The study on mechanical properties of pack carburized low carbon steel using BaCO$_3$ as energizer

D N K P Negara* and I M Widiyarta
Mechanical Engineering Department of Udayana University, Street of Bukit Jimbaran, Badung, Bali, Indonesia 80362

E-mail: devputranegara@gmail.com

Abstract. Machine components such as crankshaft and gear require hard surface and ductile core characteristics. One method to obtain such characteristics is pack carburizing. This research concern to compare the mechanical properties of carburized low carbon steel under different carburizers; GBC (80% goat bone charcoal + 20% BaCO$_3$) and BC (80% bamboo charcoal + 20% BaCO$_3$) and derived from reference. Pack carburizing was carried out by heating up to a temperature of 950°C, holding for 4 hours and quenching in the oil. The results showed that hardness, yield strength, tensile strength and modulus elasticity of carburized steels increased significantly, however, there was a decrease in elongation. The closer to the core the lower of hardness obtained until reach a total case depth of 1.5 mm and 2 mm for carburized using BC and GBC, respectively. The use of carburizer GBC produces carburized steel with a higher yield strength (51.75 kg.mm$^{-2}$), tensile strength (74.58 kg.mm$^{-2}$), and elongation (5.78 %) than carburizer BC but lower in hardness (558.13 HV1), modulus elasticity (256.79 GPa), and effective case depth (0.33 mm). The mechanical properties of carburized low carbon steels have fulfilled requirements as the material of gear or shaft.

1. Introduction
Many steel components in the automotive industry such as cams, gears, and shafts which are subjected to surface damages like wear and corrosion. Also, the static and dynamic loads applied to them demand that they possess both tough cores and hard surfaces [1]. Such properties assure the components have high shock-resistant cores and wear-resistant surfaces [2] therefore they also can withstand tensile, impact, compressive, torsion, abrasive, bending, and shear stresses. Finally, those properties give a longer lifetime [3]. The components failures such as wear, deformation, tearing and cracking will more easily occur if the requirements are not met [4]. The materials commonly used to produce the components are Steel Forging Carbon Chrom Molybdenum (SFCM), Steel Nickel Forging Chrome Molybdenum (SNFCM) and Carbon Steel (SC). Carbon steel is categorized as low, medium and high carbon steel when their carbon content is less or equal to 0.25 %, in the range of 0.25 % to 0.55 % and more than 0.55 % respectively. High carbon steel with carbon content around 0.8 % is hard, but also brittle, and therefore cannot be used in machine parts such as gears and shafts that are exposed to dynamic banding and tensile stress during operation. Besides, high carbon steel with a carbon content as high as 1 % C is also difficult to be manufactured by a machining process such as turning, drilling or milling. These limitations can be eliminated by using low carbon steel. Low carbon steel has properties similar to iron [5]. It is ductile and easier to machine a component to its final form and dimensions before being given surface hardening such as pack carburizing process. The purpose of this process is
to produce a hard, wear-resistant case which will be resistant to both bending and contact fatigue whilst still maintaining its toughness and ductility core [6].

Table 1. The use of carbon from different materials for carburizer

| No | The sources of carbon | Authors |
|----|------------------------|---------|
| 1  | Palm kernel shell, mammalian bones from cattle, oyster shell | Oyetunji et al., 2012 [6] |
| 2  | Sugar cane waste, melon shells waste, aracacceae flower wastes | Ihom et al., 2013 [7] |
| 3  | Graphite, charcoal, palm kernel shell | Alagbe, 2011 [8] |
| 4  | Sugar cane, melon shell, rice husks, plastics, egg shell, arecacceaea flower droppings, charcoal and polyethylene | Ihom et al., 2012 [9] |

Pack carburizing is the addition of carbon to the surface of low carbon steels by diffusion process at temperatures within the austenitic region of the steel concern, which generally is between 850°C and 950°C [1]. The longer the steel is held in the carbon-rich environment, the greater the carbon penetration will be and the higher the carbon content. Until a condition, the carbon content of the steel is proportional to its hardness [10]. As the carbon content increases, the metal becomes harder and stronger but less ductile [5]. The major influencing parameters in the carburizing process are the holding time, carburizing temperature, carbon source and the quench time [1]. Carbon sources from different material have become an interesting topic to be researched (some of them are listed in Table 1) due to different material having different carbon content potential. To improve the low carburizing potential of the material, it is commonly mixed with energizer. Also, the energizers, such as Na₂CO₃, CaCO₃ or BaCO₃ [10] with a composition in the range of 0-40%, also accelerate the process of pack carburizing. At high temperature, energizer, BaCO₃ for example, decomposes to carbon dioxide and barium oxide. Carbon dioxide reacts then with the carbon of carburizer and produces carbon monoxide. The carbon deposited on the surface of the steel is dissolved by the austenite phase of the steel and diffuses into the steel which on subsequent quenching in water or oil develops a hard case [11]. The chemical reactions follow reaction (1), (2), and (3) [10]. At reaction (3), it is showed that carbon atom of carburizer has diffused into the low carbon steel surface and form FeC.

\[
BaCO_3 \rightarrow BaO + CO_2 \tag{1}
\]

\[
CO_2 + C \rightarrow 2CO \tag{2}
\]

\[
2CO + Fe \rightarrow FeC + CO_2 \tag{3}
\]

Because the use of medium carbon steel or high carbon steel has disadvantages due to its more expensive price and more difficult to machining for gear application, in this work, the mechanical properties of low carbon steel that pack carburized using goat bone and bamboo charcoals and energizer of BaCO₃ were investigated in order to find out their characteristics that fulfil the requirement for gear applications. The investigated mechanical properties include hardness distribution, yield and ultimate strength, modulus elasticity, and elongation.

2. Method

2.1. Materials and specimens
The raw materials used in this research were low carbon steel (0.17% C), barium carbonate (BaCO₃), goat bones and bamboos. The low carbon steel and BaCO₃ were collected locally from Denpasar building materials shop, Bali-Indonesia. Goat bones and bamboos were also collected from around Denpasar. At previous work, it was reported that the carbon contents of goat bone and bamboo charcoals were 18.95% and 66.4% respectively [12]. The tensile samples were made based on ASTM E8/E8M.
Each end of the sample is made 25 mm extra, prepared as samples for the hardness and microstructure test.

2.2. Pack carburizing process
The goat bones and bamboos are heated until form charcoal. They were then pulverized and powdered. Both are made to become carburizers by mixing with energizer (BaCO$_3$) with each ratio of charcoal: energizer was 80%: 20% weight. The carburizers made were denoted as GBC (80% goat bone charcoal + 20% BaCO$_3$) and BC (80% bamboo charcoal + 20% BaCO$_3$). The experiment was carried out by placing a specimen in a steel box containing a carburizer. The steel box was tightly sealed with clay case to prevent unwanted furnace gas from accessing it during heating so the carburizer is no burn [13]. The steel box was then placed in an electric furnace (Nabertherm, 0-1300 °C), heated to a temperature of 950 °C and held at this temperature for 4 hours. The steel box is then removed from the furnace, the specimens were taken from the steel box and cooled in the oil.

2.3. Mechanical properties characterization
The end of each tensile test samples was cut to 25 mm length, polished, etched and measured for their cross-section area hardness from the surface to the core by use of Vickers Hardness Tester Machine Zwicle (0.1-10 kg) and observed of their microstructure by use of Metallurgical Microscope Nicon Eclipse LV150 (50-1500x magnification). The tensile tests were undertaken by applied ASTM E8/E8 using Universal Tensile Machine, Hung-Ta, Type HT-501, serial number 1562, capacity 500 kN and resolution 0.025 kN.

3. Results and discussion
3.1. Hardness distribution of carburized low carbon steels
The hardness distribution of raw material (RM) and carburized low carbon steels at the cross-section area (25 mm in diameter) from the surface to the core are presented in Figure 1. It can be seen that hardness distributions of samples have a similar pattern; the closer to the core the lower hardness obtained and at a distance the hardness is relatively the same to the hardness of raw material (183.13 HV$_1$). This pattern is typical all of the carburized steel [14,15]. The highest surface hardness of 575.23 HV$_1$ is obtained at carburized steel with carburizer BC with the total case depth of around at 1.5 mm. The total case depth is the distance when the hardness of carburized steel is the same as the hardness of raw material. In this case, the carburized steel with carburizer GBC has a lower surface hardness (558.13 HV$_1$) but higher in total case depth (2 mm) than the carburized steel with carburizer BC.

Another important parameter of carburizing product is the effective case depth or case-hardened depth (CHD). Under European Standard EN ISO 2639 [16], CHD is defined as the depth from the surface to the point (distance) where the hardness is 550 HV$_1$. By use of the interpolation method, it was found that carburized low carbon steels with carburizer GBC and BC have an effective case depth of 0.44 mm and 0.33 mm respectively. The effective case depth obtained has fulfilled the common case depth of carburized steel which is in the range of 0.1 – 1.5 mm [17]. The increase of hardness on the surface is also indicated by presenting of thin ring signs at the cross-section area fracture of carburized specimens as shown in Figure 2 (B) and 2(C). This ring sign does not exist on the raw material surface, as shown in Figure 2 (A). These signs indicated that there are higher carbons content at the surface due to carbon diffusion, consequently, the higher hardness on the surface than in the core. The change of the hardness from raw material to the carburized low carbon is also indicated by the change of raw material microstructure after carburized, as shown in Figure 3. The raw material, as shown in Figure 3 (A) has original microstructures containing ferrite (light) and pearlite (dark). Ferrite and pearlite are relative ductile structures affecting the low hardness of raw material. During pack carburizing, cementite (Fe$_3$C) is formed due to the diffusion of carbon into the steel surface and reacts with Fe of the steel. The increasing of C and the forming of cementite structure affecting the higher hardness obtained after pack carburizing.
3.1. Mechanical properties from tensile test

Table 2 represents the mechanical properties of raw material and carburized steels. Generally, yield strength, ultimate strength, and modulus elasticity of carburized low carbon steels increase significantly compared to raw material, on the other hand, there is a decrease in elongation. These results agree with the work of Shristee et al., 2013 [18] and Fatai et al., 2009 [19]. After pack carburizing process, the yield strength (31.99 kg.mm$^{-2}$), ultimate strength (42.08 kg.mm$^{-2}$) and modulus elasticity (208.19 GPa) of raw material increase to each 51.75 kg.mm$^{-2}$, 74.58 kg.mm$^{-2}$ and 256.79 GPa for carburized steel.
using carburizer GBC and 45.78 kg.mm\(^{-2}\), 57.91 kg.mm\(^{-2}\) and 260.10 GPa respectively for carburized steel using carburizer BC. The increases of these mechanical properties are affected by increasing specimen hardness after carburizing process. On the other hand, increasing of hardness produces declining of material ability to strain significantly. The elongation of raw material (30.07 %) drops to 5.78 % and 5.85 % for carburized steel using carburizer GBC and BC respectively. Carburizing process by use of carburizer BC yields higher surface hardness, modulus elasticity and elongation than carburizer GBC but lower in yield strength, and ultimate strength. The higher hardness of carburized steel by use of carburizer BC (as shown in Figure 1) yields also higher modulus elasticity, this represents that the steel is stiffer than carburized steel with carburizer GBC.

### Table 2. Mechanical properties of raw material and carburized steels.

| Samples | Mechanical Properties |
|---------|-----------------------|
|         | Yield Strength, \(\sigma_y\) [kg.mm\(^{-2}\)] | Ultimate Strength, \(\sigma_u\) [kg.mm\(^{-2}\)] | Elongation, \(\varepsilon\) [%] | Modulus Elasticity, \(E\) [GPa] |
| RM      | 31.99                 | 42.08                 | 30.07                 | 208.19                 |
| GBC     | 51.75                 | 74.58                 | 5.78                  | 256.79                 |
| BC      | 45.78                 | 57.91                 | 5.15                  | 260.10                 |

The comparison of mechanical properties among carburized steels, materials SFCM (Steel Forging Carbon Chrome Molybdenum), SNFCM (Steel Nickel Forging Chrome Molybdenum) and SC (Carbon Steel) that are commonly used for gear and shaft is shown in Table 3. It can be seen that the mechanical properties of carburized steel with carburizer GBC have fulfilled the mechanical properties of JIS G 3221 (type SFCM 75S and SFCM 75D), JIS S 3222 (type SNFCM 70S and SNFCM 70D) and S45 C. Meanwhile, carburized steel with carburizer BC yields mechanical properties which are close to JIS G 3221 (type SFCM 60S and SFCM 60D) and S35 C. It is shown that carburized steel with carburizer GBC produces better mechanical properties than with energizer BC. This is proved by higher mechanical properties specified of SNFCM, SFCM and SC can be achieved by the carburized steel with carburizer GBC than carburizer BC.

### Table 3. Mechanical properties comparison of carburized steel, SNFCM, SFCM and SC [20].

| Materials       | Yield strength \(\sigma_y\) [kg.mm\(^{-2}\)] | Ultimate strength \(\sigma_u\) [kg.mm\(^{-2}\)] | Surface hardness \(HV_i\) |
|-----------------|---------------------------------------------|---------------------------------------------|-------------------|
| Carburized steel, GBC | 51.75                                      | 74.58                                      | 558.13            |
| Carburized steel, BC     | 45.78                                      | 57.91                                      | 575.23            |
| SNFCM 70S/70D       | 50                                         | 70-85                                      | 210               |
| SFCM 75S/75D       | 50                                         | 70-95                                      | 228               |
| S45C              | 50                                         | 70                                         | 247               |
| SFCM 60S/60D       | 37                                         | 65-75                                      | 179               |
| S35C              | 40                                         | 58                                         | 210.5             |

### 4. Conclusions

By adding of energizer BaCO\(_3\), goat bone and bamboo charcoal are potential carbon sources that can be used as carburizer in the pack carburizing process. After the process, the mechanical properties of low carbon steels increase except in elongation. The carburized steel using carburizer GBC gives greater mechanical properties than by use of carburizer BC due to higher yield and ultimate strength being achieved. The mechanical properties obtained of carburized steel have fulfilled the mechanical properties some types of SNFCM, SFCM, and SC so that can be used as materials of gear or shaft.
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