Consecutive Casting of Iron Bimetal with Low-Carbon Steel Interface Plate

by Rendi Reynaldi

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Consecutive Casting of Iron Bimetal with Low-Carbon Steel Interface Plate

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Abstract

Consecutive[13,14] casting[15] of bimetallic applies consecutive[16] sequences of pouring of two materials into a sand mold. The outer ring is made of NiHard1, whereas the inner ring[17] is made[18] of nodular cast iron. To enable a consecutive sequence of pouring[19], an interface plate made of low carbon steel was inserted into the mold and separated the two cavities. After pouring the inner material at the predetermined temperature[20] and[21] the interface had reached the desired temperature[20], the NiHard1 liquid was then[22] poured immediately into the mold. This study determines the pouring temperature[20] of nodular cast iron and the temperature[20] of the interface plate at which the pouring of white cast iron into the mold[23] should be done[24]. Flushing the interface plate for 2 seconds by flowing nodular cast iron liquid as inner material generated a diffusion bonding between the inner ring and interface plate at pouring temperatures of 1350 °C, 1380 °C, and 1410 °C.[25] The interface was heated[26] up to a maximum temperature of 1242 °C, 1260 °C, and 1280 °C respectively.[27,28] The subsequent pouring of white cast iron into the mold to form the outer ring at the interface temperature of 1000 °C did not produce a sufficient diffusion bonding. Pouring the outer ring at the temperature[20] of 1430°C and at[29] the interface plate temperature of 1125 °C

produced[30] a sufficient[31] diffusion bonding. The presence of Fe3O2 oxide on the outer surface of the interface material immediately after the interface was heated[32] above 900 ^{0}C has been identified.[33] Good metallurgical bonding was achieved by pouring the inner ring at the temperature[20] of 1380°C, interface temperature[20] of 1125 °C and[34] then followed by pouring[35] of the outer ring at 1430^{0}C and flushing time of 7 seconds.

Keywords: Consecutive casting[15], Bimetal, White cast iron, Interface plate, Casting temperature[20,36]

Introduction

Casting product requires, in some cases, a combination of special[37] properties such as abrasion resistance, corrosion resistance, high shock resistance, and good machinability.[38] These properties are contradictory for[39] a single material. The hardness is mostly contrary to the impact of resistance and machinability. For a particular application, the requirements of high-performance properties are only for the working surface of cast objects (Wróbel, Cholewa, & Tenerowicz, 2011). Bimetallic Casting[15] is a method of combining[40] two metallic materials with different properties by means of[41] the casting process. The diffusion bonding in bimetallic casting[15] is influenced[42] by pressure, contact surface

cleanliness, contact time, and contact temperature (Kumar, Krishnamoorthi, Ravisankar, & Angelo, 2009). The contact temperature in the diffusion process is at the rate of[43] 50%-80% of the lowest material melting point (Li et al., 2018). In the previous study (Avcı, İlkay a, Şimşir, & Akdemir, 2009), the Grinding Roll prototype was made[44] using the gravity casting method. A die blank of nodular cast iron was inserted[45] into the mold, and the liquid white cast iron was then subsequently poured. Inserting[46] an interface plate between the inner and outer material enables pouring[47,48] of the inner and outer material in a sequence into the same mold. However, the interface plate served as a die blank as well, and the optimum temperature[20] was set[49] up in order to[50] avoid initiation[51] of cracks and produce a metallurgical bonding. The

preheating[52] of[53] the interface plate as a consequence of the first pouring created a good[54] condition for a diffusion bonding between the interface plate and the subsequently poured outer ring material.

The volume ratios of liquid to solid[55] affect significantly[56] the interfacial microstructure. To achieve a sound interfacial microstructure[57] a liquid–solid[58,59] volume ratio of 10:1 and 12:1 is required (Xiong, Cai, & Lu, 2011). This ratio was then referred[60] as[61] the minimum ratio in designing the interface plate. An epitaxial interfacial layer of austenite can be precipitated[62] onto the steel substrate from the liquid phase, and that the[63] thickness of the layer[64] can be controlled by soak time at 1250 °C (Lucey et al., 2012). In this study[65] the soak temperature was set lower but[66] the soaking time is longer due to higher mass provided by the inner ring. This study is aimed[67] to produce a bimetallic casting of nodular cast iron-NiHard1 by applying[68] an interface plate and pouring both of the materials in a sequence into the same mold.

Materials and Method

Bimetallic casting[15] consists of the inner ring made of nodular cast iron and an outer ring made of NiHard1 white cast iron. Mold made of resin sand were[69] used[7] to form the casting[15]. Two cavities in the mold[71] were separated by a carbon steel interface plate.[72] It was inserted[73] into the mold[74] prior to[75] the pouring of liquid. A gating system was designed[76] to enable the pouring of both materials in a certain sequence. Flow off tanks were[78] designed[79] to ensure the filling time of the cavity so that the interface temperature could be assured.

Figure 1 describes the gating system, flow off tanks and[80] the interface plate.

Two middle frequency[81] induction furnaces were used[82] to melt the two materials separately at the same time. First, the nodular cast iron liquid was poured into the mold to form the inner ring. After the interface plate gained the desired temperature,[20] which was measured by placing a contact thermocouple in the bottom position of the interface plate, the NiHard1 liquid was then[83] poured into the mold to form the outer ring.

a) b)

Fig. 1. Mold drag (a) and gating system and flow off tanks (b)

Table 1.

The chemical composition of the material

Material

Elements in Wt%

C

Si

Mn

Cr

Ni

Mo

P

S

other

Nodular CI

3.41

2.62

0.30

Mg 0.023

NiHard1

3.19

0.50

0.58

2.11

3.32

0.02

0.047

0.026

Interface plate

0.12

0.03

0.56

Material

This research was performed for two types of cast iron, nodular cast iron as the inner ring material and white cast iron (NiHard1) for the outer ring material. Low carbon steel was used[84] as the material for the interface plate. The chemical composition was tested for each material[85] by Optical Emission Spectrometry using ARL 3460.

Table 1 describes the elemental composition of materials as average[86] value. The inner ring had an outer diameter of 147 mm, an inner diameter[87] of 106 mm and[88] a height of 120. The outer ring

had an outer diameter of 188.45 mm, an inner diameter of 149.95 mm and[89] a height of 100 mm.

Interface Temperature

To produce a diffusion bonding on the interface, the interface temperature at the time of pouring must have been in the range of[90] 50%-80% of the lowest liquid-material point (Li et al., 2018). Pretrials[91] by pouring liquid nodular cast iron at 1410°C into the mold caused a partial[92] melting of the interface plate. Based on this, the pouring temperature[20] of 1410°C was set[93] as the maximum pouring temperature[20] for the nodular cast iron. Pre-trials[91] by

pouring[94] Nihard1 liquid directly to die blank of low carbon steel plate have also been conducted[95] to set the reference for determining the interface temperature. It was found[96] that the die blank temperature of 1150 °C and pouring temperature[20] of 1430

°C produced a diffusion bonding between poured Nihard1 and the die blank.

The interface temperatures were then set up slightly below 1150°C. To achieve the determined interface temperature,[97] the cavity for the inner ring was added with a flow off tank,[98,99] so that the nodular cast iron had enough time to raise the interface temperature up[100] to slightly above the determined interface temperature. Pouring of the outer ring was done immediately after cooling[101] process and[102] the interface plate was at the correct temperature.[20] A SolidCAST simulation was used[103] to design the flow off tank.[104,105] Figure 2 shows the flow off tank[106,107] and the simulation. Interface temperature is considered[108] as preheating temperature[20] and[109] this is related to crack.

a)

□

A cracking index (CI) is used to evaluate the probability of cold cracking and is expressed[110] as equation (3)

$CI = CE + 0.15\log HJIS + 0.3\log(0.017kt\sigma w)$ (3)

The required preheating temperatures to avoid cold cracking is then determined by the following criterion t100 [illegible] (t100)Cr where t100 is the cooling time to 100 °C (212 °F). Critical time (t100)Cr is given[111] as equation (4):

$(t100)Cr = \exp(67.6CI3 - 182CI2 + 163.8GI - 41)$ (4)

Contact Pressure

Pressure[112] at the contact area between the interface plate and casting material was necessary to facilitate a bonding[113] and avoid any gap. The interface plate expanded during the heating process, which was[114] caused by the direct[115] contact to[116] the inner ring liquid. During the following cooling process, the interface plate and the inner ring experienced a contraction. Since the coefficient of thermal expansion of low carbon steel is higher than those of nodular cast iron, the interface plate achieved higher contraction[117] and[118] this led further to a buildup of pressure at the contact area.

Table 2 shows the coefficient of thermal expansion of nodular cast iron, low carbon steel and[119] NiHard1.

Table 2.

The coefficient of material thermal expansion

No

Material

Coefficient of thermal expansion

at 700°C (m m-1 °C-1)

1

Nodular Cast Iron

13.8 (Davis, Mills, & Lampman, 1990)

2

Low-Carbon Steel

14.8 (Davis, Mills, & Lampman, 1990)

3

Ni-Hard 1

12.8 (Laird, Gundlach, & Rohrig, 2000)

Contraction and expansion of material can be expressed[120] as follows:

$\Delta L = L0C\Delta T$

(5)

$L1 = L0 + \Delta L$

(6)

b)

Fig. 2. Schematic of flow-off tanks as initial heater interfaces

and SolidCAST simulation (b)

Crack is to be avoided, and the susceptibility of steel to cold cracking is expressed as equation (1 and 2) below (Yurioka & Suzuki, 1983; Yurioka, Suzuki, Ohshita, & Saito, 1983) :

$CE = C + A(C)\ \{Si + Mn + Cu + Ni + Cr{+}Mo{+}Nb{+}V + 5B\}$ (1)

Where: ΔL = Change in diameter (m) L0 = Diameter at low temperature (m) L1 = Diameter at high temperature (m)

C = Thermal expansion coefficient (m m-1 ^{0}C-1)

Dimensional changes at high temperatures and room temperatures are shown[121] in Table 3. It can be identified[122] that there was a slight difference in dimension[123] between the two contact areas. The inner diameter of outer[124] ring was smaller than the outer diameter of the interface, which indicated a contact pressure between the interface plate and the outer ring. Since the inner

Whereas,

□24 6

□15 20 5

□diameter[125] of the interface plate was smaller than the outer diameter of the inner ring, a[126] contact pressure was generated[127] between the interface plate and the outer ring.

$A(C) = 0.75 + 0.25\tanh\{20(C - 12)\}$ (2)

Table 3.

Material diameter before and after expansion

Temperature

(oC)[128]

The diameter of the Inner Ring (mm)

The diameter of the Interface Ring (mm)

Diameter[129] of Outer Ring (mm)

inner

center

outer

inner

center

outer

inner

center

outer

700

106

127.25

148.5

148.5

150

151.5

151.5

170.75

190

20

106

126.12

147.37

147

148.5

150

149.9

169.2

188.45

Contact Surface

A clean contact surface is a requisite for achieving diffusion bonding (Li et al., 2018). The interface plate was therefore cleaned [130] from dirt and oxides prior to [131] the assembly of the mold, and the interface plate was also rinsed[132] with ethanol. During the pouring of the inner ring and prior to[133] the pouring of the outer ring, there was time available that may have facilitated a formation of dirt on the surface of the interface plate.[134] By the flowing of the liquid (flushing) for several seconds by applying a flow off tank[135,136] , dirt[137] was removed. It is found[138] that a flushing time of 7 seconds by the liquid temp erature[139] of 1430°C was adequate to generate a sufficient bonding (Avcı et al., 2009). Figure 3 and Figure 4 describe the flushing process by the flowing of the liquid to the flow off tank for the inner ring and outer ring.[140]

Fig. 3. Schematic of flushing material from the inlet for the inner ring

Fig. 4. Schematic of flushing the material towards the flow off tank[141]

Contact Time

The contact time between the liquid and interface plate was needed to preheat the interface plate to facilitate a diffusion bonding. This[142] was achieved[143] by adding flow off tanks to the design[144] as shown in Figure 5. The contact time in this study was set[145] for two seconds for the inner material and seven seconds for the outer material.

Fig. 5. Flow off tank

To minimize the turbulence during the filling process[146], a pressurized gating system was applied. Contact time was determined[147] by calculating the velocity, volume of cavities, and cross-section area of ingate.[148] This[149] was then verified and simulated with the SolidCAST application (Figure 6).

a)

b)

Fig. 6. The simulation of liquid[150] flow of inner material (a) and outer material (b)

Casting Process

The inner ring was cast[151] by pouring the liquid nodular cast iron at the pouring temperature[20] of 1320 °C, 1350 °C, 1380 °C, and

1410 °C. The casting[15] was then cooled until the interface plate reached the determined temp erature,[152] which was set[153] as 1000°C and 1125 °C.[154]

Table 4.

Trial

Pouring Temperature[20] of inner[155] ring

(oC)[156]

Temperature[157] of interface plate (oC)[158]

Pouring Temperature[20] of inner[159] ring

(oC)[160]

1

1320

1125

1430

2

1320

1000

1430

3

1350

1125

1430

4

1350

1000

1430

5

1380

1125

1430

6

1380

1000

1430

7

1410

1125

1430

8

1410

1000

1430

Shows the trial parameters

a)

NiHard1 liquid was then immediately poured into the mold to form the outer ring at a constant temperature of 1430 °C. The increase of the interface plate temperature was measured[161] with a thermocouple, which was placed[162] in contact with it. Table 4 shows the trial parameters and[163] three casting[15,164] were made[165] for each trial.

Microstructural observation and hardness testing

Testing of hardness was conducted by applying Vickers' micro hardness[166] testing with a constant static load of[167].0.2 kg. Optical[168] microscope (OLYMPUS GX 71) was used[169] to observe the microstructure. EDS Testing (SEM HITACHI SU 3500 and EDAX) was carried[170] out to identify the elemental composition on[171] a micro area. Samples were etched[172] with Nital 3%.

Results and discussion

Casting

Pouring the NiHard1 liquid for the outer ring at the interface temperature of the 1000 °C did not produce any bonding between the interface plate and the outer material, so the[173] initial heating temperature range had to be increased to 80%-90% of the lowest liquid point. By pouring temperature[20] of 1410 °C for the inner ring, the interface plate was partially melted[174] so that the inner ring material entered the outer ring cavity. Samples were taken[175] from the casting[15] (Figure 7a) and[176] testing was conducted[177] on the cross section[178] area (Figure 7b).

b)

Fig. 7. Casting tree incl. Flow off tanks (a) and cut off position (b)

Temperatures

The temperature[20] of the interface plate was monitored[179] by using a data logger and thermocouple which[180] was placed[181] in contact with the interface plate.[182] Directly after pouring the inner ring at diverse[183] temperatures, a maximum temperature of the interface plate was achieved. Table 5 shows the pouring temperature[20] of the inner ring[184] and the maximum temperature[20] of the interface plate. All of pouring[185] temperatures resulted in an interface temperature above the targeted temperature[20] (1125°C). However, the pouring temperature[20] of the inner ring of 1320 °C and the maximum interface temperature of 1219 °C did not produce a bonding.

Table 5.

Pouring and maximum interface temperature

Pouring temperature[20] of the

inner ring (oC)[186]

Max. Interface Temperature

(oC)

1320

1219

1350

1242

1380

1260

1410

1280

Microstructures of Material

Pouring the inner ring at a temperature of 1320 ^{0}C

By pouring[187] the inner ring[188] at 1320 °C, metallurgical bonding between the interface plate and the inner ring[189] only occurred near to[190] the ingate[191] area. The micrographs in Figure 8 show the presence[192]

of[193] a gap at the contact area (a) and the microstructure on the inner ring (b) which[194] consists of ferrite, pearlite and[195] nodular graphite[196] [197].

a)

b) Fig. 8. Micrograph by pouring temperature[20] of 1320 ^{0}C; (a) contact section (b) inner part. Etched with 3% Nital

Pouring the inner ring at a temperature of 1350 oC

By pouring the inner ring at 1350 ^{0}C, metallurgical bonding between the interface plate and the inner ring[198] was achieved[199] on the entire contact surface. The micrograph in Figure 9 shows the presence of flake Graphite in some spots due to the considerably insufficient Mg treatment. Pearlite formed close to the contact area and[200] cementite formed along the boundary of pearlite islands. The hardness value of pearlite was found[201] to vary by the area/zone and its cooling rate, respectively[202].

By pouring the inner ring at 1350 ^{0}C, metallurgical bonding between the interface plate and the inner ring[203] was achieved[204] on the entire contact surface. The presence of pearlite may indicate the higher content of carbon compared to the rest[205] part of the interface plate.[206] This additional content of carbon may have considerably come from the inner ring material. Table 6 shows the distribution of pearlite hardness which[207] indicated difference[208] in the carbon content in the pearlite for each area (Davis et al., 1990). The difference in carbon content was also an indication of carbon

diffusion [209] in the contact area between the inner material and the interface material (Avcı et al., 2009) and a diffusion bonding. [210]

a)

b)

Fig. 9. Micrographs of the contact area interface-inner ring by pouring temperature [20] of 1350 ^{0}C; (a) contact section; (b) inner parts. Etched with 3% Nital

Table 6.

Pearlite hardness in average values at some positions

Hardness (HV)

Interface

Contact area

Inner

196.7

286.1

372.8

Pouring the inner ring at the temperature [20] of 1380 °C

By pouring [211] the inner ring [212] at 1380 °C, the interface plate became softer and weaker so that pressure generated by the inner [213] ring liquid might tear off the interface plate and [214] the liquid subsequently entered the outer material cavity.

The micrograph in Figure 10 shows the presence of nodular Graphite [196] in the matrix of ferrite. Along the contact line to the interface plate, the microstructure of the inner ring is dominated [215] by pearlite. [216] Cementite formed along the boundary of pearlite islands and at [217] the contact area. The hardness value of cementite at the interface is 499.8 HV. Table 7 shows the hardness value of pearlite at the interface plate and contact area. As can be seen in Figure10(b),

the liquid cast iron teared [218] off some of the interface plate [219] and flowed into the outer ring cavity.

Table 7.

Pearlite hardness values at p our temperature [20] of 1380 °C

Hardness (HV)

Interface

Contact area

Inner

233.1

338.7

-

Fig. 10. micrograph by pouring temperature [20] of 1380 ° C; (a) interface area; (b) interface plate. Etched with 3% Nital

Pouring the inner ring at the temperature[20] of 1410 °C

Pouring the inner ring at the temperature[20] of 1410°C raised the temperature[20] of the interface plate enormously,[220] so that the interface plate heated up to 1280°C. The interface p late[222] became soft and tore off at some spots. The inner ring material flowed through these spots into the outer ring cavity. This material came to direct contact with the NiHard1 liquid by subsequent[223] pouring of the outer ring. Figure 11 shows the microstructure of the contact area which[224] consists of martensite and M3C Carbide in the NiHard1 area, pearlite and cementite in the rest interface plate and[225] nodular graphite[196] in the inner ring material.[226]

□

Table 8.

Value of phase hardness at pouring temperature[20] 1410 °C

Section

Hardness (HV 0.2)

Perlite on interface

321.1

Martensite in the contact area

504

M3C on NiHard 1

985

Martensi[227] t e on NiHard1

607.8

a)

b)

Fig. 11. Micrographs by pouring the inner ring at temperature 1410 ^{0}C; (a) nodular cast iron in outer and inner ring cavities; (b) direct contact inner and outer ring material .[228] Etched with Nital 3%.

The hardness values of each phase are listed[229] in Table 8. There were differences in martensite hardness in the contact area and martensite on the NiHard1 base material, which was considerably determined by the concentration of carbon in martensite in both regions.[230]

Subsequent pouring of the outer ring at the interface temperature of 1000 pC[231] Nihard1 liquid was poured at the pouring temperature[20] of 1430°C into the mold immediately after the interface p late[232] reached the temperature[20] of 1000°C (shown in the Table[233] 4 as trial[234] 2, 4, 6 and[235] 8). Macro and microstructural observations have been conducted[236] to[237] the casting product. As shown in Figure 11, there[238]

Interface plate

Outer ring

was no bonding achieved by pouring the outer ring material at this interface temperature.[239] It can be therefore concluded[240] that the interface temperature of 1000 ^{0}C is inadequate to produce a diffusion bonding.[241]

a)

□produce a metallurgical bonding of the outer ring to the interface plate, whereas an excellent bonding of interface[242] plate to the inner ring[243] was obtained (Figure 12a). Bonding between the interface and the outer material did not occur at the entire contact surface. Figure 13 shows the microstructure at the contact area between the outer ring and interface[244] plate. The NiHard1 area (outer ring) consisted predominantly of martensite and M3C carbide.

Fig. 13. Micrograph of contact area as[245] resulted from pouring temperature[20] of 1430°C, interface temperature[20] of 1125^{0}C and pouring temperature[20] of the inner ring at 1350°C

The appearance of iron oxide at the pouring time interval of inner material and outer material prevented flawless contact at the interface and the bonding respectively[246] [247].

Outer ring

b)

Fig. 12. Micrograph by 1000 ^{0}C interface temperature; (a) gap between interface and the outer ring; (b) the closest contact area of the outer part to the interface plate

Since there was no achieved bonding between the material and the interface plate, it can be concluded[248] that the interface temperature of 1000 ^{0}C was inadequate to produce a diffusion bonding.

Subsequent pouring of the outer ring at the interface temperature of 1125^{0}C Pouring the inner ring at 1320 °C and followed by pouring the outer ring at 1430°C at the interface temperature of 1125 °C (90% of the lowest melting temperature[20]) as shown in Table 4 as trial 1[249] did not produce a metallurgical bonding of the outer ring to the interface plate. Bonding between the interface and the outer material did not occur at all. Metallurgical bonding between inner material[250] and outer material was not identified[251]. Gap[252] was found[253] at[254] almost along the contact line between the interface plate and inner material (Figure 8a). Pouring the inner ring at 1350 °C and followed by pouring the outer ring at 1430°C at the interface temperature of 1125 °C as shown in the Table[255] 4 as trial 3[256] did not[257]

Fig. 14. EDS results in the contact area of the interface

Iron[258] oxide formed due to the reaction between iron and oxygen or iron with water vapor. The appearance of oxide on the interface is proven by the EDS test results as[259,260] shown in Figure 14. The EDS results show the high oxygen values found in the contact[261] area interface with the outer material. This oxygen is present in the form of iron oxide. Referring to the Ellingham diagram, it is found[2] that the reaction of Fe and O with the lowest Gibs energy is the reaction for the formation of Fe2O3.[263]

Pouring the inner ring at 1380 °C and followed by[264] pouring the outer ring at 1430°C at the interface temperature of 1125 °C as shown in the Table[265] 4 as trial 5 generated metallurgical bonding between the interface plate and the outer ring. Bonding between the interface plate and the inner material also occurred at the entire contact surface of both materials.[266] The contact area at the interface plate became softer. In addition to this, the flushing time of 7 seconds pushed the oxide upwards and rinsed the contact[267]

surface[268]. Flushing time is the time needed for the liquid to pass through the cavity of the outer ring to the flow off tank[269,270]. Figure 15 shows that at the contact area, the pearlite grain became very fine and was surrounded by cementite at the grain boundary.[271] Pearlite in other areas in[272] the interface plate remained coarse. The microstructure of NiHard1 material close to the contact area was predominantly martensite.

Fig. 15. Micrograph by interface temperature of 1125^{0}C and pouring temperature[20] of the inner ring of 1380°C (trial 5)

Pouring the inner ring at 1410 °C and followed by[273] pouring the outer ring at 1430°C at the interface temp erature[274] of 1125 °C as shown in the Table[275] 4 as trial 7[276] did not produce a good[277] bimetallic casting. The interface plate was torn off in some spots resulting in the inner ring material entering into the cavity of outer[27 ring.[279] Furthermore, this caused a direct contact to the inner ring material by subsequent[280] pouring of the outer ring material (Figure 15).

Bonding Fraction

The diffusion bonding between the inner material and the interface plate occurred at pouring temperatures of 1350 °C, 1380

°C, and 1410 °C and the resulting highest interface temperatures of 1242 °C, 1260 °C, and 1280 °C, respectively (Table 5). At these temperatures, the bonding fraction varies from 78 to 100%. In some spots, gaps and porosities at the contact area have been identified.[281] By pouring the inner ring liquid at the temperature[20] of 1320 °C and the maximum interface temp erature[282] of 1219 °C, diffusion bonding occured[283] only in a small area in the inner ring close to the ingate[284] area. The percentage fraction of bonding is described[285] in Figure 16. By pouring the outer material at the interface temperature of 1000°C, diffusion bonding was not performed.[286] Higher interface temperature (1125°C) and pouring temperature[20] of inner[287] ring of 1350°C could not generate a bonding as well.[288] By pouring[289] the inner ring[290] at the temperature[20] of 1380°C, the interface temperature of 1125°C and[291] subsequent pouring of outer[292] ring at a temperature of 1430°C, diffusion bonding occurred almost in all area[293] of the interface.

Fig. 16. The bonding fraction of the interface plate to the inner ring at various pouring temperature[20]

Conclusions

Bimetallic products of nodular cast iron-white cast iron can be produced by consecutive[294] casting,[15] in which nodular cast iron as inner material is poured prior to[295] the pouring of the outer material. An interface plate made of low carbon steel is inserted into the mold to separate inner and outer material.[296] Good surface cleanliness, available contact pressure during solidification and cooling process, accurate pouring and interface temperatures, and adequate flushing time ensure the diffusion bonding. Since the available[297] contact time between interface plate and base material by a casting process is very limited, the required interface temperature prior to[298] the pouring of base material liquid for enabling diffusion bonding should be increased[299] up[300] to 90% of the lowest melting point. Flushing the interface plate by flowing liquid nodular cast iron for 2 seconds at pouring temperature[20] of 1350 °C to 1410 °C created sufficient diffusion bonding between the inner ring and interface plate. The diffusion bonding may be hindered by the formation of iron oxide on the surface of the interface plate during the interval time between the first and second pouring.[301] To form a metallic bonding between the interface plate and NiHard1 outer ring, an interface temperature of 1125°C, pouring temperature[20] of 1430°C and[302] flushing[303] time of 7 seconds are to be applied.

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1.	~~o f~~ → of	Confused Words	Correctness
2.	~~u~~ → you	Inappropriate Colloquialisms	Delivery
3.	0 ,	Improper Formatting	Correctness
4.	~~, I~~ → ; I, , and I, . I	Punctuation in Compound/Complex Sentences	Correctness
5.	~~u~~ → you	Inappropriate Colloquialisms	Delivery
6.	0 ,	Improper Formatting	Correctness
7.	~~o f~~ → of	Confused Words	Correctness
8.	~~u~~ → you	Inappropriate Colloquialisms	Delivery
9.	0 ,	Improper Formatting	Correctness
10.	~~, I~~ → ; I, , and I, . I	Punctuation in Compound/Complex Sentences	Correctness
11.	~~u~~ → you	Inappropriate Colloquialisms	Delivery
12.	0 ,	Improper Formatting	Correctness
13.	~~Consecutive~~ → Continuous, Serial	Word Choice	Engagement
14.	The consecutive	Determiner Use (a/an/the/this, etc.)	Correctness
15.	*casting; Casting*	Text Inconsistencies	Correctness
16.	~~consecutive~~ → following, successive	Word Choice	Engagement
17.	~~ring~~ → circle	Word Choice	Engagement

18.	*is made*	Passive Voice Misuse	Clarity
19.	*To enable a consecutive sequence of pouring*	Misplaced Words or Phrases	Correctness
20.	*temperature; Temperature*	Text Inconsistencies	Correctness
21.	, and	Punctuation in Compound/Complex Sentences	Correctness
22.	~~then~~	Wordy Sentences	Clarity
23.	~~mold~~ → image, frame, pattern, shape	Word Choice	Engagement
24.	*be done*	Passive Voice Misuse	Clarity
25.	*Flushing the interface plate for 2 seconds by flowing nodular cast iron liquid as inner material generated a diffusion bonding between the inner ring and interface plate at pouring temperatures of 1350 °C, 1380 °C, and 1410 °C.*	Incomplete Sentences	Correctness
26.	*was heated*	Passive Voice Misuse	Clarity
27.	, respectively	Punctuation in Compound/Complex Sentences	Correctness
28.	~~respectively~~	Wordy Sentences	Clarity
29.	~~at~~	Wordy Sentences	Clarity
30.	~~produced~~ → created	Word Choice	Engagement
31.	~~a sufficient~~ → an adequate	Word Choice	Engagement
32.	*was heated*	Passive Voice Misuse	Clarity

33.		Intricate Text	Clarity
34.	, and	Comma Misuse within Clauses	Correctness
35.	~~pouring~~ → flooding	Word Choice	Engagement
36.	temperature.	Closing Punctuation	Correctness
37.	~~special~~ → unique, select	Word Choice	Engagement
38.		Intricate Text	Clarity
39.	~~for~~ → to	Wrong or Missing Prepositions	Correctness
40.	combines	Wordy Sentences	Clarity
41.	~~by means of~~ → using, utilizing, employing, through	Wordy Sentences	Clarity
42.	*is influenced*	Passive Voice Misuse	Clarity
43.	~~at the rate of~~	Wordy Sentences	Clarity
44.	*was made*	Passive Voice Misuse	Clarity
45.	*was inserted*	Passive Voice Misuse	Clarity
46.	~~Inserting~~ → Adding	Word Choice	Engagement
47.	the pouring	Determiner Use (a/an/the/this, etc.)	Correctness
48.	~~pouring~~ → streaming	Word Choice	Engagement
49.	*was set*	Passive Voice Misuse	Clarity
50.	~~in order to~~ → to	Wordy Sentences	Clarity
51.	the initiation	Determiner Use (a/an/the/this, etc.)	Correctness

52.	~~preheating~~ → Preheating	Improper Formatting	Correctness
53.	~~preheating of~~ → Preheating	Wordy Sentences	Clarity
54.	~~a good~~ → an excellent	Word Choice	Engagement
55.	~~solid~~ → substantial	Word Choice	Engagement
56.	significantly affect	Misplaced Words or Phrases	Correctness
57.	microstructure,	Punctuation in Compound/Complex Sentences	Correctness
58.	~~liquid–solid~~ → liquid-solid	Misspelled Words	Correctness
59.	~~solid~~ → stable	Word Choice	Engagement
60.	*was then referred*	Passive Voice Misuse	Clarity
61.	to as	Wrong or Missing Prepositions	Correctness
62.	*be precipitated*	Passive Voice Misuse	Clarity
63.	~~, and that the~~ → . The	Hard-to-read text	Clarity
64.	~~layer~~ → coating, sheet	Word Choice	Engagement
65.	study,	Comma Misuse within Clauses	Correctness
66.	, but	Punctuation in Compound/Complex Sentences	Correctness
67.	*is aimed*	Passive Voice Misuse	Clarity
68.	applying for	Wrong or Missing Prepositions	Correctness
69.	~~were~~ → was	Faulty Subject-Verb Agreement	Correctness
70.	*were used*	Passive Voice Misuse	Clarity

71.	~~mold~~ → image, frame, pattern, womb	Word Choice	Engagement
72.		Passive Voice Misuse	Clarity
73.	*was inserted*	Passive Voice Misuse	Clarity
74.	~~mold~~ → frame, image, shape	Word Choice	Engagement
75.	~~prior to~~ → before	Wordy Sentences	Clarity
76.	*was designed*	Passive Voice Misuse	Clarity
77.	~~certain~~ → specific, particular	Word Choice	Engagement
78.	~~were~~ → was	Faulty Subject-Verb Agreement	Correctness
79.	*were designed*	Passive Voice Misuse	Clarity
80.	, and	Comma Misuse within Clauses	Correctness
81.	middle-frequency	Misspelled Words	Correctness
82.	*were used*	Passive Voice Misuse	Clarity
83.	~~then~~	Wordy Sentences	Clarity
84.	*was used*	Passive Voice Misuse	Clarity
85.	~~material~~ → article, element, content, document	Word Choice	Engagement
86.	an average, or the average	Determiner Use (a/an/the/this, etc.)	Correctness
87.	~~diameter~~ → width	Word Choice	Engagement
88.	, and	Comma Misuse within Clauses	Correctness
89.	, and	Comma Misuse within Clauses	Correctness

90.	~~in the range of~~	Wordy Sentences	Clarity
91.	*Pretrials; Pre-trials*	Text Inconsistencies	Correctness
92.	~~a~~ partial	Determiner Use (a/an/the/this, etc.)	Correctness
93.	*was set*	Passive Voice Misuse	Clarity
94.	~~pouring~~ → Pouring	Improper Formatting	Correctness
95.	*been conducted*	Passive Voice Misuse	Clarity
96.	*was found*	Passive Voice Misuse	Clarity
97.	*To achieve the determined interface temperature*	Misplaced Words or Phrases	Correctness
98.	~~off tank~~ → off-tank	Misspelled Words	Correctness
99.	the tank	Determiner Use (a/an/the/this, etc.)	Correctness
100.	~~up~~	Wordy Sentences	Clarity
101.	the cooling	Determiner Use (a/an/the/this, etc.)	Correctness
102.	, and	Punctuation in Compound/Complex Sentences	Correctness
103.	*was used*	Passive Voice Misuse	Clarity
104.	~~off tank~~ → off-tank	Misspelled Words	Correctness
105.	the tank	Determiner Use (a/an/the/this, etc.)	Correctness
106.	~~tank~~ → container	Word Choice	Engagement

107.	the tank	Determiner Use (a/an/the/this, etc.)	Correctness
108.	*is considered*	Passive Voice Misuse	Clarity
109.	, and	Punctuation in Compound/Complex Sentences	Correctness
110.	*is expressed*	Passive Voice Misuse	Clarity
111.	*is given*	Passive Voice Misuse	Clarity
112.	The pressure	Determiner Use (a/an/the/this, etc.)	Correctness
113.	~~a~~ bonding	Determiner Use (a/an/the/this, etc.)	Correctness
114.	~~which was~~	Wordy Sentences	Clarity
115.	~~the~~ direct	Determiner Use (a/an/the/this, etc.)	Correctness
116.	~~to~~ → with	Wrong or Missing Prepositions	Correctness
117.	~~contraction~~ → decrease, shrinkage	Word Choice	Engagement
118.	, and	Punctuation in Compound/Complex Sentences	Correctness
119.	, and	Comma Misuse within Clauses	Correctness
120.	*be expressed*	Passive Voice Misuse	Clarity
121.	*are shown*	Passive Voice Misuse	Clarity
122.	*be identified*	Passive Voice Misuse	Clarity
123.	the dimension	Determiner Use (a/an/the/this, etc.)	Correctness

124.	the outer	Determiner Use (a/an/the/this, etc.)	Correctness
125.	the diameter	Determiner Use (a/an/the/this, etc.)	Correctness
126.	~~, a~~ → ; a, . A	Punctuation in Compound/Complex Sentences	Correctness
127.	*was generated*	Passive Voice Misuse	Clarity
128.	~~oC~~ → C	Misspelled Words	Correctness
129.	The diameter	Determiner Use (a/an/the/this, etc.)	Correctness
130.	*was therefore cleaned*	Passive Voice Misuse	Clarity
131.	~~prior to~~ → before	Wordy Sentences	Clarity
132.	*was also rinsed*	Passive Voice Misuse	Clarity
133.	~~prior to~~ → before	Wordy Sentences	Clarity
134.		Intricate Text	Clarity
135.	~~off tank~~ → off-tank	Misspelled Words	Correctness
136.	the tank	Determiner Use (a/an/the/this, etc.)	Correctness
137.	~~dirt~~ → soil, trash, earth	Word Choice	Engagement
138.	*is found*	Passive Voice Misuse	Clarity
139.	~~temp erature~~ → temperature	Confused Words	Correctness
140.		Intricate Text	Clarity
141.	the tank	Determiner Use (a/an/the/this, etc.)	Correctness

142.	*This*	Intricate Text	Clarity
143.	*was achieved*	Passive Voice Misuse	Clarity
144.	design,	Punctuation in Compound/Complex Sentences	Correctness
145.	*was set*	Passive Voice Misuse	Clarity
146.	*To minimize the turbulence during the filling process*	Misplaced Words or Phrases	Correctness
147.	*was determined*	Passive Voice Misuse	Clarity
148.	*ingate*	Unknown Words	Correctness
149.	*This*	Intricate Text	Clarity
150.	the liquid	Determiner Use (a/an/the/this, etc.)	Correctness
151.	*was cast*	Passive Voice Misuse	Clarity
152.	~~temp erature~~ → temperature	Confused Words	Correctness
153.	*was set*	Passive Voice Misuse	Clarity
154.		Intricate Text	Clarity
155.	the inner, or an inner	Determiner Use (a/an/the/this, etc.)	Correctness
156.	~~oC~~ → C	Misspelled Words	Correctness
157.	The temperature	Determiner Use (a/an/the/this, etc.)	Correctness
158.	~~oC~~ → C	Misspelled Words	Correctness
159.	the inner, or an inner	Determiner Use (a/an/the/this, etc.)	Correctness

160.	~~oC~~ → C	Misspelled Words	Correctness
161.	*was measured*	Passive Voice Misuse	Clarity
162.	*was placed*	Passive Voice Misuse	Clarity
163.	, and	Punctuation in Compound/Complex Sentences	Correctness
164.	~~casting~~ → castings	Incorrect Noun Number	Correctness
165.	*were made*	Passive Voice Misuse	Clarity
166.	~~micro hardness~~ → microhardness	Confused Words	Correctness
167.	*of*	Inappropriate Colloquialisms	Delivery
168.	An optical	Determiner Use (a/an/the/this, etc.)	Correctness
169.	*was used*	Passive Voice Misuse	Clarity
170.	*was carried*	Passive Voice Misuse	Clarity
171.	~~on~~ → in	Wrong or Missing Prepositions	Correctness
172.	*were etched*	Passive Voice Misuse	Clarity
173.	~~, so the~~ → . The	Hard-to-read text	Clarity
174.	*was partially melted*	Passive Voice Misuse	Clarity
175.	*were taken*	Passive Voice Misuse	Clarity
176.	, and	Punctuation in Compound/Complex Sentences	Correctness
177.	*was conducted*	Passive Voice Misuse	Clarity
178.	~~cross section~~ → cross-section	Misspelled Words	Correctness

179.	*was monitored*	Passive Voice Misuse	Clarity
180.	, which	Punctuation in Compound/Complex Sentences	Correctness
181.	*was placed*	Passive Voice Misuse	Clarity
182.		Intricate Text	Clarity
183.	~~diverse~~ → different	Word Choice	Engagement
184.	~~ring~~ → circle	Word Choice	Engagement
185.	the pouring	Determiner Use (a/an/the/this, etc.)	Correctness
186.	~~oC~~ → C	Misspelled Words	Correctness
187.	~~pouring~~ → flooding	Word Choice	Engagement
188.	~~ring~~ → circle	Word Choice	Engagement
189.	~~ring~~ → circle	Word Choice	Engagement
190.	~~to~~	Wordy Sentences	Clarity
191.	~~ingate~~ → gate	Misspelled Words	Correctness
192.	presence.	Closing Punctuation	Correctness
193.	~~of~~ → Of	Improper Formatting	Correctness
194.	, which	Punctuation in Compound/Complex Sentences	Correctness
195.	, and	Comma Misuse within Clauses	Correctness
196.	*graphite; Graphite*	Text Inconsistencies	Correctness

197.	*of a gap at the contact area (a) and the microstructure on the inner ring (b) which consists of ferrite, pearlite and nodular graphite.*	Incomplete Sentences	Correctness
198.	~~ring~~ → circle	Word Choice	Engagement
199.	*was achieved*	Passive Voice Misuse	Clarity
200.	, and	Punctuation in Compound/Complex Sentences	Correctness
201.	*was found*	Passive Voice Misuse	Clarity
202.	~~, respectively~~	Wordy Sentences	Clarity
203.	~~ring~~ → circle	Word Choice	Engagement
204.	*was achieved*	Passive Voice Misuse	Clarity
205.	~~rest~~ → best	Confused Words	Correctness
206.		Intricate Text	Clarity
207.	, which	Punctuation in Compound/Complex Sentences	Correctness
208.	the difference, or a difference	Determiner Use (a/an/the/this, etc.)	Correctness
209.	~~diffusion~~ → Diffusion	Improper Formatting	Correctness
210.	*diffusion in the contact area between the inner material and the interface material (Avcı et al., 2009) and a diffusion bonding.*	Incomplete Sentences	Correctness
211.	~~pouring~~ → flooding	Word Choice	Engagement
212.	~~ring~~ → circle	Word Choice	Engagement

213.	~~inner~~ → internal	Word Choice	Engagement
214.	, and	Punctuation in Compound/Complex Sentences	Correctness
215.	*is dominated*	Passive Voice Misuse	Clarity
216.		Intricate Text	Clarity
217.	~~at~~ → in	Wrong or Missing Prepositions	Correctness
218.	~~teared~~ → tore	Misspelled Words	Correctness
219.	~~plate~~ → plates	Incorrect Noun Number	Correctness
220.	enormously,	Punctuation in Compound/Complex Sentences	Correctness
221.		Intricate Text	Clarity
222.	~~p late~~ → plate	Confused Words	Correctness
223.	the subsequent	Determiner Use (a/an/the/this, etc.)	Correctness
224.	, which	Punctuation in Compound/Complex Sentences	Correctness
225.	, and	Comma Misuse within Clauses	Correctness
226.		Intricate Text	Clarity
227.	~~Martensi~~ → Martens	Misspelled Words	Correctness
228.	material .	Improper Formatting	Correctness
229.	*are listed*	Passive Voice Misuse	Clarity
230.	*There were differences in martensite*	Hard-to-read text	Clarity

	hardness in the contact area and martensite on the NiHard1 base material, which was considerably determined by the concentration of carbon in martensite in both regions.		
231.	~~pC~~ → PC, Pc	Misspelled Words	Correctness
232.	~~p late~~ → plate	Confused Words	Correctness
233.	~~the~~ Table	Determiner Use (a/an/the/this, etc.)	Correctness
234.	~~trial~~ → trials	Incorrect Noun Number	Correctness
235.	, and	Comma Misuse within Clauses	Correctness
236.	*been conducted*	Passive Voice Misuse	Clarity
237.	~~to~~ → on	Wrong or Missing Prepositions	Correctness
238.	there.	Closing Punctuation	Correctness
239.	*was no bonding achieved by pouring the outer ring material at this interface temperature.*	Incomplete Sentences	Correctness
240.	*be therefore concluded*	Passive Voice Misuse	Clarity
241.		Intricate Text	Clarity
242.	the interface	Determiner Use (a/an/the/this, etc.)	Correctness
243.	~~ring~~ → circle	Word Choice	Engagement
244.	the interface	Determiner Use (a/an/the/this, etc.)	Correctness
245.	~~as~~	Wordy Sentences	Clarity
246.	, respectively	Punctuation in	Correctness

		Compound/Complex Sentences	
247.		Intricate Text	Clarity
248.	*be concluded*	Passive Voice Misuse	Clarity
249.	~~1~~ → one	Improper Formatting	Correctness
250.	~~material~~ → content	Word Choice	Engagement
251.	*was not identified*	Passive Voice Misuse	Clarity
252.	The gap	Determiner Use (a/an/the/this, etc.)	Correctness
253.	*was found*	Passive Voice Misuse	Clarity
254.	~~at~~	Wordy Sentences	Clarity
255.	~~the~~ Table	Determiner Use (a/an/the/this, etc.)	Correctness
256.	~~3~~ → three	Improper Formatting	Correctness
257.		Intricate Text	Clarity
258.	The iron	Determiner Use (a/an/the/this, etc.)	Correctness
259.	~~as~~	Wordy Sentences	Clarity
260.	, as	Punctuation in Compound/Complex Sentences	Correctness
261.	~~the contact~~ → the contact	Improper Formatting	Correctness
262.	*is found*	Passive Voice Misuse	Clarity
263.		Intricate Text	Clarity

264.	~~followed by~~ → then	Wordy Sentences	Clarity
265.	~~the~~ Table	Determiner Use (a/an/the/this, etc.)	Correctness
266.		Intricate Text	Clarity
267.	contact.	Closing Punctuation	Correctness
268.	~~surface~~ → Surface	Improper Formatting	Correctness
269.	~~off tank~~ → off-tank	Misspelled Words	Correctness
270.	the tank	Determiner Use (a/an/the/this, etc.)	Correctness
271.		Intricate Text	Clarity
272.	~~areas in~~ → regions of, regions in	Word Choice	Engagement
273.	~~followed by~~ → then	Wordy Sentences	Clarity
274.	~~temp erature~~ → temperature	Confused Words	Correctness
275.	~~the~~ Table	Determiner Use (a/an/the/this, etc.)	Correctness
276.	~~7~~ → seven	Improper Formatting	Correctness
277.	~~a good~~ → an excellent	Word Choice	Engagement
278.	the outer	Determiner Use (a/an/the/this, etc.)	Correctness
279.		Intricate Text	Clarity
280.	the subsequent	Determiner Use (a/an/the/this, etc.)	Correctness
281.	*been identified*	Passive Voice Misuse	Clarity
282.	~~temp erature~~ → temperature	Confused Words	Correctness

283.	~~occured~~ → occurred	Misspelled Words	Correctness
284.	~~ingate~~ → gate	Misspelled Words	Correctness
285.	*is described*	Passive Voice Misuse	Clarity
286.	*was not performed*	Passive Voice Misuse	Clarity
287.	the inner	Determiner Use (a/an/the/this, etc.)	Correctness
288.	~~as well~~	Wordy Sentences	Clarity
289.	~~pouring~~ → flooding	Word Choice	Engagement
290.	~~ring~~ → circle	Word Choice	Engagement
291.	, and	Punctuation in Compound/Complex Sentences	Correctness
292.	the outer	Determiner Use (a/an/the/this, etc.)	Correctness
293.	~~area~~ → areas	Incorrect Noun Number	Correctness
294.	~~consecutive~~ → continuous, serial	Word Choice	Engagement
295.	~~prior to~~ → before	Wordy Sentences	Clarity
296.	~~material~~ → element	Word Choice	Engagement
297.	~~available~~ → possible	Word Choice	Engagement
298.	~~prior to~~ → before	Wordy Sentences	Clarity
299.	*be increased*	Passive Voice Misuse	Clarity
300.	~~up~~	Wordy Sentences	Clarity

301.		Intricate Text	Clarity
302.	, and	Comma Misuse within Clauses	Correctness
303.	a flushing	Determiner Use (a/an/the/this, etc.)	Correctness
304.	~~to~~	Wrong or Missing Prepositions	Correctness
305.	, which	Punctuation in Compound/Complex Sentences	Correctness
306.	the HIBAH	Determiner Use (a/an/the/this, etc.)	Correctness
307.	~~to~~	Wrong or Missing Prepositions	Correctness
308.	~~POLMAN~~ → Polman	Confused Words	Correctness
309.	~~sector~~ → sectors	Incorrect Noun Number	Correctness
310.	Abrasion-resistant	Misspelled Words	Correctness
311.	, Illinois	Punctuation in Compound/Complex Sentences	Correctness
312.	*les*	Unknown Words	Correctness
313.	~~ratio of~~ → ratio of	Improper Formatting	Correctness