes devastating damage to the piston while the engine is in service. For the aforementioned reasons these processes should be controlled precisely. So, the surfaces of the ring carrier material are shot blasted using small balls. This process is the pre-process of an alfin (AlFin) bath for better bonding quality. The AlFin bath is a method for preparing a ferrous surface for intermetallic bonding [4]. The alfin bonding process is commonly used to bond a nonferrous Al alloy and a ferrous alloy, such as aluminium diesel engine pistons and Niresist ring carriers, directly together. It is well known that cast iron contains carbon as a result of the casting process. The carbon precipitates out of solution and is present in the piece as graphite flakes on cooling. The size and the distribution of the graphite flakes can vary as a function of the alloy. "It is well known that certain elements, when combined with iron containing carbon, act as retarders, that is, impede the graphitization of the carbon, and that others act as accelerators, that is, promote graphitization, during the malleableizing process. For example, sulphur, manganese and chromium are retarders, while aluminium, nickel, and copper, in small quantities, are accelerators of the phenomena of graphitization [5]." It is also a parameter of the casting and cooling processes. The alfin bonding process begins with the growth of an Al alloy intermetallic surface layer on the ring carrier by immersion of the ring carrier in a molten Al alloy bath. The Al alloy bath usually includes Al and 6 % Si. The immersion time is determined according to the required layer thickness. The Al alloy intermetallic layer is typically grown to about 50 μm or more in thickness. Bath temperatures typically range from 700 °C to 750 °C. The thickness of the intermetallic layer increases with the alfin bath temperature and immersion time. The immersion time ranges from 3 min to 18 min. The alfin bond is a real bond, which has a chemical composition close to the $FeAl_3$ and is formed by the Fe and Al alloy.

As mentioned previously a diesel piston is produced by casting. Firstly, Al alloys are melted in an induction furnace. The temperatures are 780 °C for a 12 % Si alloy, 800 °C for an 18 % Si alloy, and 850 °C for a 24 % Si alloy. The modification and gas-removing processes are applied to the molten Al alloy and then the molten alloy is taken to the waiting furnace. The molten Al-Si alloy is poured into the mould over the ring carrier. This ring carrier is observed to embed with the Al alloy after solidification. Then the piston is subjected to machining to create the final shape.

Ultrasonic inspection techniques are widely used in an industry where a non-destructive evaluation of a workpiece is required. The ultrasonic imaging technique is founded on pulse-echo techniques: a transducer emits a short pulse of ultrasonic waves towards the sample and records the signal reflected back from the various acoustic boundaries. Using ultrasonic methods, not only the travel time of the ultrasonic pulse through the testing device, and consequently the velocity of waves, but also the frequency content and the relative energy are recorded. The ultrasonic inspection test is usually made in a liquid since the sound waves broadcast in liquid better than in any other environment. In the manufacturing plant, it is observed by ultrasonic inspection that some pistons have defects. In this study, the causes of these defects have been investigated. Mainly, two processes were considered. These are the alphin bath and the machining process. A variation in the alloying content is very important in terms of graphitization, which affects the bonding significantly. It is also thought that the piston may be damaged during the machining process. In this research, the effects of variations in the alloy content and the machining process parameters on the intermetallic bonding between the diesel piston and the ring carrier are investigated.

2 EXPERIMENTAL WORK

2.1 Variation in Alloy Content

The alloy contents of non-defective and defective pistons were investigated statistically. The purpose of the study is to see the influence of the alloy content on the intermetallic bonding quality. They were categorized in two groups, as Group 1 and Group 2, respectively. Group 1 represents the alloy content of the defective pistons and Group 2 shows the non-defective pistons. A sample group was selected in both groups and the average and standard deviation values of the alloys were calculated. These calculations are summarized in **Table 1**. The last column in the table indicates the desired target values for each individual alloy. Finally, the alloying contents were related to the intermetallic bonding quality. In addition to this statistical study, the effect of the graphite flake's size on the bonding quality was studied. It was mentioned previously that some elements accelerate or retard the graphitization.

Table 1: Statistical study on variations in the alloy content (in mass fractions, *w*/%)

Alloying Elements	Group 1		Group 2		Target Standard Deviation
	Average	Standard Deviation (SD)	Average	Standard Deviation (SD)	
C	2.61	0.15	2.67	0.08	0.03
Si	2.26	0.12	2.22	0.08	0.03
S	0.03	0.005	0.03	0.01	0.05
P	0.09	0.08	0.08	0.01	0.03
Ni	15.99	0.76	14.84	0.32	0.30
Cr	1.48	0.05	1.24	0.04	0.05
Cu	6.04	0.27	6.34	0.28	0.20

2.2 Effects of the Machining Parameters

For the study of the effects of the machining parameters, non-defective pistons were chosen. The aim was to determine the effects of machining the parameters on the failure accumulation. The non-defective pistons were determined by ultrasonic inspection. For this inspection the piston was immersed into the liquid. If there is any disconnection in the ring carrier region, the transducer sound waves make an echo and the waves cannot return to the receiver. This is an indication of a failure. If the transducer sound waves are caught by the receiver, it is an indication of there being no defect. In addition, six of the samples were also cut and examined. An example of a non-defective ring carrier is given in **Figure 1**. Based on the piston diameters, the machining parameters, such as the cutting speed and the feed rate of the turning machines, are determined as given in **Table 2**. The effect of the blunt cutter on the defect accumulation was also investigated.

Table 2: Chip thickness and feed rate for the different piston diameters

Diameters (mm)	Cutting Speed r/min	Feeding Rate mm/min
60–80	1900	0.28-0.40
80–100	1500	
100–120	1220	
120–140	1050	
140–160	900	

3 RESULTS AND DISCUSSION

The strength of the intermetallic bonding is related to the bonding quality. **Figure 2** shows the microstructure of the ring carrier. The left side of the dark boundary belongs to the Niresist ring carrier material; the right side shows the Al alloy piston's microstructure. The middle dark region displays the debonding area. Various other structures are presented in **Figure 3–5**. **Figure 3 and 4** show insufficient and inhomogeneous Si thinning,

Figure 1: Non-defective ring carrier
Slika 1: Nosilec obročka brez napake

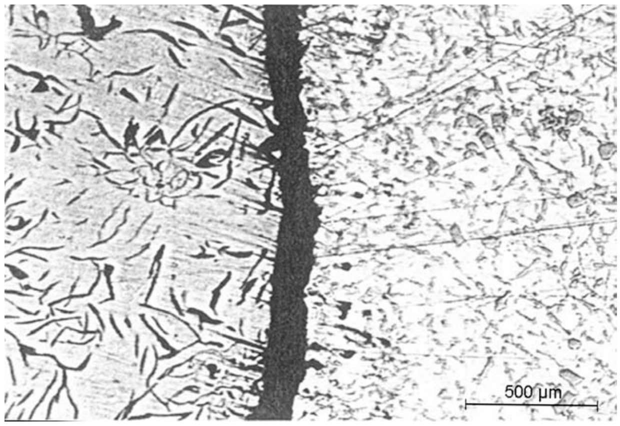

Figure 2: Microstructure of ring carrier (100X)
Slika 2: Mikrostruktura nosilca obročka (povečava 100-kratna)

respectively. It is very important that the Al alloy should be in an appropriate microstructure for a good-quality bond. **Figure 5** indicates sufficient and homogenous Si thinning, which is necessary for a good bond. These microstructures are given for the evaluation and calibration purposes of the bonded region. A defective ring carrier is shown in **Figure 6**. The dark region in **Figure 6** indicates the defect. It is clear that the ring carrier is weakly bonded to the Al alloy piston. It this study, the basic effects of the variation in the alloying content and the machining parameters are investigated. **Table 1** clearly indicates that the standard deviation of the alloying element with respect to the desired target value has a great influence on the bond quality. The standard deviation for Group 2 is close to the target value and a better bond quality is achieved. The pistons in Group 1 were defective due to the excessive variations in alloy content. The statistical results explain that by reaching the target deviation value, the variations in alloy content affected the bonding in a positive way. It is clear that choosing the right amount of alloys prevents graphite formation. However, in addition to the statistical study,

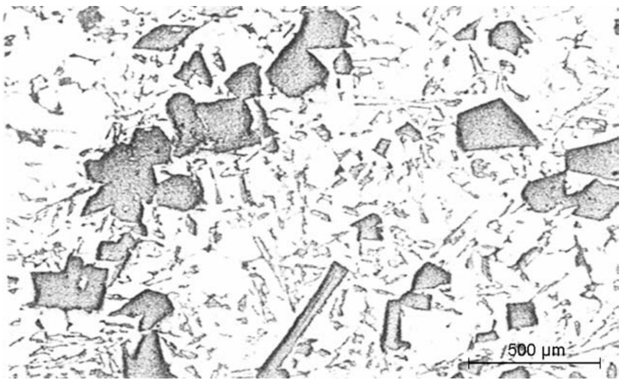

Figure 3: Microstructure of ring carrier (Insufficient Si thinning) (100X)
Slika 3: Mikrostruktura nosilca obročka (nezadostno zmanjšanje vsebnosti silicija (povečava 100-kratna)

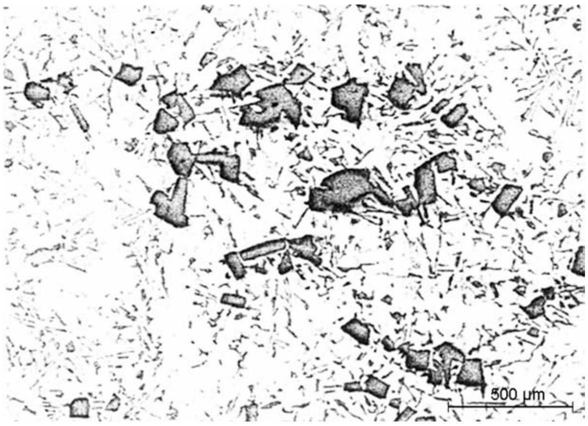

Figure 4: Microstructure of ring carrier (Inhomogeneous Si thinning) (100X)
Slika 4: Mikrostruktura nosilca obročka (nehomogeno zmanjšanje vsebnosti silicija (povečava 100-kratna)

Figure 6: Defective ring carrier
Slika 6: Nosilec obročka z napako

the effect of graphite size on the bonding quality is also investigated. The experimental observations show that graphite flakes accumulate on the nonferrous material and fill the cavities. Eventually, they make the bond strength weaker due to insufficient bonding surfaces, since the aluminium alloy does not wet the graphite. They are seen on the nonferrous material as dark regions and help in the propagation of the cracks. These findings indicate that the amount of graphite is very important and is directly related to the quality of the bond, which was previously reported [6]. It is concluded that the material that has graphite was dissolved in the alfin bath and changed the condition of the alfin bath adversely. These graphite flakes decrease the bonding force. The strengthening of the intermetallic bonding between the ferrous and the nonferrous metal through the elimination of the graphite flakes as a phase is present in the intermetallic bond region. This can be accomplished by removing the graphite from the intermetallic bond region by either removing the graphitic contaminants from the surface region of the ferrous metal or by sealing the graphite into the surface of the ferrous metal [6]. The results show that the size of the graphite flakes in the ring carrier material has an influence on the bonding. The small size flakes mean a better bond quality. The recommended flake size and the distribution of the graphite are shown in **Figures 7a–d** [7]. These figures are similar to the ASTM flake graphite types [8]. These microstructures can be achieved by the precision of the alloying elements. The absence of graphite flakes as a participant in the bond results in an increased bond strength. In the intermetallic bonding layer, debonding can be seen at the nonferrous material, which has less graphite accumulation or attack. The graphite generally accumulates particle by particle on the nonferrous material and fills in the moving cavities. This process reduces the bonding force. The graphite flakes can be seen as dark regions in the microstructure view and cause easy crack propagation. The defect during the formation of the intermetallic bonding depends on the temperature of the alfin bath and the pressure of the casting. These small flakes or particles are cooled at a

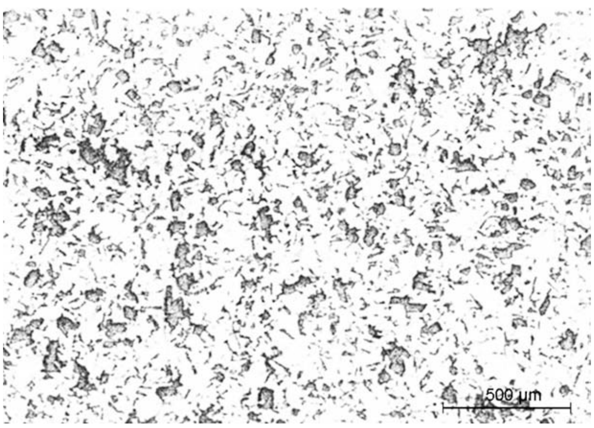

Figure 5: Microstructure of ring carrier (Sufficient and homogeneous Si thinning) (100X)
Slika 5: Mikrostruktura nosilca obročka (zadostno in homogeno legiranje silicija) (povečava 100-kratna)

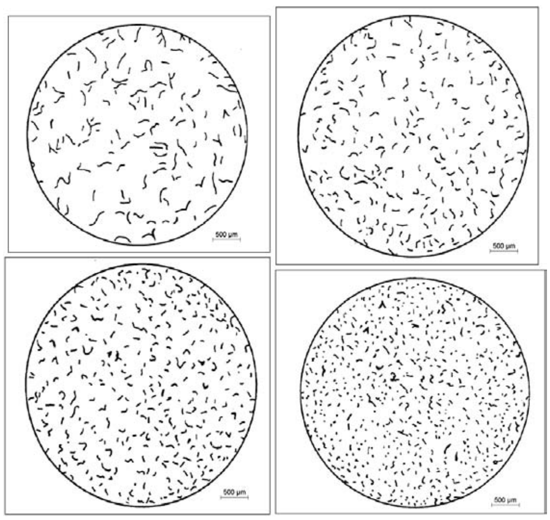

Figure 7: (a) d = 0.06–0.12, (b) d = 0.03–0.06, (c) d = 0.015–0.03, (d) d < 0.015 [7]

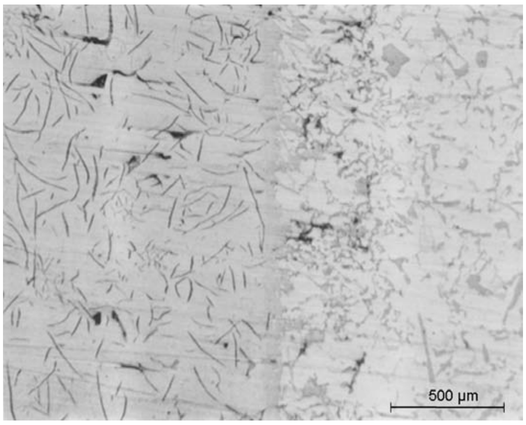

Figure 8: Strong bonding microstructure (100X)
Slika 8: Mikrostruktura trdne zveze

Table 3: Effects of machining parameters

Chip Thickness mm	Feed Speed mm/min	Chip Volume mm^3	Chip Shrinkage Factor	Cutting Force (N)	Power (kW)
2.5	0.28	329.50	75.36	1360	6.46
5.0	0.28	659.40	37.68	3305	32.75
2.5	0.35	412.12	75.36	1360	8.98
5.0	0.35	824.25	37.68	3305	43.67

different stage and show up on the top surface of the iron part like small- and large-shaped graphite crystal sediments. As the size of the graphite gets smaller, a stronger intermetallic bonding is observed. A strong bonding microstructure is given in **Figure 8**. The figure reveals the presence of graphite flakes, extending from the ring carrier through the bond and into the aluminium alloy.

In the second part of the study, non-defective pistons were machined by turning at prescribed cutting speeds and rates. **Table 2** shows all the tested conditions. The machining calculations are summarized in **Table 3**. All the possible chip thickness and feed rates were applied. The cutting forces and powers were calculated for each case. The selected pistons were inspected by an ultrasonic technique for defects. No defects on the piston were observed from all these studies. Finally, the machining was performed with a blunt cutter. No defects were determined to be caused by the blunt cutter. It was concluded that the machining parameters have no influence on the intermetallic bonding defects.

4 CONCLUSION

The effects of variations in the alloy contents and the machining parameters on the strength of the intermetallic bonding between a diesel piston and a ring carrier have been investigated. It was determined that the variations in the alloy contents and the graphite sizes have a great influence on the bonding quality. As the size of the graphite gets smaller, a stronger intermetallic bonding is observed. The graphite accumulation can be resolved by choosing the right amount of alloying elements. It should be noted that no defects were caused by the machining-processes parameters.

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